

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.

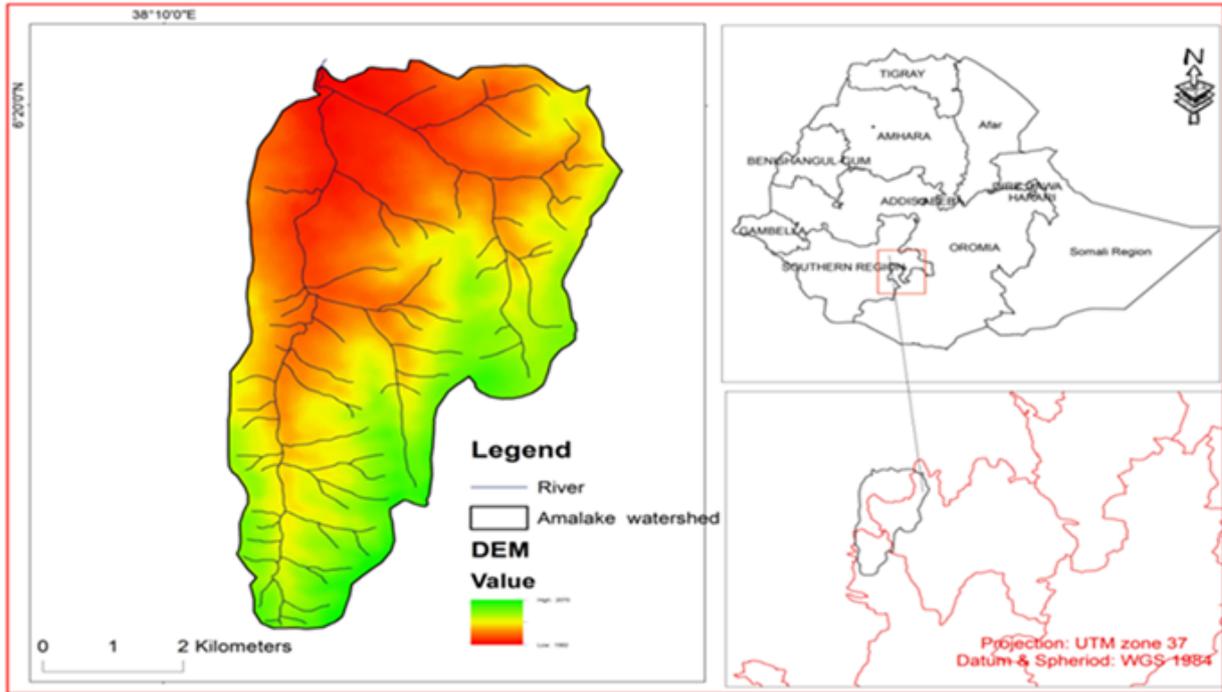


Figure 1. Location map of Amalake Watershed

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:

$$\%AS = [AR(g) - \frac{CM(g)}{4g - CM(g)}] \times 100 \quad (1)$$

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, micro-basin (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 bund, 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.

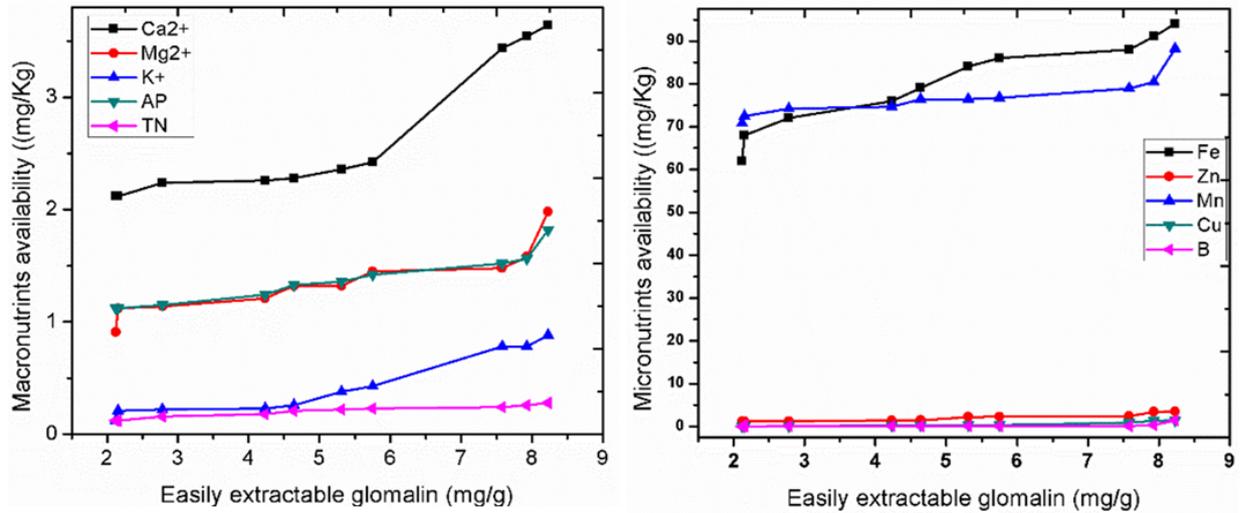


Figure 2. Correlations between soil glomalin contents and macronutrients (left) and micronutrients (right) availability

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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Factors associated with Household Satisfaction with Community Based Health Insurance and Policy Implication in Southern Ethiopia: A cross-sectional Study

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Abstract

Ethiopia has been implementing the CBHI program since 2011 in an effort to increase access to healthcare and improve universal health coverage by lowering costs for low-income families. Research on household satisfaction with health care is still lacking. The major objective of this study is to assess the level of household satisfaction with community-based health insurance services and related factors. A multistage sampling procedure was used to select participating families. In each of the selected kebeles, 406 households participating in the CBHI program were selected by simple random sampling according to the population proportional to sample size (PPS). Primary information was collected using a pre-tested questionnaire completed by an interviewer. Bivariate and multivariable logistic regression analysis as well as descriptive statistics were carried out. To identify independent predictors of household satisfaction with the CBHI, p -values <0.05 and 95% confidence intervals were used. The finding of this study showed that, household satisfaction with the CBHI scheme was moderate in Southern Ethiopia. Age, marital status, payment fairness, healthcare coverage, waiting time, service quality, and drug availability were significant predictors of satisfaction with CBHI service. This study recommends that comprehensive health care coverage, e.g., for non-communicable diseases (chemotherapy, kidney disease, diabetes, hypertension, and others) and major surgeries, as well as improvements in overall services and their quality, are critical to increasing satisfaction in the region.

Keywords/Phrases: Community-based health insurance, Household satisfaction, Southern Ethiopia

1 Introduction

1.1 Background

As part of the Sustainable Development Goals, the world community pledged to achieve universal health coverage by 2030. Despite this dedication, half of the world's population still does not have access to basic medical care (Asante, Price, Hayen, Jan, & Wiseman, 2016; Dieleman *et al.*, 2018; Kutzin, 2013). Consequently, many individuals are driven into poverty due to the necessity of allocating a sig-

nificant portion of their household budgets to healthcare (Asante, Price, Hayen, Jan, & Wiseman, 2016; Dieleman *et al.*, 2018; Kutzin, 2013).

Designing an adequate health financing system in developing countries, particularly low-income ones, remains challenging and is a topic of intense discussion. According to Mebratie, Sparrow, Yilma, Alemu, and Bedi (2015), this problem is caused by a shortage of financial resources, slow economic growth, limitations on the public sector, and restricted organizational capacity. Healthcare spending

adversely affects the lower socioeconomic sectors of society, leading to dire living conditions for many households. Every year, some 150 million individuals worldwide suffer from financial difficulties, and about 100 million of them—the majority of whom live in developing nations—are forced into poverty as a result of high healthcare costs (Asante *et al.*, 2016; Dieleman *et al.*, 2018; Kutzin, 2013). In sub-Saharan Africa, where resources are scarce, over 90% of financial difficulties stem from healthcare and its associated impacts (Maeda *et al.*, 2014; Xu *et al.*, 2007). Between 7% and 13% of households in the Middle East and North Africa experience catastrophic medical costs (Elgazzar *et al.*, 2013).

Ethiopia is striving for universal health coverage (UHC), which includes high-quality healthcare that is accessible, cheap, and acceptable to every household (FDRE MoH, 2015/16). Ethiopia has established comprehensive and long-lasting financial risk protection through a community-based health insurance (CBHI) program as it is an essential part of UHC. This initiative aims to promote financial protection, facilitate cost-sharing between the government and citizens, ensure equitable access to healthcare, foster social inclusion, and mobilize domestic resources (Solomon, Hailu, & Tesfaye, 2011).

CBHI, which is based on the ideas of social solidarity and mutual aid, is mainly intended for people who don't have access to public, private, or employer-sponsored health insurance and who live and work in rural or urban informal sectors. It serves as an alternative financing method that is controlled, established, and managed by its members through contributions of a specified amount of money (Chankova, Sulzbach, & Diop, 2008; Tabor, 2005; Uzochukwu *et al.*, 2010). In the event of illness, it aims to mitigate unpredictable or high healthcare costs through regular premiums (Guide, 2006).

1.2 Problem Statement

Improved services are necessary for client satisfaction and the long-term viability of the CBHI program since CBHI subscribers demand higher-quality care. Although research on health insurance satisfaction is ongoing, existing studies indicate that satisfaction levels vary by region (Assefa & Mosse, 2011; Devadasan *et al.*, 2011; Naseer, Zahidie, &

Shaikh, 2012). a research investigation conducted in Nigeria revealed that 42.1% of participants were not happy with their health insurance plan (Devadasan *et al.*, 2011). In contrast, 54.7% of satisfaction rate was reported among households enrolled in CBHI in southwest Ethiopia (Mitiku Kebede & Geberetsadik, 2019).

Household healthcare service satisfaction is a multi-dimensional concept that encompasses clients' perceptions, expectations, and experiences (Naseer *et al.*, 2012; Nyandekwe, Nzayirambaho, & Kakoma, 2014). It is influenced by service quality, customer expectations, personal disappointments, and the feelings experienced during service delivery (Al-Abri & Al-Balushi, 2014; Assefa & Mosse, 2011; Devadasan *et al.*, 2011). Understanding insured household satisfaction and its influencing factors provides valuable evidence for policy and decision-making (Mohammed, Sambo, & Dong, 2011). Additionally, customer satisfaction studies amplify service users' voices and validate their experiences, contributing to improved healthcare planning (Bekele *et al.*, 2008; Kuzma *et al.*, 2012).

The primary reasons for dissatisfaction with healthcare services include a lack of medications, long waiting times, discourtesy from facility staff, and inadequate availability of diagnostic services (Bekele *et al.*, 2008). Because CBHI members must pay for prescription drugs, diagnostics, and other medical services at non-contracted facilities out of pocket, these problems are especially difficult for them (Nyandekwe *et al.*, 2014). This leads to additional costs and increased dissatisfaction among CBHI program members. In order to address these problems and preserve the allure of contracted care, surveys in this field are crucial for evaluating home satisfaction with CBHI and associated community factors.

Studies on Ethiopian households' satisfaction with CBHI services are very scarce (Badacho, Tushune, Ejigu, & Berheto, 2016; Mitiku Kebede & Geberetsadik, 2019). There are methodological and measurement shortcomings, and the research field is still understudied. In order to improve household satisfaction and acceptance of the CBHI program after health service visits in southern Ethiopia, this study aims to measure satisfaction levels, evaluate the factors associated with household satisfaction

with the CBHI scheme, and offer recommendations to policymakers and program designers.

2 Materials and Methods

2.1 Description of the study area

In the southern region of Ethiopia, a cross-sectional community-based survey was carried out between February 2021 and December 2022. The Southern Nations, Nationalities, and Peoples' Region (SNNPR) is one of the regional states of Ethiopia. Kenya (including a small area of Lake Turkana) borders the SNNPR on the south; South Sudan borders it on the west; the Gambela National Regional

State borders it on the northwest; the Oromia National Regional State borders it on the north and east; and the Ilemi Triangle, a region that both Kenya and South Sudan claim, borders it on the southwest. There will be 14,929,548 people living in the area, with 7,425,918 men and 7,503,630 women (Central Statistical Authority [CSA], 2007). There are 1,495,557 urban dwellers (10.02%) and 13,433,991 rural persons (89.98%). According to these figures, the SNNPR is the most rural region of Ethiopia. The area is roughly 105,887.18 square kilometers in size, and its population density is 141 persons per square kilometer. The average household size in the 3,110,995 homes in the region is 4.8 people (3.9 people in urban areas and 4.9 people in rural areas).

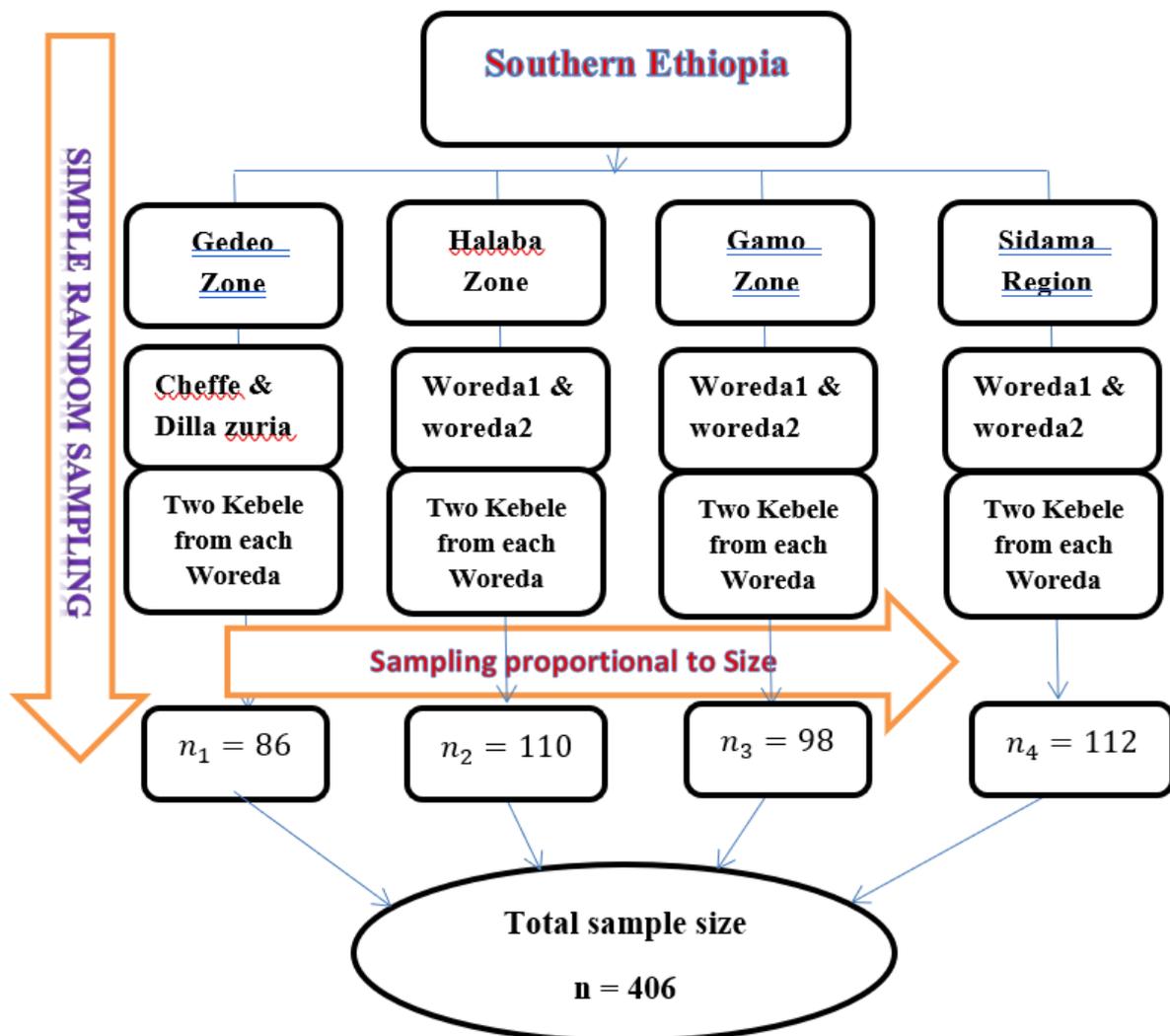


Figure 1. Sampling of study participants in the CBHI program, Southern Ethiopia. NB. Southern Ethiopia not refer to the region, we used to refer the southern part of Ethiopia

2.2 Study population

The second study area, Sidama, is around 275 kilometers south of Addis Ababa and was named Ethiopia's newest regional state in June 2020. In November 2019, Sidama—which had previously been one of the SNNPR's administrative zones—was officially recognized as Ethiopia's tenth regional state. Sidama is located geographically between latitudes 6°10' and 7°05' north and longitudes 38°21' and 39°11' east. It shares borders with the Gedeo zone and Oromia to the south, the Bilate River to the west, and the Oromia area to the east and south.

The CBHI program has been in place in the region since 2011. There are 3,975 health posts, 731 health clinics, and 79 government hospitals in the area.

All CBHI members who joined or renewed their membership during the study period, as well as those who received medical services, made up the study population. The study eliminated those who had not sought medical attention at least once.

2.3 Sample size determination and sampling techniques

The sample size was calculated using the formula for a single population proportion based on the following assumptions: a respondent satisfaction proportion of 80% from a previous study conducted by other researchers, with a margin of error of 5% at a 95% confidence level. The final sample size was determined to be 406, accounting for a design effect of 1.5 and a non-response rate of 10%.

The participating households were chosen using a multi-stage sampling procedure. Three zones and one region were selected at random to serve as the primary sample units in the first stage. Eight woredas, two from each zone, were chosen at random to serve as secondary sample units in the second stage. From the eight woredas that were picked, 16 kebeles were selected at random for the third stage. The study subjects (households) were chosen using simple random sampling within each specified kebele, adhering to population proportional to sample size (PPS).

2.4 Data collection tools and procedures

A pretested, interviewer-administered questionnaire was used to gather data. The National Health Insurance Agency's CBHI evaluation study in Ethiopia provided the data used to create the survey (Agency, 2015). To collect data, the questionnaire's English version was translated into the local tongue. Five percent of the actual sample size was pretested in two kebeles outside the target area that shared similar sociodemographic traits with the research population. Certain items were added or changed, and any unclear parts were explained, in light of the pretest results. Together, the supervisors and data collectors examined the pretest data to improve comprehension of the data gathering procedure. Five graduate nurses fluent in the local language and two professional nurses with bachelor's degrees in healthcare participated in the data collection. After participants were made aware of the purpose of the study and the importance of their involvement, in-person interviews took place.

Daily checks were performed to ensure that the questionnaires completed by the data collectors were accurate, consistent, and relevant, with oversight from the supervisors and the lead investigator. The next morning, before regular data gathering started, the data collectors received all relevant feedback.

2.5 Ethical Considerations

The Institutional Review Board (IRB) of Dilla University's College of Medicine and Health Sciences granted ethical approval for this study in compliance with the Helsinki Declaration. Additionally, permission letters were acquired from the Zone Health Department, the Woredas Health Department, and the SNNP Regional Health Office. The information was anonymized and all respondent IDs were kept private. Each participant gave verbal informed permission after IRB approval. Literacy levels were taken into account when collecting oral informed consent because the majority of the study group was from a rural location. Participants were still free to decide whether or not to take part in the study.

2.6 Household head's overall satisfaction

One outcome variable was household heads' overall satisfaction with the CBHI program. Nine statements on a five-point Likert scale, from "strongly disagree" to "strongly agree," were used to gauge satisfaction. The answers to each of the nine items were used to gauge the degree of satisfaction. The total of these answers produced a minimum value of 9 and a maximum value of 45. This sum was then converted to yield an individual satisfaction score ranging from 0 to 100%, which was used to calculate a percentage average. Responses of 75% or more on the nine satisfaction items were classified as "satisfied," while those scoring less than 75% were classified as "dissatisfied" (Sagaro, Yalew, & Koyira, 2015).

2.7 Data analysis

Data review, cleaning, and entry into SPSS version 21 were completed prior to analysis. The data was assessed using both descriptive and inferential statistics. Household satisfaction with the CBHI scheme was presented using frequency distributions, percentages, and graphs in the descriptive statistics, utilizing both qualitative and quantitative approaches.

The correlation between each explanatory factor and household satisfaction was assessed using the chi-square test. Factors from the bivariate analysis with a p-value of less than 0.15 were included in the final multivariable logistic regression analysis. The Hosmer-Lemeshow statistic and the coefficient of deviation were used to assess the model's fit, and the results showed a good fit ($P = 0.102$). The variance inflation factor (VIF) test was used to check potential variables for multicollinearity; no multicollinearity was found (all candidate variables had a VIF value of less than 1.7).

The association between home satisfaction and the CBHI scheme variables was examined using binary logistic regression. If a variable's p-value in the final model was less than 0.05, it was deemed to have a statistically significant relationship with household

satisfaction. A 95% confidence interval for the odds ratio was used to assess the association's strength.

3 Results

3.1 Socio-demographic characteristics of the respondents

The distribution of CBHI participants based on their demographic and socioeconomic factors is presented in Table 1. This study included 406 households, achieving a response rate of 100%. Among the respondents, 136 (33.5%) were families headed by females, while the remaining 270 (66.5%) were headed by males. The majority of respondents, 143 (35.2%), were between the ages of 40 and 50. Additionally, 68 respondents (16.7%) were under 34 years, 75 (18.5%) were between 35 and 39, and 120 (29.6%) were over 50.

Of the participants, 236 (58.1%) were primarily from rural areas, followed by 81 participants (20.0%) from semi-urban regions and 89 (21.9%) from urban areas. In terms of occupation, 94 respondents (23.2%) were day laborers, while 202 (49.8%) were farmers. The remaining respondents included 63 (15.5%) who were engaged in trade and 47 involved in other occupations.

Regarding education, 125 households (30.8%) had at least a secondary education, while 122 households (30.0%) had no formal education, and 159 households (39.2%) completed primary school. Additionally, over 349 households surveyed (or 86.0%) were married (Table 1).

3.2 Description of household satisfaction with CBHI services

Most respondents (81.3%) agreed or strongly agreed that service providers are professional and well-trained. Approximately 79.8% of respondents felt that the payment is commensurate with the services provided. Additionally, about 76.6% of respondents agreed or strongly agreed that the timing of premium payments is convenient (Table 2).

Table 1. Southern Ethiopian respondents' socio-demographic details, 2022 (n = 406)

Variables	Category	Frequency	Percent	Variables	Category	Frequency	Percent
Gender	Male	270	66.5	Education	no formal education	122	30
	Female	136	33.5		Primary	159	39.2
Age	less than 34	68	16.7		secondary & above	125	30.8
	35-39	120	29.6	Marital status	Single	22	5.4
	40-50	143	35.2		Married	349	86
greater than 50	75	18.5	Other		35	8.6	
Residence	Urban	89	21.9	Payment fairness	Fair	359	88.4
	semi-urban	81	20		Not fair	46	11.3
	Rural	236	58.1	Service availability	Not enough	204	50.2
Occupation	Farmer	202	49.8		Enough	202	49.8
	Merchant	63	15.5	Service quality	Not good	214	52.7
	Daily laborer	94	23.2		Good	192	47.3
	Other	47	11.6	Drug availability	Inadequate	301	74.1
			Adequate		105	25.9	

Table 2. Household satisfaction with CBHI services

Characteristics	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
CBHI benefit packages are sufficient to cover your household's medical expenses.	0	38(9.4)	103(25.4)	239(58.9)	26(6.4)
CBHI management is trustworthy	3(0.7)	25(6.2)	95(23.4)	249(61.3)	34(8.4)
Health care services are of good quality.	2(0.5)	22(5.4)	82(20.2)	268(66.0)	32(7.9)
Long waiting time to get the service	6(1.5)	52(12.8)	109(26.8)	194(47.8)	45(11.1)
Timing of premium payment is convenient	1(0.2)	20(4.9)	74(18.2)	206(50.7)	105(25.9)
Availability of drugs	7(1.7)	60(14.8)	123(30.3)	179(44.1)	37(9.1)
The provider makes a good diagnosis	2(0.5)	24(5.9)	80(19.7)	256(63.1)	44(10.8)
The service providers are professionals/well-trained	3(0.7)	10(2.5)	63(15.5)	256(63.1)	74(18.2)
The payment is commensurate with the service provision	10(2.5)	15(3.7)	57(14.0)	188(46.3)	136(33.5)

N.B. Each cell's numbers represent frequencies, and the percentages are enclosed in parentheses.

3.3 The degree of contentment with the CBHI program

Prior to evaluating respondents' overall happiness with the CBHI system, we used Cronbach's alpha to assess the internal consistency of the scale items measuring satisfaction. The nine-item scale had a Cronbach's alpha of 0.802. With a 95% confidence range (CI) ranging from 76.1% to 83.9%, the study found that 58.1% of households were pleased with CBHI health services.

3.4 Factors associated with household satisfaction with CBHI service

Multivariable analysis ($P < 0.05$) revealed significant associations between several variables and satisfaction with CBHI services: respondent age, marital status, payment fairness, healthcare coverage, waiting time, perceived quality of service, and availability of drugs (Table 3).

Table 3. A multivariable logistic regression analysis on variables related to the general level of home satisfaction in Southern Ethiopia

Variables	Satisfaction		COR (95% CI)	AOR(95% CI)
	Dissatisfied	Satisfied		
Gender				
Male	106	164	1.375(0.907, 2.085)	0.988 (0.553, 1.767)
Female	64	72	1	1
Household head age				
Less than 34	33	35	0.669(0.344, 1.300)	0.458 (0.186, 1.132)
35-39	62	58	0.590(0.328, 1.060)	0.482 (0.234, 0.993)*
40-50	46	97	1.329(0.743, 2.380)	1.095 (0.549, 2.182)
Greater than 50	29	46	1	1
Residence				
Urban	28	61	1.468(0.875, 2.463)	2.050 (0.937, 4.486)
Semi-urban	47	34	0.487(0.292, 0.813)	1.091 (0.517, 2.303)
Rural	95	141	1	1
CBHI service package awareness				
Aware			7.312(1.581, 33.819)	3.292 (0.537, 20.171)
Not aware			1	1
Payment fairness				
Fair	136	223	4.288(2.186, 8.412)	3.179 (1.480, 6.829)*
Not fair	33	13	1	1
Education				
No formal education	51	71	0.992(0.598, 1.645)	1.014 (0.504, 2.040)
Primary	67	92	0.978(0.608, 1.573)	0.865 (0.481, 1.557)
Secondary and above	52	73	1	1
Marital status				
Single	12	10	1.410(0.477, 4.168)	1.804 (0.444, 7.325)
Married	136	213	2.65(1.292, 5.438)	3.027 (1.194, 7.674)*
Other (divorce/widow)	22	13	1	1
Occupation				
Farmer	74	128	1.174(0.613, 2.246)	1.339 (0.567, 3.164)
Informal sector operator	34	29	0.579(0.269, 1.243)	0.663 (0.269, 1.634)
Daily laborer	43	51	0.805(0.396, 1.637)	0.802 (0.344, 1.870)
Other	19	28	1	1
Health care coverage				
Not enough	92	112	0.387(0.255, 0.587)	0.570 (0.337, 0.964)*
Enough	78	124	1	1
Waiting time				
Waiting less than 30 minutes	61	136	2.430(1.619, 3.647)	1.961 (1.223, 3.146)*
Waiting more than 30 minutes	109	100	1	1
Perceived Service quality				
Not good	121	114	0.378(0.249, 0.575)	0.593 (0.353, 0.997)*
Good	49	122	1	1
Drug availability				
Inadequate	149	151	0.25(0.148, 0.425)	0.277 (0.152, 0.505)*
Adequate	21	85	1	1

Families who agreed with the fairness of CBHI premium payments were three times more likely to be satisfied than those who disapproved, according to the multivariable logistic regression results (AOR = 2.978; 95% CI: (1.394, 6.36)). Furthermore, compared to respondents who were divorced or widowed, married respondents were around three times more likely to be satisfied with CBHI services (AOR = 3.228; 95% CI: (1.279, 8.151)).

The likelihood of satisfaction was 1.96 times higher among those who received treatment within 30 minutes compared to those who waited longer (AOR = 1.961; 95% CI: (1.223, 3.146)). Participants over 50 were more likely to be happy with CBHI services than those between the ages of 35 and 39 (AOR = 0.469; 95% CI: (0.229, 0.962)).

Furthermore, the odds ratio for participants who rated the quality of services as poor was 0.39 (AOR = 0.392; 95% CI: (0.243, 0.632)). Those who believed healthcare coverage was insufficient had an

odds ratio of 0.57 (AOR = 0.392; 95% CI: (0.337, 0.964)), and participants who perceived drug availability as inadequate had an odds ratio of 0.25 (AOR = 0.25; 95% CI: (0.14, 0.448)), making them less likely to be satisfied with CBHI services compared to their peers.

3.5 The role of CBHI for the Beneficiaries

Participants were asked seven questions on a five-point Likert scale, ranging from "strongly disagree" to "strongly agree," to assess the role of CBHI in service delivery. The majority of respondents (74.4%) indicated that they agreed or strongly agreed that CBHI reduces the cost of healthcare. Additionally, 60.9% of respondents agreed or strongly agreed regarding the accountability and responsiveness of healthcare providers, while 61.6% felt that CBHI improves the provision of reliable healthcare services. In contrast, 55.4% of respondents were neutral or disagreed about the availability of sufficient drugs (Table 4).

Table 4. Respondents' responses about the role of CBHI implementation in southern Ethiopia

Characteristics	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Improved health care access	5(1.2)	39(9.6)	117(28.8)	227(55.9)	18(4.4)
Improved the provision of consistent and timely health care services	5(1.2)	46(11.3)	105(25.9)	235(57.9)	15(3.7)
Improved the availability of health equipment	17(4.2)	42(10.3)	112(27.6)	217(53.4)	18(4.4)
Improved the provision of reliable health care services	9(2.2)	26(6.4)	108(26.6)	241(59.4)	22(5.4)
Raises the accountability and responsiveness of health care service providers	4(1.0)	52(12.8)	103(25.4)	207(51)	40(9.9)
Provides sufficient drugs	26(6.4)	76(18.7)	149(36.7)	136(33.5)	19(4.7)
Reduces expense of health care service	7(1.7)	29(7.1)	68(16.7)	151(37.2)	151(37.2)

N.B. The numbers in each cell are frequencies and the percentages are in parentheses.

4 Discussions

This study aimed to identify factors associated with household satisfaction with the CBHI program. We found that 58.1% of the 406 CBHI members surveyed were satisfied with the program. This result is slightly higher than satisfaction levels reported in Ethiopia's Anilemo district (54.1%) (Addise, Alemayehu, Assefa, & Erkalo, 2021) and Sheko district (54.8%) (Mitiku Kebede & Geberetsadik, 2019).

However, our findings are lower than those of previous studies in Ethiopia (Badacho *et al.*, 2016; Hailie, Hassen, & Temesgen, 2021).

The discrepancies may be attributed to differences in the definition of satisfaction, the characteristics of study participants, the location, and the time periods of the studies. In some regions, higher satisfaction levels in earlier studies might be linked to the ini-

tial phase of the program and subsequent improvements in the quality of health services. Additionally, some studies were conducted in healthcare facilities, particularly hospitals, which may have influenced participants' experiences with the CBHI program.

4.1 Socio-demography

In this study, age (Addise *et al.*, 2021; Badacho *et al.*, 2016; Jadoo, Puteh, Ahmed, & Jawdat, 2012; Mohammed *et al.*, 2011) and marital status (Jadoo *et al.*, 2012; Mohammed *et al.*, 2011) were found to be associated with satisfaction with the CBHI program. Households with older heads were more satisfied with care compared to those with younger heads. This may be attributed to the fact that older individuals are generally more likely to experience health issues; as they age, their likelihood of needing healthcare increases, making them more inclined to utilize health services without incurring out-of-pocket expenses for each service.

Several studies have indicated that member satisfaction with health insurance is significantly related to socio-demographic variables such as gender (Jadoo *et al.*, 2012), occupation (Badacho *et al.*, 2016), and educational status (Jadoo *et al.*, 2012). However, this study found that other variables—such as gender, residence, education, and occupation—were not significant predictors of satisfaction. This finding aligns with studies on satisfaction with national health insurance in Ethiopia (Badacho *et al.*, 2016) and India (Devadasan *et al.*, 2011).

4.2 Waiting time

In this study, we found that respondents who experienced a shorter time between registration and their physician visit were more satisfied than those who faced longer waits. This finding is consistent with previous studies (Molyneux, Hutchison, Chuma, & Gilson, 2007; Robyn *et al.*, 2013; Sagaro *et al.*, 2015). Thus, prolonged waiting times before a doctor consultation negatively affect customer satisfaction.

4.3 Payment fairness

According to Molyneux *et al.* (2007), participants who agreed with the premium amount were more likely to be satisfied than those who disagreed.

4.4 Health care coverage

The survey also found that individuals were more likely to be satisfied if they agreed with the healthcare coverage than if they disagreed. This is consistent with findings from research carried out in Senegal, Ethiopia, and the Lao People's Democratic Republic (Bodhisane & Pongpanich, 2019; Demissie & Gutema Negeri, 2020; Mebratie *et al.*, 2015). A lack of services—such as treatment for noncommunicable diseases (e.g., chemotherapy, kidney disease, diabetes, hypertension) and major surgeries—may negatively impact respondent satisfaction in many developing countries.

4.5 Perceived Service quality

Satisfaction was higher among participants who agreed with the quality of services than among those who disagreed. This result is in line with earlier research from Bangladesh, Ethiopia, and Uganda (Badacho *et al.*, 2016; Mitiku Kebede & Geberetsadik, 2019; Nshakira-Rukundo, Mussa, Nshakira, Gerber, & Von Braun, 2019; Sarker *et al.*, 2018). The availability of reagents, laboratory services, medical personnel, and equipment, as well as the general quality of health services, may all be related to this relationship.

4.6 Drug availability

The likelihood of satisfaction was higher for those who received sufficient medication than for those who did not. This result is consistent with research from Bangladesh (Sarker *et al.*, 2018) and Ethiopia's Anilemo district (Addise *et al.*, 2021). This could be due to the fact that participants who did not acquire their prescription drugs at public health facilities were forced to pay more at private pharmacies, which resulted in discontent and a lower level of satisfaction with the CBHI program as a whole.

5 Conclusion

According to this study, 58.1% of households in southern Ethiopia were generally satisfied with the CBHI program. Respondent age, marital status, payment equity, healthcare coverage, waiting time, perceived service quality, and medicine availability were all significant determinants of satisfaction.

In addition to improving the general quality of services, comprehensive healthcare coverage for major procedures and non-communicable diseases (such as chemotherapy, kidney disease, diabetes, and hypertension) is crucial for raising satisfaction in the area.

Policy Recommendations

A study on household satisfaction with the Community-Based Health Insurance (CBHI) program in southern Ethiopia indicates that the program has to be improved through a number of policy changes:

- **Expand Healthcare Coverage:** The study suggests that policymakers should broaden the CBHI benefit package to include comprehensive services, particularly for major surgeries and non-communicable diseases. Currently, limited coverage for these conditions negatively impacts member satisfaction.
- **Boost Service Quality and Drug Access:** Enhancing the overall quality of healthcare services and ensuring that essential medications are readily available at health facilities is critical. The research identified that a lack of medications and poor service quality are major causes of dissatisfaction, often forcing members to pay out-of-pocket at private pharmacies.
- **Minimize Waiting Times:** Long waiting periods for services are a primary source of dissatisfaction. Policies should focus on streamlining patient registration and consultations to reduce the time patients spend waiting to see a doctor.
- **Promote Fair and Transparent Payments:** The study found that the fairness of payment is a significant factor in member satisfaction. Policies should aim to establish premium payment structures that are transparent and perceived as fair in relation to the services provided.

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Conflict of interest

The authors hereby declare that they have no potential conflicts of interest regarding the research, authorship, and/or publication of this work.

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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 sys-

tems, including overgrazing, deforestation, excessive trafficking, erosion, repeated cultivation, industrialization, and urbanization (Fazekášová *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).

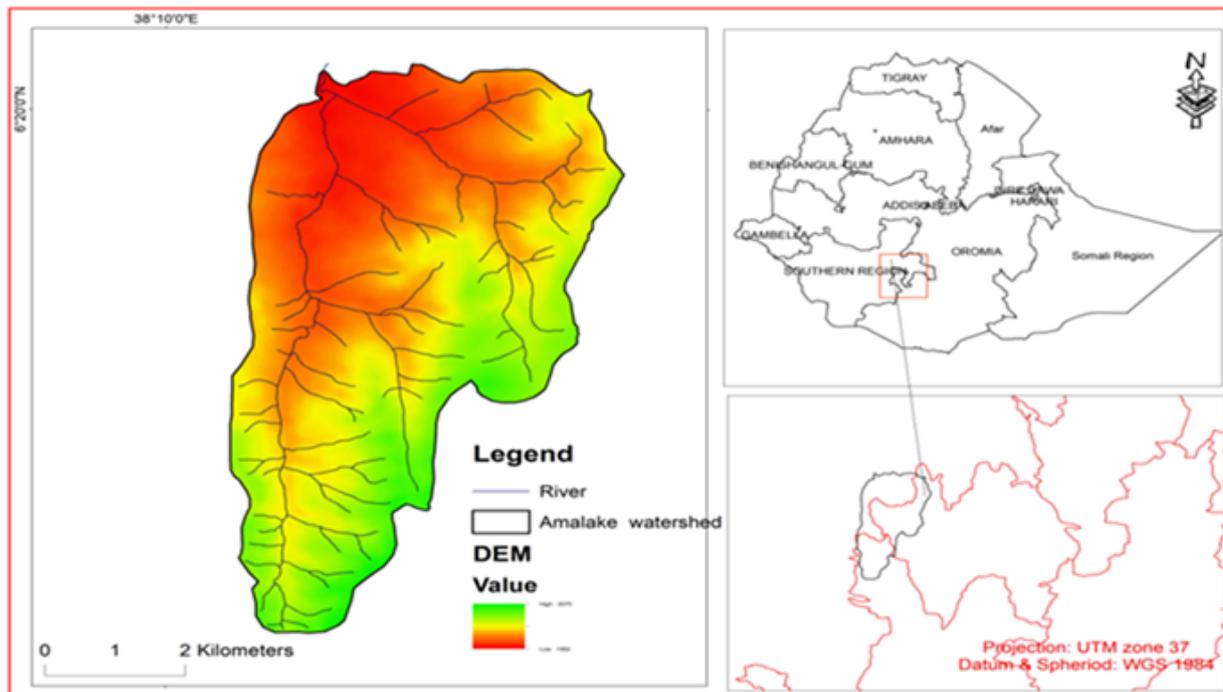


Figure 1. Location Map of the Study Area

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 col-

lected 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.

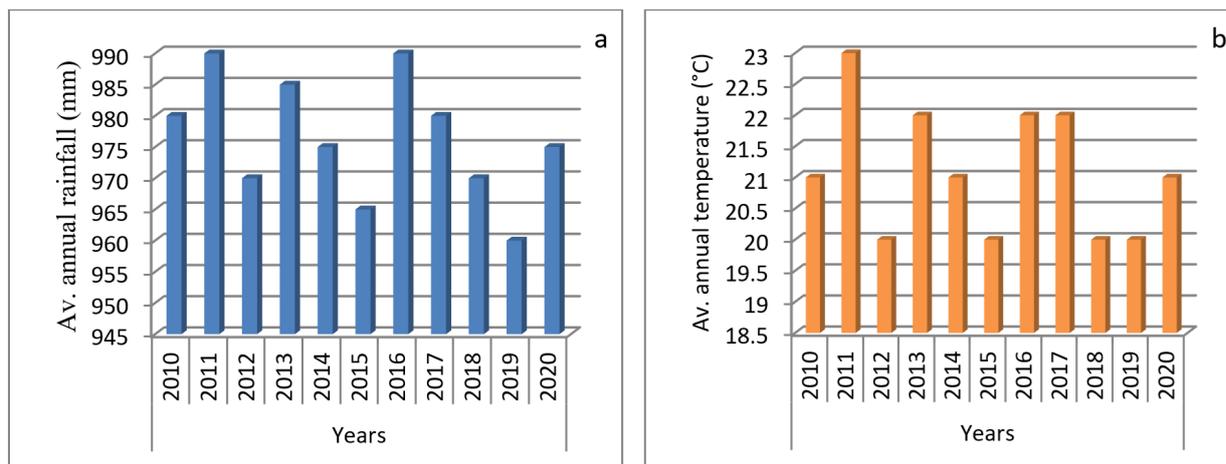


Figure 2. Average annual rainfall (a) and average annual temperature (b): source World Weather Online : <https://www.worldweatheronline.com/dilla-weather-averages/et.aspx> (Accessed 10/09/2024)

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 of K_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 pH $CaCl_2$). 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.

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

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).

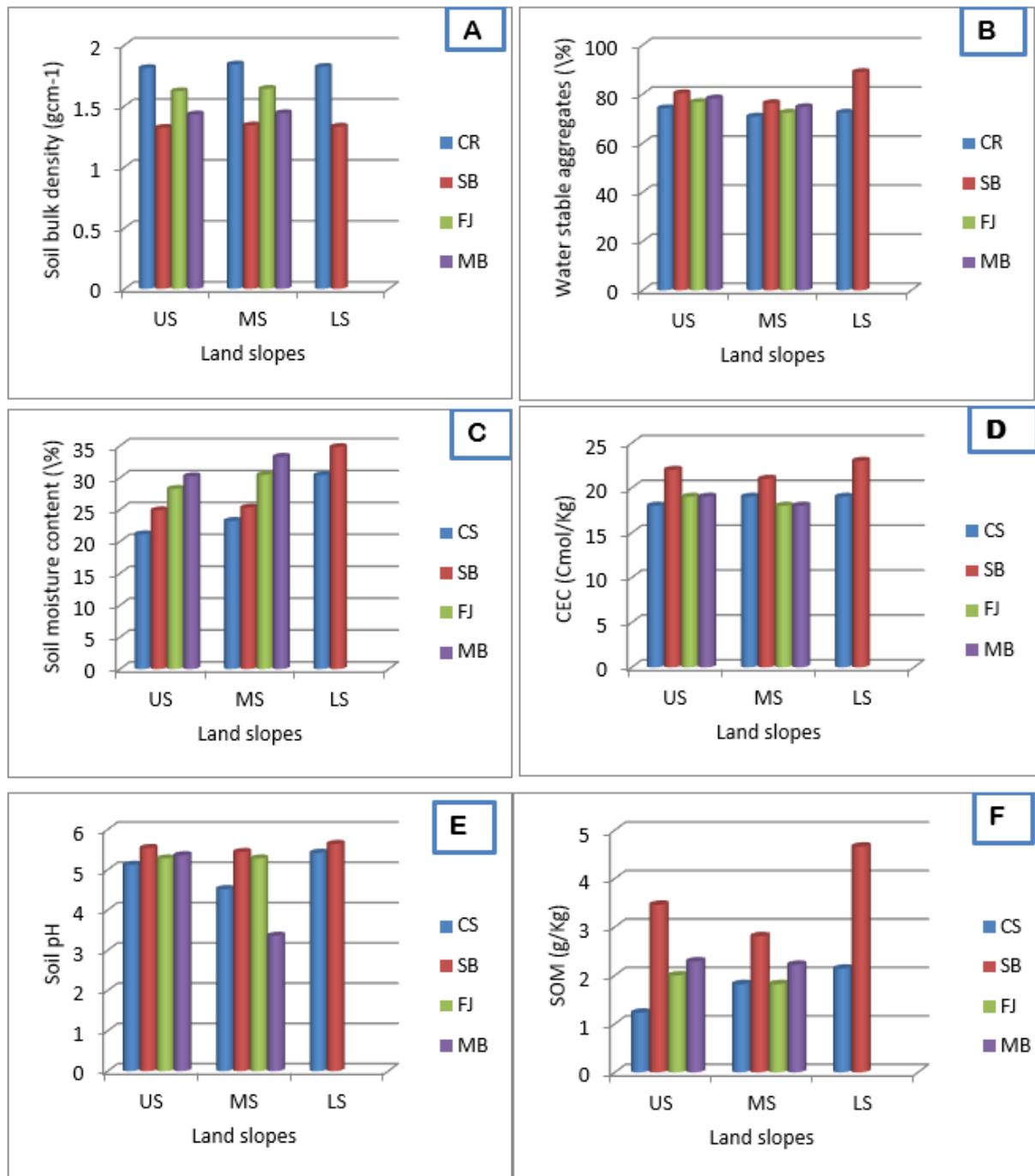


Figure 3. Changes of soil physicochemical properties: bulk density (A), water stable aggregates (B), soil moisture contents (C), cation exchange capacity (D), soil pH (E), and soil organic matter (F)

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 $0.78 \text{ cmolc kg}^{-1}$ 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.

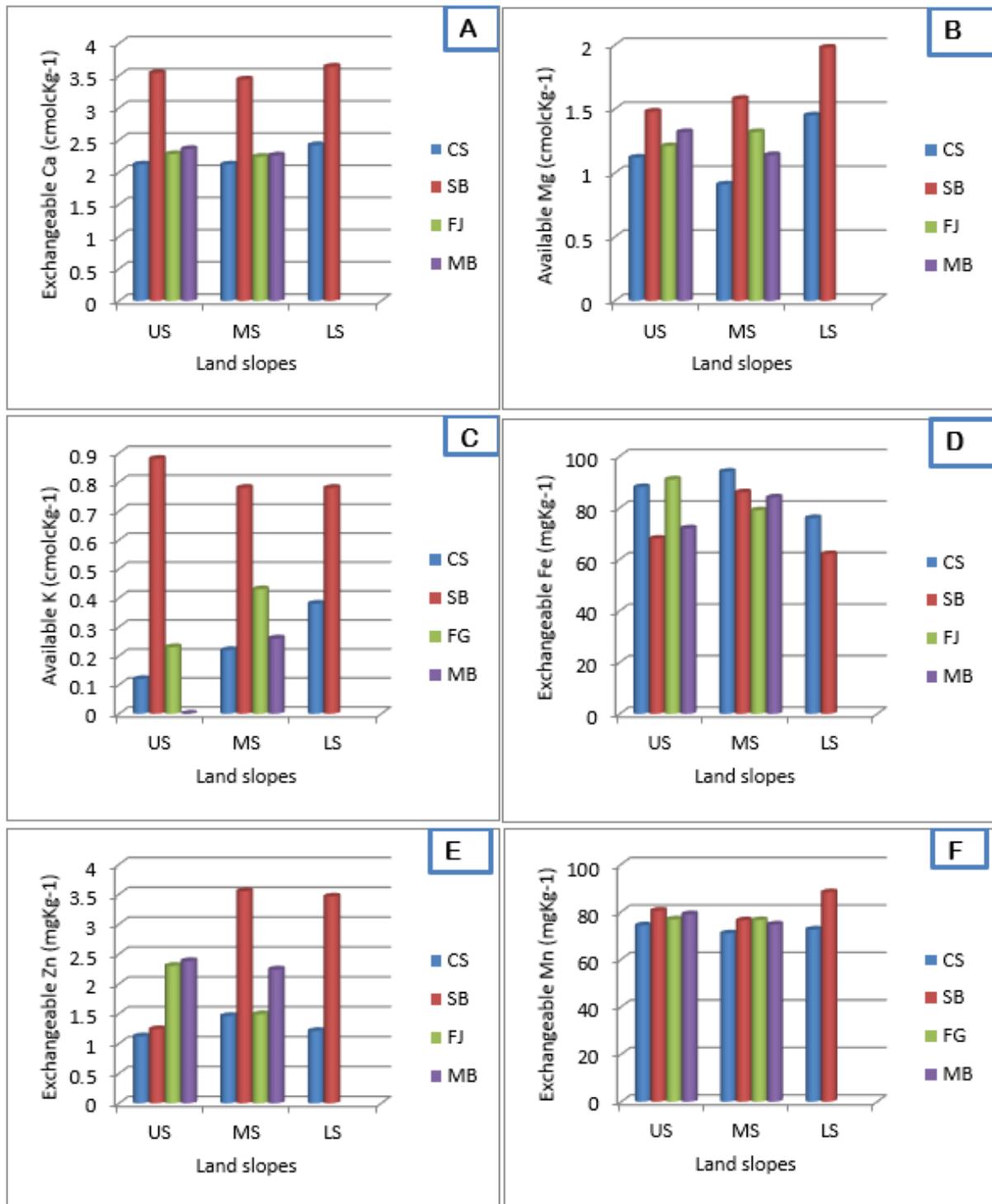


Figure 4. Nutrients dynamics under different soil conservation practices and land slop US – Upper slope, MS = Middle slope, LS = Lower slope, CS = Control sample, SB = Soil bend, FJ = Fanya-juu, MB = Micro basin

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 ef-

fectively 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

In 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.

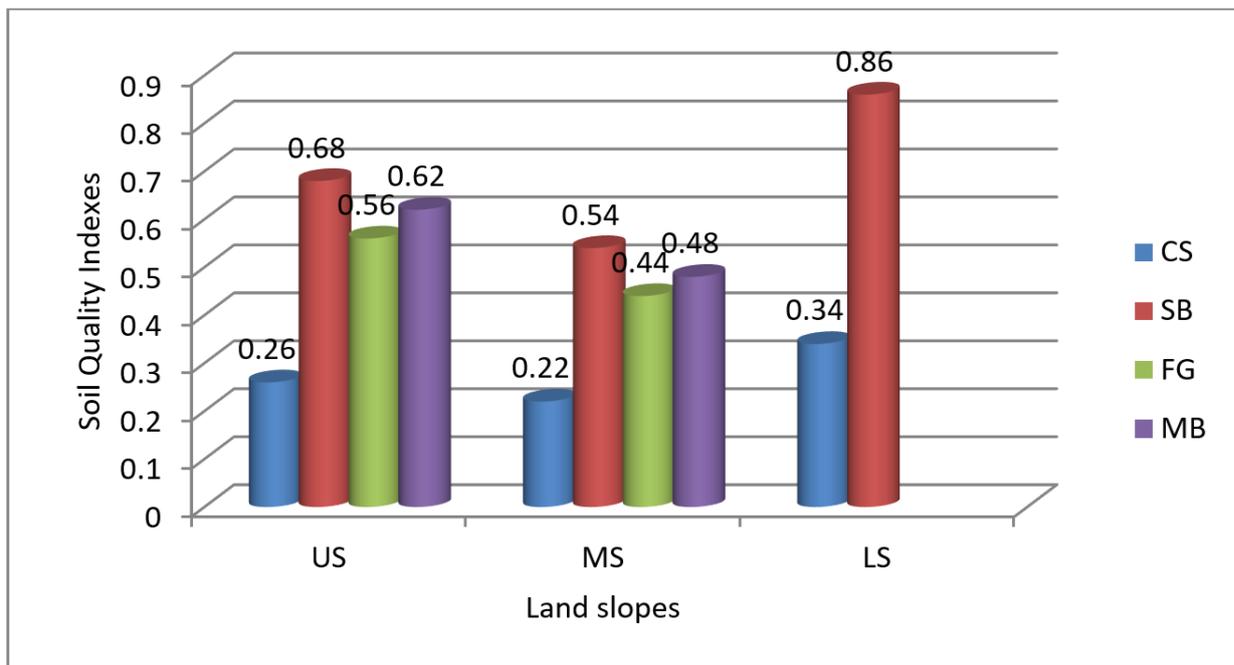


Figure 5. Soil quality indexes as impacted by soil conservation practices US – Upper slope, MS = Middle slope, LS = Lower slope, CS = Control sample, SB = Soil bend, FJ = Fanya-juu, MB = Micro basin

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 consis-

tent 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 (%)	Porosity (%)	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, Porosity = 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) (mg.Kg ⁻¹)
		Ca ²⁺	Mg ²⁺	K ⁺	Fe	Zn	Mn	Cu	B	
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.



Land Use Land Cover Change and its Implications for Livestock Production and Food Security in Kuyu District, Ethiopia

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Abstract

Although Kuyu district has significant potential for animal-source food production due to its large livestock population and diverse species, the effects of land use and land cover (LULC) change on these resources remain underexplored. This study examines LULC changes over three decades (1991–2021) and their impact on livestock production and food security among rural households. Data from Landsat images from 1991, 2001, 2011, and 2021 were used to develop land use maps and quantify changes through visual interpretation and supervised classification using ArcGIS Version 10.7.1. Key informant interviews, focus group discussions, and transect walks were employed to complement the study with qualitative data. Six LULC classes were identified: forest/plantation, grass/shrub land, bare land, cropland, rural settlement, and urban built-up areas. Over the study period, cropland and bare land experienced net gains of 45.4% and 6.5%, respectively. In contrast, forest/plantation land and grass/shrub land showed net losses of 29.3% and 23.7%, respectively. The decline in grassland is a major cause of animal feed scarcity, although the expansion of croplands provides low-quality crop by-products as alternative feed sources. Livestock relying on such feeds exhibit poor production and health performance, jeopardizing food security for rural households. The LULC changes observed in this study underscore their adverse effects on livestock production. To mitigate the constraints on livestock production and improve food security, interventions such as diversifying livestock production, enhancing mixed crop-livestock farming, adopting agroecological practices, and implementing effective livestock development planning, policies, and strategies are recommended.

Keywords/Phrases: Food security, Kuyu district, Land use land cover change, Landsat images, Livestock production

1 Introduction

1.1 Background

Ethiopia is located in the tropics and boasts a varied eco-environmental landscape, which includes arid and semiarid lowlands as well as cool afro-alpine highlands and mountains (Mekasha *et al.*, 2014). The nation is marked by tropical monsoons, with local precipitation patterns shaped by elevation (Paracchini *et al.*, 2020). Consequently, the highlands expe-

rience cool, humid conditions, whereas the lowlands are characterized by heat and aridity. These diverse geographic conditions allow rural communities to implement various land use systems for crop and livestock production, thereby enhancing food security and livelihoods. Nevertheless, Ethiopia's cultural and natural heritage faces threats from multiple factors, including global climate change, overpopulation, and land degradation (Mekasha *et al.*, 2014). In

this context, the Intergovernmental Panel on Climate Change (2022) emphasizes that increasing temperatures and erratic rainfall, caused by climate change, have reduced agricultural productivity throughout Ethiopia, worsening food insecurity.

Food insecurity remains a critical social challenge in Ethiopia, with significant disparities across regions and agroecological zones (Abebe, 2018). Studies indicate that 38.1% of households experience food insecurity nationally, while 31% lack adequate caloric intake and 20.5% face severe food shortages (Shone *et al.*, 2017). Compounding these challenges, 26.2% of Ethiopians live below the poverty line, with rural communities disproportionately affected by both poverty and food scarcity (CSA, 2019).

The issue of food insecurity remains a persistent challenge for many residents of Kuyu District. Despite its potential for crop and livestock production, the district has been classified as food insecure since 2005 (MoARD, 2017, as cited in Feleke, 2018). As of 2018, 3,301 households in Kuyu District received food aid, with this number rising significantly over time (Feleke, 2018). For instance, Phase 4 of 2020 recorded 5,900 beneficiaries, increasing to 14,758 by 2024 (KWAO, 2024). This indicates that many households struggle to cope with food insecurity due to various recurrent shocks. Current data reveal that a significant proportion of both the country's and the district's population is living in a state of chronic or transitory food insecurity. Therefore, addressing these interconnected issues is vital for ensuring food security.

Comprehensive studies conducted in Ethiopia have recorded changes in land use and land cover (LULC) concerning drought vulnerability (Biazin & Sterk, 2013) and community perceptions (Oba & Kaitira, 2006; Beyene, 2009). Although current research generally examines the drivers of LULC (Amsalu *et al.*, 2007; Meshesha *et al.*, 2012) and their consequences (Meshesha *et al.*, 2012), there is a scarcity of studies that concentrate on their systemic effects. For example, Alem-Meta and Singh (2017) examined LULC linkages to rural household food insecurity, while Mekasha *et al.* (2014) explored community perceptions of livestock feed availability, management strategies, and the capacity of degraded lands to sustain livestock productivity. Despite this body

of work, integrated analyses of LULC dynamics and their impact on livestock systems and food security remain limited, particularly in contexts like Kuyu District, where mixed crop-livestock livelihoods dominate.

To our knowledge, only a few studies have been conducted in Kuyu District to explore the state of LULC change. For instance, Messay and Tsetargachwe (2013) studied the implications of spatiotemporal environmental dynamics on rural livelihoods in the Wasarbi-Garba Guracha Watershed, but their scope was confined to that specific watershed. Moreover, their study did not cover the entire district, limiting the applicability of their results. Additionally, they did not examine the relationship between LULC change and livestock production. Consequently, comprehending the patterns and degrees of Land Use and Land Cover (LULC) change is essential for producing practical insights for policymakers and development professionals regarding livestock production and food security.

This study addresses the critical research gap in understanding how LULC transformations in Kuyu District influence livestock production and rural household food security. It primarily aims to investigate LULC patterns in the district and assess how these changes impact livestock production, as well as their broader implications for rural households' food security.

2 Materials and Methods

2.1 Description of the study area

This research was carried out in the Kuyu District, which is one of the twelve districts within the North Shewa Zone of the Oromia Regional State, found in central Ethiopia. The district lies between 9°31'32" and 9°56'28" North Latitude, as well as 38°3' 1" and 38°30' 14" East Longitude (refer to Figure 1).

The study covered three agroecological zones within the district: high altitude, mid-altitude, and low altitude. Climate data from 1981 to 2018, obtained from Ethiopia's National Meteorological Agency (ENMA), was utilized. The dataset indicates that over the 38-year period, the district's average annual rainfall ranges from 1,014 mm to 1,100 mm

in the low-altitude agroecology and from 1,201 mm to 1,256 mm in the high-altitude agroecology. The average annual minimum temperature ranges from 14.2°C to 17.2°C in the low-altitude zone and from 7.4°C to 9.9°C in the high-altitude zone. Both annual mean rainfall and maximum temperatures show a slight increase over the years, while minimum temperatures exhibit a decreasing trend. These climatic variations reflect the district’s diverse agroecological settings and their potential implications for land use,

agricultural practices, and livelihood strategies. A summary of the disaggregated climate data for the district from 1981 to 2018 is presented in Table 1.

In the study area, agriculture is the primary economic activity, supporting more than 87% of the population (Messay & Tsetargachew, 2013). A mixed crop-livestock agricultural production system serves as the main livelihood for people across all agroecological zones of the district.

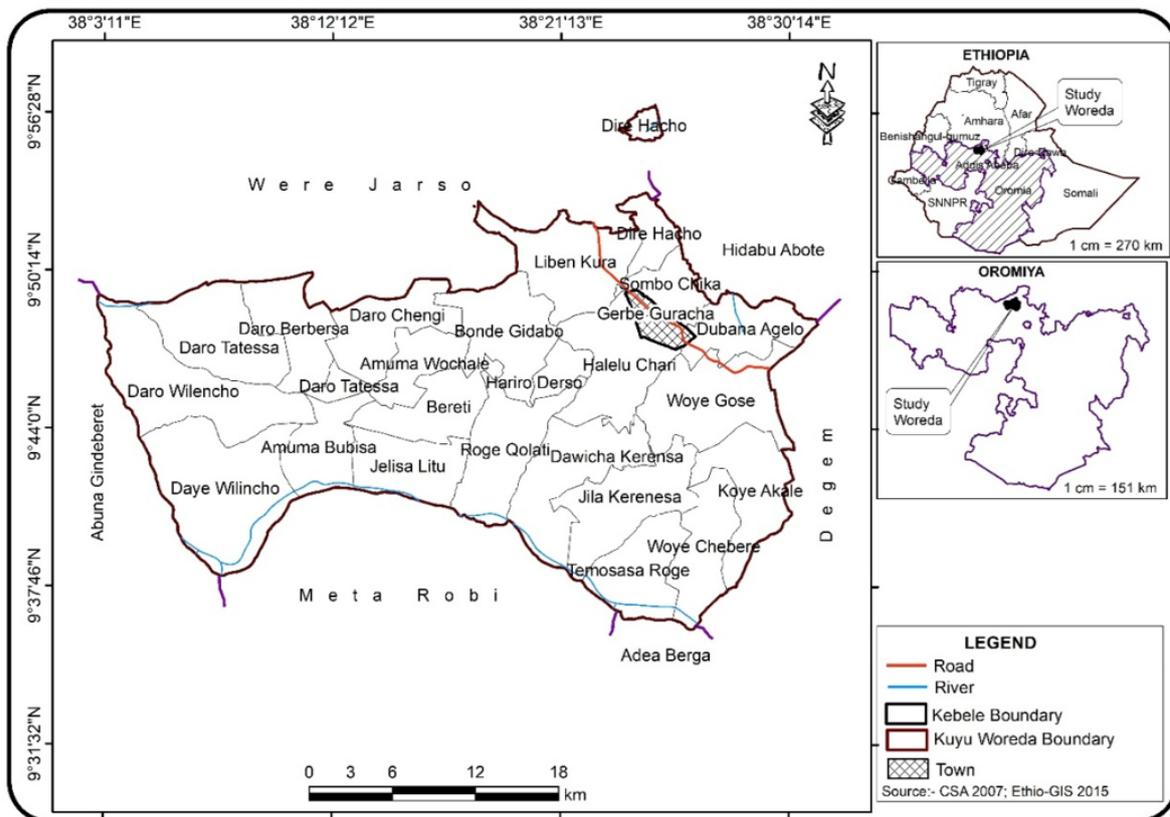


Figure 1. Location Map of the Study Area

Table 1. A disaggregated rainfall and temperature data of Kuyu District (1981-2018)

Climate Elements	Years			
	1981-1993	1994-2006	2007-2018	1981-2018
Annual mean rainfall (mm)	1008– 1178.5	1018.8-1257.8	1015- 1330.6	1014-1256
Annual mean min. temperature (°C)	7.8 -17.4	7.2-18.5	7.1-15.5	7.4-17.2
Annual mean max. temperature (°C)	21.0 - 28.1	22.1-29.1	21.5- 28.9	21.5- 28.9

Source: Computed from 1981-2018 meteorological data set obtained from ENMA.

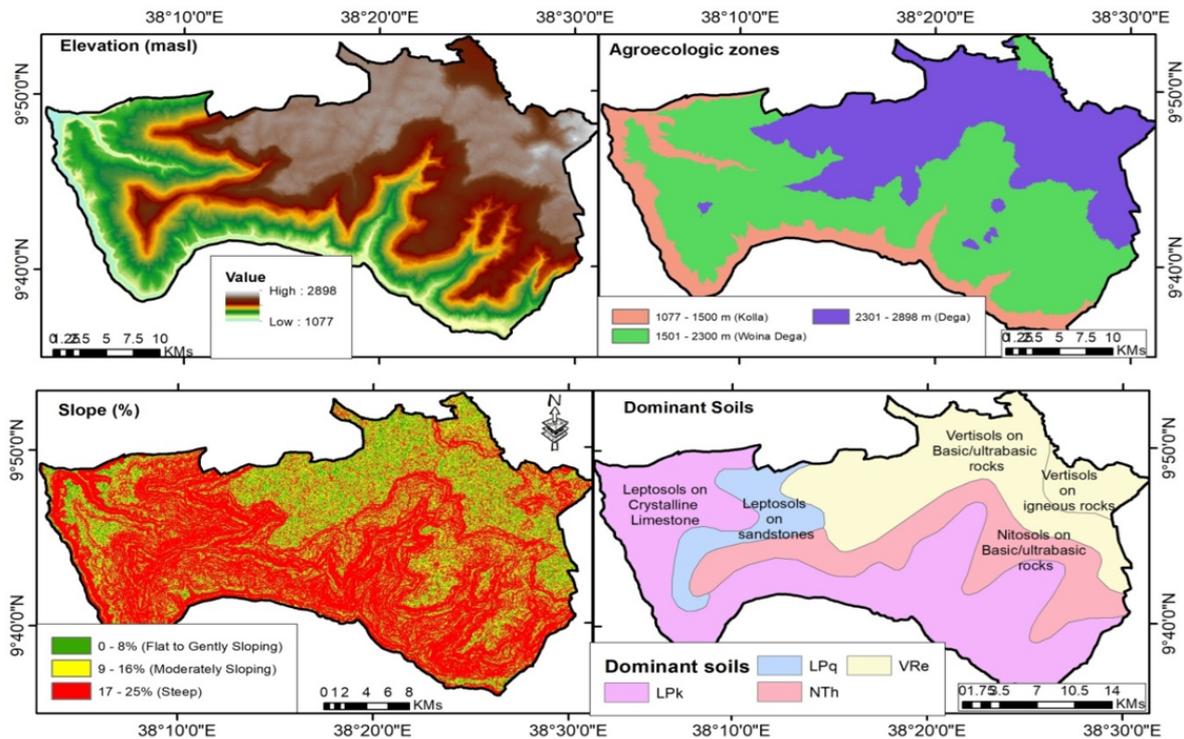


Figure 2. Physical characteristics of Kuyu District

An agroecological framework is employed to characterize the physical environment of the study area, as crop and livestock production in Ethiopia fundamentally depend on these conditions. The high-altitude agroecology (Dega-Baddaa in the local language) is primarily characterized by elevations ranging from 2,301 to 2,898 meters above sea level (masl), with flat to gently sloping terrain. The main soil types in this zone are vertisols found on basic or ultrabasic rocks and vertisols on igneous rocks.

The mid-altitude agroecology (Weinadaga-Badadaree in the local language) features elevations ranging from 1,501 to 2,300 masl, predominantly steep slopes but also some moderate slopes. The soil types here include nitosols on basic/ultrabasic rocks, leptosols on crystalline limestone, and leptosols on sandstones.

The low altitude agroecology (Kolla-Gammojjii in the local language) is characterized by elevations between 1,077 and 1,500 masl, primarily steep slopes with fewer moderate slopes. The main soil type in this zone is leptosols on sandstones, with leptosols on crystalline limestone also dominating the area. Figure 2 illustrates the physical characteristics of the study area.

2.2 Datasets and sampling approach

This study utilizes both quantitative and qualitative data, with the latter serving to augment the former. The quantitative data were gathered from satellite imagery, whereas the qualitative data were sourced from key informants and focus group discussions. In order to present a detailed overview of land use and land cover (LULC) patterns, the study categorized all rural Kebeles (the lower administrative units) of the district into three agroecological zones and utilized remotely sensed satellite imagery along with GIS to measure LULC changes across these zones.

Land Use and Land Cover (LULC) alterations within the study region were identified through a series of satellite images utilizing Remote Sensing (ERDAS Imagine 14) and Geographic Information System (GIS) software (ArcMap 10.7.1). Specifically, the following datasets were utilized: Landsat 5 Thematic Mapper (TM) (1991) with medium resolution (30 m) for LULC classification in 1991; Landsat 7 Enhanced Thematic Mapper (ETM+) (2001) with medium resolution (30 m) and panchromatic (15 m) for LULC classification in 2001; Landsat 7 ETM+ (2011) with medium resolution in blue, green, red, and near-infrared (30 m) and panchromatic (15

m) for LULC classification in 2011; and Landsat 8 OLI/TIRS (2021) with medium resolution in blue, green, red, and near-infrared (30 m) and panchromatic (15 m) for LULC classification in 2021.

To identify spatial and temporal changes in land use and land cover (LULC), Landsat images from the years 1991, 2001, 2011, and 2021 were examined. Supervised classification methods, which utilize field survey data or high-resolution imagery, along with visual interpretation, were applied using ArcGIS Version 10.7.1 software. True-color composites were generated using bands such as green, gray, dark gold, yellow, brown, and red. Microsoft Excel was employed to create summary tables and figures. Very high-resolution images from Geo-Eye (2021) obtained through Google Earth Pro (1 m resolution) were utilized for the purpose of accuracy assess-

ment, aiding in the validation of classifications via the Kappa Index of Agreement and a confusion matrix.

Supplementary qualitative data gathered through six focus group discussions with elder farmers, interviews with six local leaders, and field observations conducted in three randomly selected Kebeles, one from each agroecological zone. Elder farmers contributed to identifying patterns of LULC changes, key livestock feed resources, and discussed the challenges of livestock production, the causes of these challenges, and priorities for improvement. Further details were acquired through an examination of literature, governmental reports, and other pertinent publications. Table 2 provides a summary of the features of the remote sensing data.

Table 2. Description of remote sensing data

Satellite Images	Sensor	Path/Row	Resolution or Pixel size (m)	Year of Data Data Acquisition	Source
Landsat 5	TM	169/053	30x30	10/01/1991	USGS
Landsat 7	ETM +	169/053	30x30	23/01/2001	USGS
Landsat 7	ETM+	169/053	30x30	18/01/2011	USGS
Landsat 8	OLI/TIRS	169/053	30x30	15/01/2021	USGS
Accuracy Assessment	Geo-eye	—	—	17/01/2021	Google Earth Pro

2.3 Data analysis

The qualitative data are narrated and summarized, while the quantitative data undergo cleaning, coding, and analysis through descriptive statistics. The results are presented in tables, maps, or figures utilizing Excel Software Version 2016. The analysis of land use and land cover (LULC) changes

is conducted using time-series satellite imagery obtained from the United States Geological Survey (USGS) website (<https://earthexplorer.usgs.gov>). Consequently, the LULC categories for the study area were classified into forestland, grassland, bare land, cropland, and construction land across four distinct periods.

Table 3. Description of LULC categories

LULC type	Description
Forest/plantation	The land that includes natural and plantation forest
Grass/shrub land	Is the land that includes areas covered with grass land and shrub land
Bareland	Land that covers areas with no vegetation, degraded or quarries, or road segments
Cropland	The land that dominantly expressed by mosaic of small holder farms
Rural Settlement	Land that includes small villages or areas with agglomeration of huts or iron sheet roofed houses but at distance of at least 200m from urban built-up structures
Built-up area	This land coverage includes urban built-up, iron sheet roofed houses, and roads structures.

Source: Adapted from Anderson *et al.* 1976.

The LULC classes employed and their corresponding descriptions are detailed in Table 3. The classified images were vectorized by exporting them from the ERDAS Imagine 9.1 image analysis software to ArcGIS Version 10.7.1. Based on the computed results, the LULC changes between the analyzed periods were quantified to facilitate a comparison of changes across the study periods.

3 Results and Discussion

3.1 Land use land cover change detection

Time series analysis of LULC changes in Kuyu District identified six distinct classes: forest/plantation, grass/shrubland, bare land, cropland, rural settlement, and urban built-up areas (Table 3). Multi-

temporal LULC maps were generated using satellite images from 1991, 2001, 2011, and 2021, illustrating the spatial and temporal evolution of these categories (Figure 3). The results, summarized in Table 2 above, also indicate that the satellite images from different periods maintain consistent spatial and radiometric resolution. Below, Figure 3 presents the LULC maps and Landsat images of the district under study.

The district’s empirical data on LULC area coverage statistics and changes from 1991 to 2021 are summarized in Tables 4 and 5, respectively. The analysis reveals significant spatial and temporal differences in LULC changes during the study periods, emphasizing the dynamic shifts in land use patterns over time.

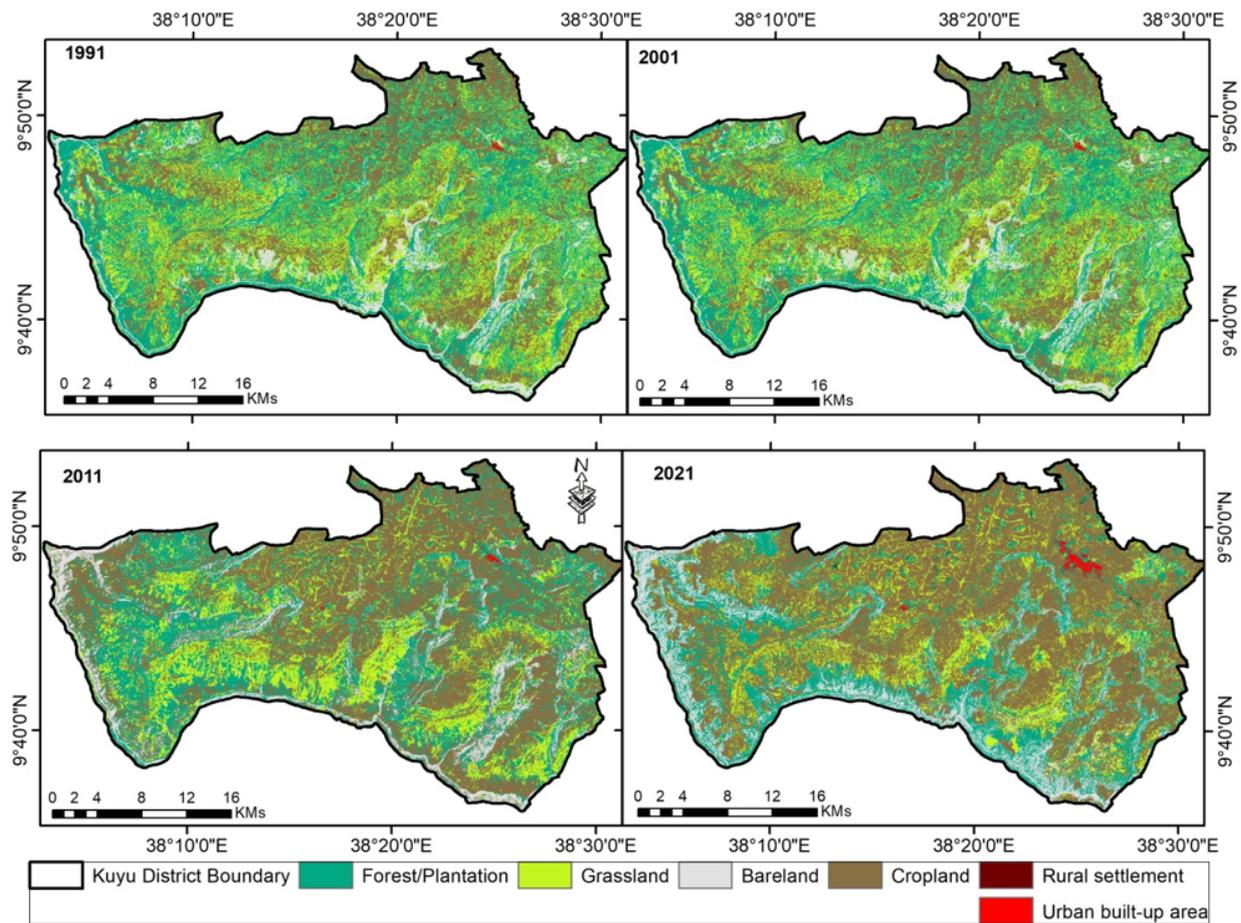


Figure 3. Land Use Land Cover Map of Kuyu District from 1991 – 2021

Table 4. Area (ha) and percentages of LULC in Kuyu District (1991 – 2021)

LULC type	1991		2001		2011		2021	
	ha	%	ha	%	ha	%	ha	%
Forest/plantation	36072	38	27253	29	26103	28	20351	22
Grass/shrub land	26567	28	18399	20	16986	18	13862	15
Bareland	6618	7	8691	9.2	7978	8.4	10114	11
Cropland	25180	27	40089	42	43379	46	49544	52
Rural Settlement	40	0	43	0	20	0	264	0.3
Built-up area	74	0.1	76	0.1	86	0.1	416	0.4
Total	94551	100	94551	100	94551	100	94551	100

The absolute (ha) and relative (%) measurements of LULC in the district demonstrate significant dynamism. Notably, there has been a shrinkage of forestland and grass/shrubland, leading to the expansion of cropland and bare lands. This substantial change is corroborated by insights from older respondents, whose firsthand accounts closely align with findings derived from satellite imagery analysis.

Empirical studies by Taye *et al.* (2024) and Getahun *et al.* (2024) examined LULC changes across different agroecologies and their drivers in Ethiopia, respectively, yielding results consistent with those of the current study. Similarly, Mehari *et al.* (2022), in their study conducted in Southern Ethiopia, reported similar patterns of LULC changes linked to population growth, settlement, and farmland expansion.

Table 5. Absolute (ha) and relative (%) LULC change (1991 – 2021)

LULC type	1991-2001		2001-2011		2011-2021		1991-2021	
	ha	%	ha	%	ha	%	ha	%
Forestland/plantation	-8818.6	-24	-1150.8	-4.2	-5751.5	-22	-15720.8	-43.6
Grass/shrubland	-8168.2	-31	-1412.9	-7.7	-3123.8	-18.4	-12704.9	-47.8
Bareland	2073	31.3	-712.53	-8.2	2135.79	26.8	3496.23	52.8
Cropland	14908.9	59.2	3290.13	8.2	6164.64	14.2	24363.6	96.8
Rural Settlement	3.2	8.1	-23.4	-54	244.71	1242	224.55	563.2
Built-up Area	1.7	2.3	9.54	12.5	330.12	385.3	341.37	458.6
Total	0	0	0	0	0	0	0	0.0

The patterns of land use and land cover (LULC) in the examined region have evolved over the years, mainly transitioning from grazing and forest areas to cropland and degraded land. The transformation of land into cropland presents a beneficial aspect, as crop residues provide a substantial feed source within the mixed crop-livestock production system. However, the study also reveals that vast areas of land are experiencing degradation and an expansion of bare land.

The most substantial changes in LULC occurred during distinct reference periods. Between 1991 and 2001, forestland experienced the highest decline (-24.4%), while bare land increased significantly (59.2%). This period coincided with the political transition from the Derg regime to the Federal Democratic Republic of Ethiopia, which precipitated sweeping governance and policy reforms that destabilized cooperative afforestation initiatives and led to widespread deforestation. The resultant loss of

forest cover likely accelerated land degradation and harmed ecosystems.

From 2001 to 2011, grass/shrub land saw the highest decline (-15.9%), while cropland expanded dramatically by 1,241.6% between 2011 and 2021. This increase can be attributed to population growth, excessive cropping pressure, and overgrazing. Drastic LULC changes during 2011-2021 included a 1,241.6% increase in rural settlements and a 385% rise in urban built-up areas. Qualitative findings from the study revealed that these shifts are driven by population growth, the establishment of new households in highland agroecologies, the planting of eucalyptus trees, and construction activities. Respondents also noted the migration of farmers from rural areas to nearby towns, particularly Garba Gurraacha and Britii, as an immediate cause of urban expansion. Wealthier farmers are investing in urban housing, further driving the expansion of these urban areas, which is accelerated by internal factors within the towns themselves.

A recent study conducted in Southwest Ethiopia identified similar patterns of LULC changes, reporting a 15.7% increase in cultivation and settlement land between 1984 and 2017, while dense forest, light vegetation, and grazing land declined by 9.2%, 4.97%, and 1.85%, respectively (Mesfin, 2022). Another study revealed that population growth, poverty, and food insecurity are immediate drivers of LULC change, alongside underlying factors such as farmland and settlement expansion, firewood collection, uncontrolled grazing, and forest fires (Getahun *et al.*, 2024). Similarly, Alem-Meta and Singh (2017) identified population pressure, unplanned agricultural expansion, and overgrazing as key drivers of LULC change in Ethiopia's Teleyayen sub-watershed. Mesfin (2022) identified population pressure, rising resource demands, and resettlement programs as significant drivers of LULC change. Such demographic pressures trigger overgrazing, which degrades vegetation, biodiversity, and soil fertility. The resulting livestock feed deficits undermine agricultural productivity, exacerbating food insecurity among rural households. According to Nyariki *et al.* (2009), severe overgrazing can escalate into desertification, compounding ecological and socioeconomic vulnerabilities.

Several studies align with the findings of the current research. For instance, Jie Xu *et al.* (2023) noted a consistent increase in built-up and aquaculture land globally, with forest and grassland areas initially declining from 1990 to 2016, followed by a slight recovery due to policies encouraging farmland reforestation. Similarly, Pérez-Vega *et al.* (2013) and Kolb *et al.* (2012) highlighted that, over the past 300 years, LULC changes worldwide have been marked by agricultural expansion at the expense of forests. Furthermore, the FAO (2015) noted that LULC changes are often associated with agricultural expansion, urbanization, and deforestation. From the holistic discussions presented, it is clear that advances in earth observation data analysis have not only enhanced the understanding of these processes but also created opportunities to develop targeted solutions for the associated social, economic, and environmental challenges (Lu *et al.*, 2004).

3.2 Accuracy Assessment

An accuracy assessment was conducted on the 2021 image data (Table 6) by comparing it with pseudo-ground-truth data derived from high-resolution Google Earth imagery. Error matrices were generated to evaluate overall accuracy, user's accuracy, producer's accuracy, and Kappa statistics. These metrics assess the classification map's accuracy relative to the reference data. The LULC outputs from the four periods were converted to .dbf format and imported into Microsoft Excel for further analysis. The data were presented as percentages for different LULC classes, and a change detection matrix was created to identify LULC transitions between 1991 and 2021.

The current study utilized very high-resolution imagery to assess the classification accuracy of LULC, achieving a Kappa Index of Agreement of 0.816 (or 81.6%) and employing a confusion matrix (Cohen, 1960). According to established standards, a Kappa Index greater than 0.80 indicates strong accuracy, a value between 0.40 and 0.80 reflects moderate accuracy, and a value below 0.40 represents weak accuracy. The overall classification accuracy for the 2021 map in this study was 82.5% (or 0.825), suggesting a high degree of agreement, as the calculated accuracy value exceeds the Kappa Index threshold (Table 6).

Table 6. Accuracy assessment for the 2021 LULC classification

LULC Types		No. of LULC Classes Observed from GPS/ Google Earth						User Accuracy	
		PF	GL	BL	CL	RS	BA	No.	%
LULC Classes Interpreted	Forest/plantation (FP)	9	1	1	0	0	0	11	81.8
	Grassland/shrub (GL)	1	10	1	0	0	0	12	83.3
	Bareland (BL)	0	1	10	2	0	0	13	76.9
	Cropland (CL)	0	1	1	20	0	0	22	90.9
	Rural Settlement (RS)	1	2	0	0	9	0	12	75
	Built-up Area (BA)	0	0	0	1	1	8	10	80
	No.	11	15	13	23	10	8	80	82.5
Producer Accuracy	%	82	67	77	87	90	100		

The producer and user accuracies, which measure the map’s reliability in identifying specific LULC classes, ranged from 67% to 100% and 75% to 90.9%, respectively. These variations highlight differences in classification accuracy among LULC types. Despite these differences, the study achieved a robust level of classification accuracy, supporting the reliability of the LULC change analysis over the study period.

3.3 Net Land use land cover change

The net change in LULC from 1991 to 2021 is summarized in Table 7. The analysis indicates that the district has undergone extensive LULC changes since 1991 due to several factors, including increased agricultural expansion, deforestation, urbanization, land degradation, and a growing human population. To evaluate the susceptibility of land cover types to change, the loss-to-persistence ratio (Brammoh, 2006) was calculated for each LULC class within the study area. A ratio exceeding 1 indicates that a particular class has a higher propensity to transition to other land cover types, while a ratio below 1 suggests greater stability and a lower likelihood of change.

The results of the current study show that all land use classes, except rural settlement and urban built-up areas, have loss percentage values greater than 1, indicating a higher tendency for these areas to undergo transitions. Consequently, land cover transitions were most prominent in cropland, forest/plantation land, and grassland, with only slight changes observed in bare land.

The persistence, defined as the percentage of the landscape that remained unaffected, was 35.7% be-

tween 1991 and 2021. This means that approximately 64.3% of the landscape experienced transitions during this period, highlighting a high level of instability in LULC in the district. This instability may disrupt mixed crop-livestock production, affect the availability of feed for livestock, and ultimately impact household food security.

The trend in LULC change over the 31 years indicates a net gain of 45.4% in cropland and 6.5% in bare land (Table 7). However, this is accompanied by a net decrease of 29.3% in forest/plantation land and 23.7% in grass/shrubland. The loss of forest and grassland has significantly contributed to the net gain in cropland and bare land during the study period. Cropland is the most favored land use, while forest/plantation and grassland are the most negatively affected.

The net change in rural settlement and urban built-up areas is also positive, albeit at a minimal level, with percentage changes in both cases being less than 1% (Table 7). These classes are identified as areas where no significant changes have occurred. In agreement with the findings of the current study, a recent assessment of LULC change conducted by Anteneh *et al.* (2018) in the Gode district of the Somali region of Ethiopia reveals increases in bare land, agricultural land, and settlement areas. Conversely, woody shrubland declined from 30% to 10%, and grassland decreased from 46% to 32.7%, indicating a declining trend.

Change matrix for LULC in the district is analyzed and presented in Table 8. It generally shows the transition of LULC from grass/shrub land and forest/plantation and to cropland, bareland, rural settlement and urban built up.

Table 7. Net LULC change in Kuyu district (1991 – 2021)

LULC Type	Persistence		Gains		Losses		Net Change	
	ha	%	Gains (ha)	%	Losses (ha)	%	ha	%
Forest/Plantation	9809.4	27	10541.7	19.6	-26262.5	-48.9	-15721	-29
Grassland/shrub	5236.2	20	8626	16.1	-21330.9	-39.7	-12705	-24
Bareland	1802.3	27	8311.7	15.5	-4815.5	-9	3496.2	6.5
Cropland	16841	67	32703.5	60.9	-8339.9	-15.5	24363.6	45.4
Rural Settlement	5.1	13	259.3	0.48	-34.7	-0.1	224.6	0.4
Urban Built-up Area	59	79	356.9	0.66	-15.5	0	341.4	0.6
Total	33752	36	60799	113	-60799	-113	0	0

Table 8. LULC change matrix (1991- 2021)

LULC Type (1991)															
	Forest/ Plantation (FP)		Grassland (GL)		Bare land (BL)		Cropland (CL)		(RS) Rural Settlement		Built-up Area (BA)		Total		
-2021	Ha	%	ha	%	Ha	%	ha	%	ha	%	ha	%	ha	%	
FP	9809.4	27.2	5676.8	21.4	1889.3	28.5	2937	11.7	24.9	63	13.8	18.5	20351	21.5	
GL	4098.9	11.4	5236.2	19.7	725.9	11	3792.2	15.1	7.9	20	1.1	1.5	13862	14.7	
BL	5289.1	14.7	1557.3	5.9	1802.3	27.2	1465.3	5.8	0	0	0	0	10114	10.7	
CL	16565	45.9	13953	52.5	2182.4	33	16841	66.9	1.9	4.7	0.6	0.8	49544	52.4	
RS	94.4	0.3	61.7	0.2	3.6	0.1	99.5	0.4	5.1	13	0	0	264.4	0.3	
BA	215	0.6	81.7	0.3	14.3	0.2	45.8	0.2	0	0	59	79.2	415.8	0.4	
Total	36072	100	26567	100	6618	100	25180	100	40	100	74	100	94551	100	

Table 9 presents details of current LULC practices by agroecology. The share of forest/plantation land is highest (38.6%) in the low-altitude agroecology of Kuyu district, while the lowest forest cover (13.7%) is found in the high-altitude zone. Similarly, vast areas of bare land (43.5%) are identified in the low-altitude agroecology, whereas this category is minimal (2.1%) in the high-altitude agroecology. Furthermore, the rural settlement area is larger in the high-altitude agroecology, with the urban built-up area primarily located in this zone.

The study reveals consistent LULC transition trends across both agroecological zones and district-level analysis. Forest/plantation cover and grasslands exhibit a persistent decline in all agroecological zones, while barren land and cropland show steady expansion over the observed period. One potential reason for these patterns is the inter-agroecological differences in topography, slope, and major soil types (Figure 2 and Table 9), which facilitate soil erosion and expose the land to degradation. To support this finding with qualitative data, farmers were asked to identify

the causes of LULC changes in their district and surrounding areas. Respondents noted that climate change has contributed to the expansion of cropland as a response to soil fertility reduction, shrinking livestock populations due to a lack of grazing lands, and widespread deforestation. Driven by socioeconomic constraints, farmers often clear forests to expand cropland and produce charcoal for income generations to secure their households' livelihoods.

Grass/shrub land coverage is minimal (2.4%) in low-altitude agroecology, suggesting that grazing land is particularly problematic in this zone. Therefore, it may be more productive to rear browsers like goats in this area, as opposed to grazers such as cattle, equines, and sheep. Participants from different agroecologies affirmed that agricultural practices align with their respective zones. For instance, farmers in the lowland agroecology primarily grow sorghum as a staple food and rear goats and cattle, while those in the highland agroecology produce teff (*Eragrostis tef*) as a staple and raise cattle, sheep, and equines.

Table 9. Current LULC practices by agroecology (1991-2021)

LULC Classes	Low altitude (1077 - 1500 m)		Mid-altitude (1501 - 2300 m)		High-altitude (2301 - 2838 m)		Total	
	ha	%	ha	%	ha	%	ha	%
	Forest/Plantation	4982	38.6	10836	22.42	4546.3	13.7	20365
Grass/shrubland	315.1	2.441	8489.4	17.57	5058.7	15.2	13863	15
Bare land	5615	43.5	3756.8	7.77	696.5	2.1	10068	11
Cropland	1995	15.46	25215	52.17	22333	67.1	49544	52
Rural Settlement	0.6	0.004	31.9	0.07	239.9	0.7	272.4	0.3
Urban Built-up Area	0	0	0	0	416	1.2	416	0.4
Total	12908	100	48330	100	33290	100	94528	100

Vegetable and fruit production supported by spring-fed irrigation is common in the low- and mid-altitude agroecologies, while diversified cereal production is more evident in the highland agroecology.

Numerous studies affirm that LULC changes are driven by the interplay of socioeconomic and environmental factors, as reported by Assefa and Singh (2017). Dinka and Chaka (2019) also highlight that inappropriate farming practices, overgrazing, rapid population growth, and weak institutional frameworks are key anthropogenic drivers of LULC changes. The rapid increase in human populations leads to encroachment on fragile land, including farming and grazing.

Moreover, literature asserts that resource constraints related to water, soil, biodiversity, and land will impact agricultural systems in the coming decades (Pretty & Bharucha, 2014). Many respondents argue that population growth is a major driver of LULC changes, as the existing land-use policy prevents new households from acquiring land. Consequently, newly emerging households share farmland with their parents, which forces them to utilize grazing and forest lands for crop production. Combined with this, the conversion of grazing land to other land cover types exacerbates the shortage of animal feeds, negatively affecting livestock production and productivity. One of the social outcomes of such livestock production constraints is food insecurity, a phenomenon from which rural households in the study area are suffering.

3.4 Implications of LULC change for livestock production and food security

Feed is one of the most critical requirements for livestock farming. Sarwar *et al.* (2002) emphasize that both the quantitative and qualitative supply of feed play a key role in determining the productivity and profitability of animal farms. Similarly, Nyariki *et al.* (2009) argue that the availability of grazing land or feed directly influences the calving, lambing, and kidding rates of herds. In other words, the availability of feed can limit the number of livestock that farmers can rear, directly affecting livestock-derived services and access to nutrient-rich animal-source foods. This issue undermines the vital role of livestock in enhancing household food security, as restricted herd sizes reduce the production and availability of quality protein and dietary diversity.

Additionally, both the quantity and quality of feed supply have been identified as major factors affecting livestock production in Ethiopia. Livestock feeds primarily come from annual foraging across large grazing areas (Mekasha *et al.*, 2014). A study by Duguma and Janssens (2021) in Southwest Ethiopia revealed that natural pastures, crop residues, grazing, and roadside grasses are the primary sources of animal feed, in that order. A significant amount of feed also comes from crop residues, agro-industrial by-products, and other farm and non-farm products (Tolera *et al.*, 2012). Feeding practices in the current study area reflect similar patterns, with fibrous crop residues and grazing being the typical feed resources for ruminant animals, often the only available feed during extended dry seasons (Mesfin *et al.*,

2009). This low-quality roughage serves as the basal feed, which is deficient in nitrogen, energy, vitamins, and minerals, leading to poor livestock production (Kabaiji & Little, 1988).

The current LULC analysis reveals a persistent reduction in grazing land, triggering overgrazing, a key driver of soil erosion and degradation. This reduction in natural pasture diminishes the land's carrying capacity, ultimately lowering livestock populations, productivity, and overall agricultural output. Moreover, the uncontrolled open grazing system leads to overgrazing, negatively impacting livestock production and productivity, and resulting in the underutilization of the district's livestock resources. This situation has significant effects on various aspects of food security and the livelihoods of rural households in the area. Consistent with the findings of this study, Anteneh *et al.* (2018) assessed LULC change in Eastern Ethiopia and found it negatively impacted local communities, livestock, and the environment.

Literature indicates that irreversible human activities, such as forest clearing, cultivation, overgrazing, settlement expansion, industrialization, urbanization, and other forms of land management, are causing changes in LULC patterns (Garedew *et al.*, 2009; Lambin & Meyfroid, 2011), resulting in shifts in livestock feed resource composition and feed deficits. Consequently, the proportional contribution of different feed resources varies according to agroecosystems, farming systems, and the types of animals reared (Rahman *et al.*, 2008). Overall, deficits in feed quantity and quality lead to poor body condition in livestock, often reflected as emaciation, which prevents animals from reaching their optimal production potential. This situation can result in low market prices for animals intended for income generation. The imbalance between income from livestock and food prices may lead to food insecurity, as income from animal sales might not be sufficient to cover food costs.

In the current study area, land management practices have significantly altered the availability of feed resources, reflecting variations in agroecology. Farmers increasingly rely on scarce green pasture during the wet season and dry pasture and crop residues during harvesting and dry seasons. Many farmers also utilize traditionally prepared hay, which is of similar

quality to crop residues. Qualitative data indicate that traditional untreated hay is primarily used for fattening animals, lactating cows, and draught oxen. In areas with limited grassland, small ruminants and equines, especially sheep and donkeys, are more efficient at utilizing available feed by grazing pasture down to the roots. This suggests that diversifying livestock species according to the diverse agroecological zones can benefit rural farmers, enhancing food security in resource-scarce environments.

It can be argued that due to these dynamic changes, traditional feed resources and existing feeding strategies are no longer adequate to sustain livestock production (Sarwar *et al.*, 2002). This necessitates the search for alternative livestock and crop production systems, including new feeding regimes. Prioritizing mixed crop-livestock farming systems can offer multiple advantages. Mixed crop-livestock production provides various opportunities for farming communities (Paris, 2002) and represents the most integrated type of agricultural production, fostering farm diversification. Research indicates that farms with greater diversity achieve 19% higher caloric crop yields compared to less-diversified farms (Hadgu *et al.*, 2009). Thus, implementing diversified mixed crop-livestock production and relevant agroecological practices is essential for addressing the challenges of livestock production and food security.

The current qualitative data analysis reveals that goats are primarily reared in low- and mid-altitude agroecological zones, where shrub and bush are relatively abundant, although grazing land remains scarce. In contrast, cattle, sheep, and equines are mainly kept in mid- and high-altitude agroecologies. Moreover, improved crossbreeding practices for cattle are common in highland agroecology, while such practices are absent in lowland areas due to differences in weather conditions and the availability of adequate natural grass and crop byproducts. This differentiation allows farmers to take advantage of agroecological variations by rearing animal species that are well-suited to specific zones and responsive to food insecurity.

Variations in agroecology present opportunities for farmers to diversify their agricultural practices. One such opportunity is the expansion of agroforestry, which can help maximize benefits derived from these

agroecological differences. By focusing on the development of multipurpose fodder trees and implementing appropriate conservation measures, farmers can mitigate challenges related to feed quality and environmental degradation.

Adam *et al.* (2021) projected a rising global demand for livestock-derived foods, driven by population and income growth, with South Asia and sub-Saharan Africa expected to see the fastest increases. Similarly, studies on livestock production suggest that growing human populations lead to higher demand for food, particularly livestock products and grains (Nyariki *et al.*, 2009). These authors emphasize that without increased livestock production, there will inevitably be a reduction in the number of livestock per person, leading to decreased availability of milk and meat. This shortage will increase the need for supplementing household diets. To improve food security in the study area, boosting livestock productivity is essential. However, efforts to enhance livestock production must align with initiatives aimed at minimizing potential conflicts between environmental conservation and crop production.

In addition to the challenges of securing adequate and quality feeds, another pressing issue in the study area is water scarcity. During the LULC classification of Kuyu district, water bodies were not identified as a distinct LULC class, indicating the absence of adequate permanent water sources or reservoirs for irrigation and other agricultural activities. This suggests that agricultural practices, both livestock and crop production, rely primarily on rainfall and limited water sources such as rivers or springs, which are increasingly under pressure from climate change.

Water, a critical component of feed nutrients, is essential for livestock physiological functions. Limited water supply severely restricts livestock performance. Combined with the seasonal availability of poor-quality feeds, such as dry pasture and crop residues, inadequate water supply results in poor animal performance.

Different agroecological farming practices, such as intercropping, soil bunds, grass strips, agroforestry systems, water conservation methods, and integrated crop-livestock farming systems, offer viable solutions that complement livestock production in the

study area. These practices not only help conserve resources but also reduce input costs, improving the economic situation of farmers (Hadgu *et al.*, 2009). Seasonal feed shortages in Ethiopia, especially severe in drought-prone areas, could be addressed through climate-smart forage production systems to support sustainable livestock production amid LULC changes (Diriba *et al.*, 2023). Therefore, livestock development planning should incorporate policies and strategies that support livestock commercialization while emphasizing indoor animal feeding management. This approach would help reduce the impacts of overgrazing, promote the treatment of poor-quality roughages, enhance livestock productivity, and ultimately foster efforts to ensure food security.

4 Conclusion

This study employed ArcGIS 10.7.1 to classify LULC types through supervised classification, utilizing satellite imagery analysis complemented by qualitative data for enhanced accuracy. The classification results demonstrate the effectiveness of satellite imagery in precisely delineating ground features and land cover dynamics. The study reveals that Kuyu district has been experiencing LULC changes since 1991, identifying six distinct LULC types. These changes have affected all three agroecological zones of the district, with the most significant net changes observed in cropland, forest land, grassland, and bare land, in that order. The alterations in LULC, particularly those negatively impacting grassland and other feed resources, are expected to lead to reduced livestock production and productivity, which could have serious implications for food security in the area.

Assessing the current LULC changes has provided valuable remotely sensed satellite imagery and GIS-based empirical data on the surface coverage of different LULC categories across the district, offering an overview of its three agroecological zones. The insights gained from this study could assist the district in designing appropriate strategies and planning to enhance livestock production and food security.

To mitigate the constraints identified and improve livestock production and food security for rural households in Kuyu District, it is recommended to enhance the mixed crop-livestock farming system, develop multipurpose and leguminous fodder

trees, implement agroforestry practices, promote diversified livestock production and alternative feed sources, treat poor-quality feed, and apply relevant agroecological practices.

Limitation of the Study

This study did not incorporate livestock data over the years to articulate the growth trend of the livestock population in relation to the LULC change patterns in the study area, due to a lack of continuous and valid data. Additionally, the study lacks a robust justification for identifying the key determinants of livestock production.

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Adaptation potential of *Opuntia ficus-indica* along altitudinal gradient of Gullele Botanical Garden, Addis Ababa

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Abstract

Ethiopia's diverse agro-climatic zones host a rich variety of endemic and introduced flowering plants, among which is *Opuntia ficus-indica*, an introduced species prized for its nutritional benefits for both humans and animals. This research aims to evaluate the adaptability of *Opuntia ficus-indica* across different altitudinal ranges within the Gullele Botanical Garden, located in the central plateaus of Ethiopia. Approximately 45 cladodes were sourced from the Gurage zone to analyze the species' adaptation and growth performance at varying altitudes in the Gullele Botanical Garden, Addis Ababa. The cladodes were planted at three distinct altitudinal levels, with their survival rates, growth metrics, and developmental timelines closely monitored over a period of 30 months. The results indicated that while initial survival rates were modest, the species demonstrated resilience across altitudes ranging from 2,559 to 3,000 meters above sea level. Notable differences were observed in growth duration, cladode height, and flowering periods. Lower altitudes facilitated quicker growth and larger cladodes, whereas higher elevations led to delayed growth and flowering, likely due to cooler temperatures. These findings suggest that *Opuntia ficus-indica* can be successfully cultivated in highland ecosystems, contributing to ecological restoration, enhancing food security, and promoting sustainable agriculture in Ethiopia's drought-prone areas. It is recommended that further long-term studies be conducted to refine cultivation techniques and assess reproductive and yield potentials. Integrating *Opuntia* into restoration programs and farming systems could provide a reliable source of food and fodder, improve soil stability, and serve as a climate-resilient crop option for local communities.

Keywords/Phrases: Adaptation, Altitude, Botanical garden, Ecological restoration, *Opuntia ficus-indica*

1 Introduction

Opuntia ficus-indica, commonly known as the cactus pear, is a perennial succulent characterized by a robust woody trunk that can grow to heights of 3 to 5 meters. Its thick, oblong to spatula-shaped stems, known as cladodes, feature a waxy, water-repellent, and reflective epidermis (Giraldo-Silva *et al.*, 2023). Cladodes aged between one and two years produce flowers, with fruits that can range in color from pale green to deep red. The plant's flowers come in three distinct colors: white, yellow, and red (Barbera *et*

al., 1995). Typically, the fruits are enjoyed after the thick outer skin is removed and they are chilled for a few hours. Their flavor is reminiscent of sweet watermelon, and the flesh, which can be bright red, purple, white, or yellowish, contains numerous tiny hard seeds. While these seeds are generally swallowed, individuals with digestive issues are advised to avoid them (Aruwa, 2019).

Opuntia ficus-indica thrives in semi-arid and arid environments and is cultivated globally for its edible fruit. It is well adapted to desert conditions marked

by irregular rainfall and erosion-prone soils, making it increasingly valued for its resilience (Inglese *et al.*, 2017). During drought periods, it provides sustenance for both people and livestock, rendering it a crucial crop in fragile agricultural systems (Ben Salem & Louhaichi, 2014).

Interest in *Opuntia* has surged in recent decades due to its contributions to sustainable agriculture in semi-arid and moderately humid regions (Fonseca *et al.*, 2019). Once viewed as a wild plant, it is now widely cultivated for both subsistence and commercial purposes, bolstering food security in marginalized areas (Barbera *et al.*, 1995). In times of severe water scarcity, the cactus has re-emerged as a critical source of food, forage, and water for rural communities and their livestock, underscoring its role in climate resilience (Kumar *et al.*, 2018). Its pads can store up to 180 tons of water per hectare, acting as a “botanical well” that supports more livestock than traditional rangelands (Zinabu, 2020). Commercial yields vary by environment and management, reaching over 20 tons of fruit per hectare in Italy and up to 50 tons under irrigation in Mexico, though production is generally lower in rain-fed systems (Caloggero & Parera, 2004).

The species’ adaptability is attributed to its unique morphology and physiology. Its crassulacean acid metabolism (CAM) allows for nocturnal water absorption and conservation, while its deep root system stabilizes soil, reduces erosion, and controls sand movement (Kumar *et al.*, 2018). These traits make *Opuntia* an effective tool against drought, soil degradation, and rising temperatures, while also providing food, fodder, and ecological benefits in drylands (Aruwa, 2019).

The Ethiopian Highlands represent a complex agro-ecological zone influenced by altitude, climate, and soil diversity, presenting both challenges and opportunities for crop adaptation (Gorfu & Ahmed, 2012). In these environments, cacti could help mitigate erratic rainfall, erosion, and water scarcity while enhancing food security and income generation (Zemu & Berhanu, 2015). However, despite their widespread distribution in lowlands and degraded landscapes, cactus cultivation in highland plateau areas remains limited (Hailemariam *et al.*, 2024). Expanding cultivation into these regions

could therefore yield significant agricultural and ecological benefits.

Previous studies have highlighted the multifunctional value of *Opuntia ficus-indica*. In Ethiopia, it serves multiple roles, including food, fuel, livestock feed, income generation, and soil conservation (Shushay, 2014). Research in Mexico, its center of origin, demonstrates its ability to thrive in rocky, mountainous terrain (Griffith, 2004). Meanwhile, Ethiopian pastoral systems are increasingly vulnerable to recurrent droughts and climate change, which are pushing suitable habitats from lowlands to montane ecosystems (Berhanu & Fekadu, 2014; Razgour *et al.*, 2020). In this context, resilient crops such as cactus pear present a strategic option for adaptation.

Despite its potential, cactus farming remains limited in the highland regions of Ethiopia, including the Gullele Botanical Garden, which lies at altitudes between 2,559 and 3,000 meters above sea level. The presence of sandy silicic rocks such as Trachyte and Rhyolite suggests that these soils could support the growth of *Opuntia ficus-indica*. However, its adaptation is hindered by a lack of knowledge regarding optimal growth conditions and cultivation practices suited to plateau regions. This shortfall impedes efforts to harness the plant’s benefits for sustainable agriculture, food security, and environmental restoration. Therefore, assessing the plant’s adaptability and growth performance under the specific environmental conditions of Gullele is essential. Such research will provide insights necessary for developing effective cultivation strategies across different altitudinal gradients, ultimately facilitating the integration of *Opuntia ficus-indica* into local agricultural systems and enhancing resilience in drought-affected areas.

This study aims to evaluate the growth performance and adaptability of the species in relation to varying altitudinal gradients, as well as to identify which altitude class best supports its growth.

The research addresses the following questions:

1. What is the growth and adaptation performance of *Opuntia ficus-indica* in the mountainous and plateau areas of Gullele Botanical Garden?
2. What are the survival and growth durations of

the species' cladodes across different altitudinal classes?

3. Can *Opuntia ficus-indica* be effectively cultivated in highland and plateau ecosystems to enhance food security and support ecological restoration?

The hypothesis posits that there is a significant difference in the growth performance and adaptability of *Opuntia ficus-indica* across the altitudinal gradients of Gullele Botanical Garden, with certain altitude classes being more conducive to its cultivation.

The objectives of the study are to:

1. Cultivate *Opuntia ficus-indica* in Gullele Botanical Garden.
2. Evaluate its growth performance across different altitudinal strata.
3. Identify the most suitable altitudinal zones for sustainable cultivation.
4. Assess its potential ecological and production benefits.

5. Provide baseline information for future adaptation research on *Opuntia ficus-indica* under changing climatic conditions.

2 Methods and Materials

2.1 Study Area

The Gullele Botanic Garden (GBG) is located on the outskirts of Addis Ababa, at elevations ranging from 2,559 to 3,000 meters above sea level. Covering an area of 705 hectares, it lies between latitudes 9°1'30" N and 9°5'35" N, and longitudes 38°41'30" E and 38°44'20" E, forming part of Ethiopia's central plateau. The climate in this region can exhibit both warm and cold conditions simultaneously, with high precipitation occurring in August (1,300 mm). February is the warmest month, averaging 20.7°C, followed closely by March and May with averages of 20.2°C and 20°C, respectively. Conversely, August is the coldest month, with an average temperature of 7.5°C. The dry season occurs from March to May, with an average annual rainfall of 1,215.4 mm (Argaw, 2015; Mehair *et al.*, 2024).

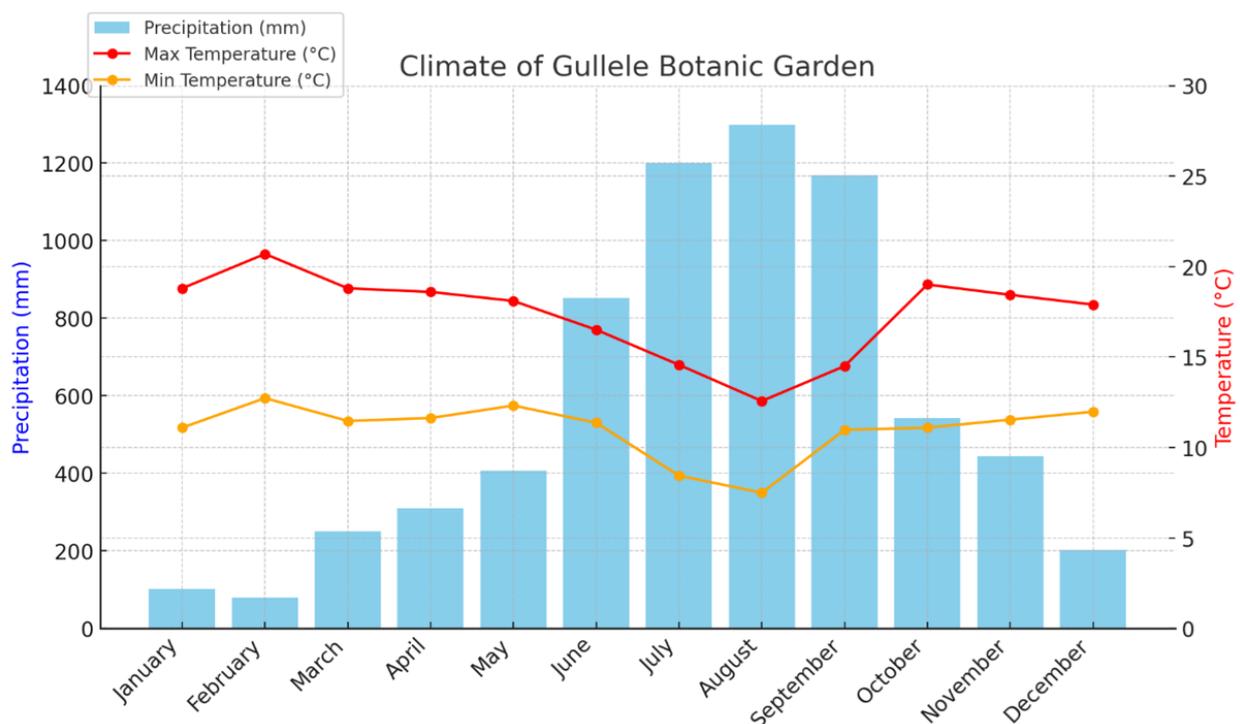


Figure 1. Climate diagram of Gullele Botanical Garden

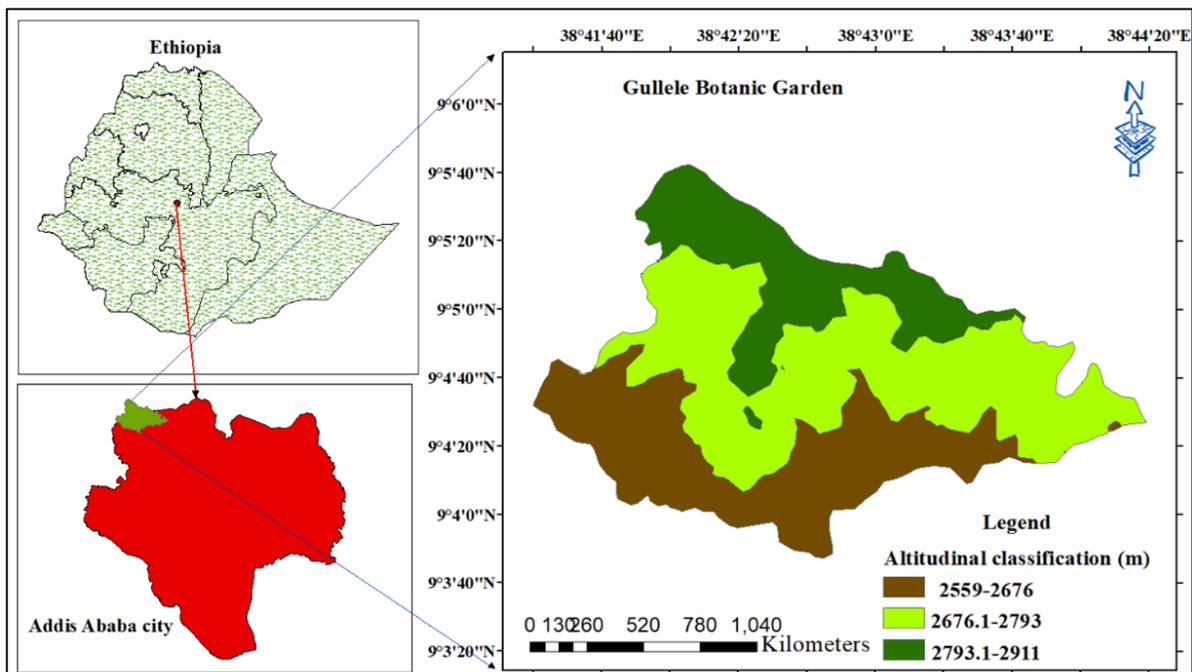


Figure 2. Location map of the study area showing Gullele botanic garden

The vegetation in the area predominantly consists of dry afro-montane and, to a lesser extent, afro-alpine structures, with *Juniperus procera* being the most prevalent species. Other notable species include *Olinia rochetiana*, *Jasminum abyssinicum*, *Erythrina africana*, *Sideroxylon oxyacanthum*, *Maesa lanceolata*, various *Maytenus* species, and *Rosa abyssinica*, along with a range of herbaceous plants that coexist with *Juniperus procera*. At higher elevations, different species of *Helichrysum* and *Erica arborea* can also be found alongside *Juniperus procera*. Historically, the garden was dominated by *Eucalyptus* species, but efforts are currently underway to remove these in favor of prioritizing indigenous species.

2.2 Planting Material Collection

The one-year-old cladodes, harvested from the top of the mother plant, were collected in late December 2022 from the Gurage zone near Welkite (1,910 meters above sea level). These cladodes were subsequently planted at three garden sites differentiated by altitudinal classes: lower (2,600 meters), middle (2,700–2,800 meters), and higher altitude (2,960 meters), following the technique outlined by Alemu *et al.* (2017).

Prior to collection, the cultivars underwent a thorough physical inspection to assess their health and

ensure uniformity in size and age. Selection criteria focused on identifying cladodes that were unpaired or non-flowered (single) and sufficiently developed for planting. Each cladode's initial size was measured before being cut with a sterilized knife, and they were then placed on cardboard for transportation. After planting, data were recorded every two weeks to monitor progress and development.

2.3 Treatments and Experimental Design

Three separate planting zones were established for the collected cladodes, accounting for the elevation differences within the Gullele Botanical Garden. The elevation stratification, with a variation of 150 meters, was divided into three categories: lower (2,600 m), middle (2,750 m), and upper (2,900 m). In each of these zones, 15 cladodes were planted, totaling 45 pads.

During the planting process, the flat edges of the cladodes were oriented east and west, while the thin sides faced north and south. This orientation helps prevent burning and desiccation when the sun shines on the narrowest part of the cladodes during peak heat. Planting was scheduled to occur within three days after collection. Mature cactus pads were placed 1 meter apart in holes approximately 30 cm



Figure 3. Partial view of *Opuntia ficus-indica* cladode growth performance

2.4 Method of Analysis

deep, ensuring that one-third of their surface area was buried while two-thirds remained above ground. The planting took place at the beginning of the dry season in December 2022 to promote optimal establishment.

Across all elevation ranges, the planting was conducted on rocky, fallow, and bare land with uniform treatment to avoid significant variations. Prior to planting, obstacles were cleared, holes were dug, and preparations were made one month in advance to facilitate successful establishment. Monitoring and watering were performed twice a week following planting. Data monitoring and recording occurred bi-monthly during the first six months to closely track survival rates and the growth of new cladodes, with all growth performance data documented in an Excel spreadsheet.

Data collected over a 30-month period were analyzed using SPSS version 22 statistical software. To examine the growth performance of different cladodes across various altitudinal classes, a stacked bar plot was generated in R. This visualization illustrated the variation in growth metrics along the altitudinal gradients. Additionally, R was used to analyze the time taken for growth performance in relation to the classified altitudinal gradients for this study.

For the analysis of altitudinal classes and parameters such as cladode survival, height of mother cladodes, developmental stages (first, second, third), and flowering time, one-way ANOVA tests were conducted using IBM SPSS Statistics version 30. These analyses aimed to determine whether significant differences exist in these variables across the different altitudinal classes.

The mean growth performance of the experimental species at each altitude was computed using the following formula:

$$\text{Overall Mean} = \frac{\sum \text{Mean Growth of All Species in Altitude A}}{\text{Number of Species in Altitude A}}$$

3 Result and Discussion

3.1 Survival rate in the first three months

After planting 15 mother cladodes (primary cuttings) in each altitudinal class, the survival and growth patterns varied across the different elevation levels over time (Figure 4). During the initial two months following planting, all species exhibited wilting symptoms and showed no immediate signs of survival. However, some previously wilted cladodes later began to sprout new growth. By the third month, the

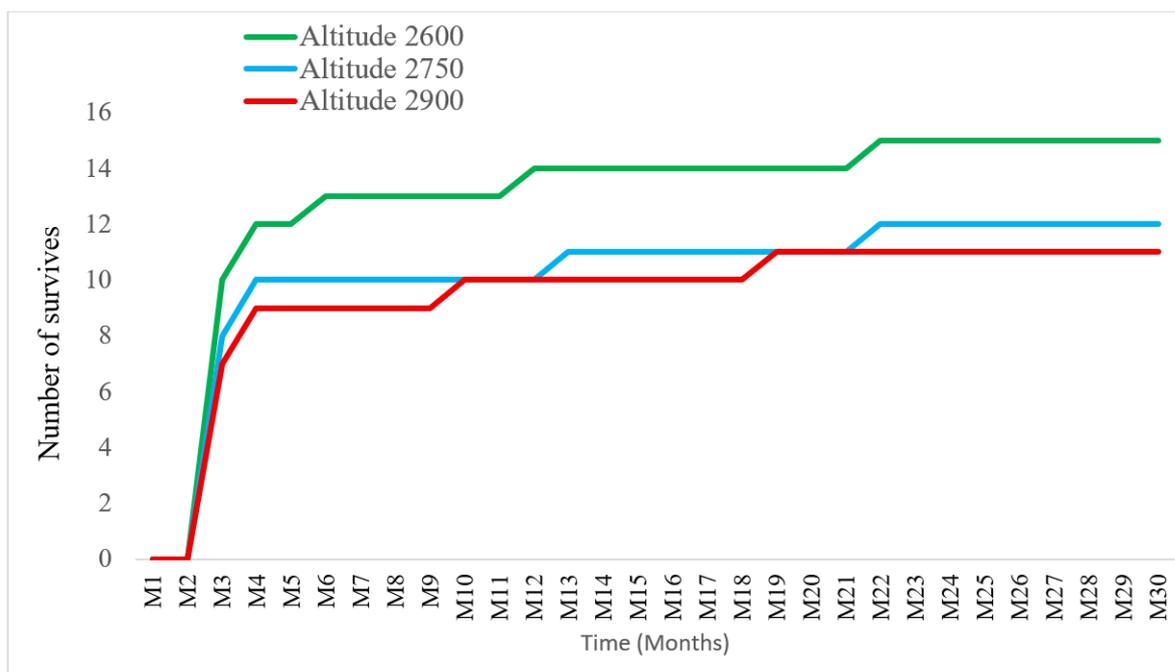


Figure 4. Number of *Opuntia ficus-indica* cladode survives vs time (months) along altitudinal classes

number of surviving cladodes differed by altitude: 12 in the lower altitude, 10 in the middle altitude, and 9 in the higher altitude. The status of each cladode, whether alive or dead, was assessed and recorded over a six-month period.

Despite most of the planted cladodes of *Opuntia ficus-indica* surviving through the monitoring period, the survival rate was low and uncertain during the first two months after planting. Many of the cladodes exhibited wilting signs due to transplant shock, environmental stress, or suboptimal microclimatic conditions. By the third month, however, survival rates improved considerably; the best results were observed in the lower altitudinal class, where 12 out

of the 15 cladodes survived. The middle altitude zone followed with 10 survivors, while 9 cladodes survived in the higher altitudinal class. This trend suggests that lower elevations may provide better conditions for initial growth, likely due to relatively warmer temperatures and favorable air conditions that support growth and establishment. These results align with findings by Aruwa (2019) and Prisa (2023).

3.2 Final total survives

Once the mother cladodes have survived, it typically takes around six months for a new generation of cladodes to develop within each altitude category (Table 1).

Table 1. Growth performance of *Opuntia ficus-indica* cladode along altitudinal classes at GBG

Altitude classes	1 st generation cladode		2 nd generation cladode		3 rd generation cladode	
	Time taken to Emerge (months)	Time taken to Cladode complete (months)	Time taken to Emerge (months)	Time taken to Cladode complete (months)	Time taken to Emerge (months)	Time taken to Cladode complete (months)
Lower (2600)	6	10	11	16	17	25
Middle (2750)	6	11	12	18	20	28
Higher (2900)	6	13	14	21	22	30

Thirty-eight *Opuntia ficus-indica* cladodes, all representing the third generation, survived the experimental conditions and exhibited diverse growth performances. Notably, survival rates varied significantly by altitude. The initial fifteen cladodes established in

the lower altitude class achieved complete survival, while the middle and higher altitude classes yielded 12 and 11 surviving cladodes, respectively (Figure 5).

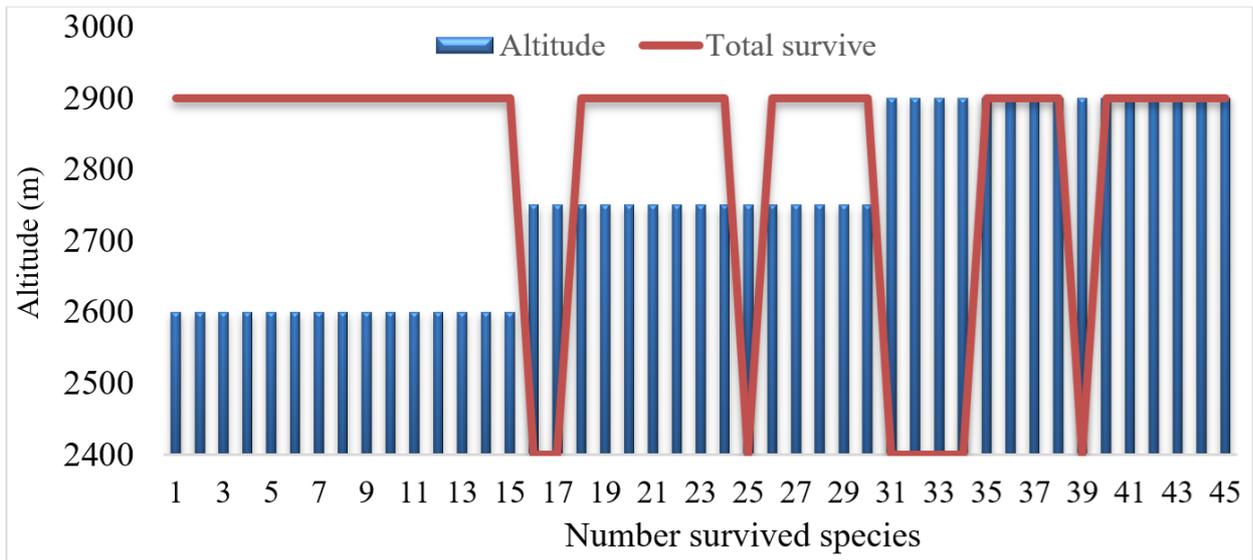


Figure 5. Relationship between altitude (m) and total mother cladodes survive

3.3 Growth performance versus altitude

The growth duration for the initial cladodes varied by altitude: approximately 10 months for lower altitudes, 11 months for middle altitudes, and 13 months for higher altitudes (Figure 6). The second cladode emerged around the 11th month in the lower altitude zone, while it took 12 months in the middle altitude and 14 months in the higher altitude. The total time to complete the growth of the second generation of cladodes is roughly 16 months for lower altitudes, 18 months for middle altitudes, and 21 months for higher altitudes. The development of the third cladode spans 17 to 25 months for lower altitudes, 20 to 28 months for middle altitudes, and 22 to 30 months for higher altitudes. By the 30th month, only two cladodes (the fourth cladode and a flower) had emerged, with no additional development noted in the other altitude classes.

Key: T1C: Time taken for the first cladode; TC1C: Time taken to complete the first cladode; T2C: Time

taken for the 2nd cladode; TC2C: Time taken to complete the 2nd cladode; T3C: Time taken for the 3rd cladode; TC3C: Time taken to complete the 3rd cladode, T4C/f: time take for the 4th cladode or/and flower.

The results of the study indicated that the time from emergence to the completion of growth for successive cladodes increased with altitude. For instance, the first cladodes emerged after six months in all zones, but the time required to develop each successive cladode grew longer from lower to higher altitudes. Specifically, the third cladode took approximately 17, 20, and 22 months to emerge at lower, middle, and higher altitudes, respectively. The slower development at higher elevations may be attributed to cooler temperatures, lower solar radiation, and reduced soil nutrients, confirming previous research that altitude affects the phenological development of cacti (Shushay, 2014; Khandelwal *et al.*, 2019).

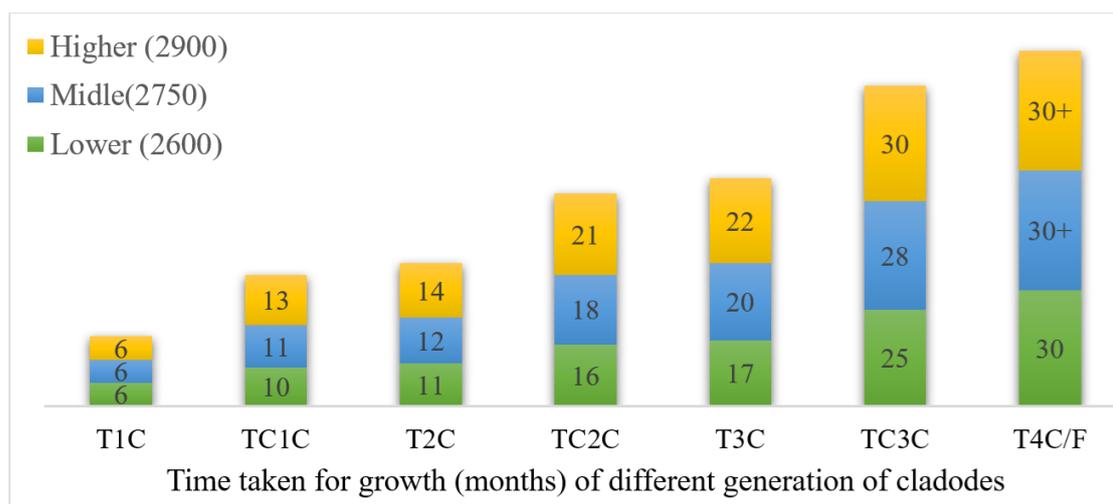


Figure 6. *Opuntia ficus-indica* cladode growth performance versus time

3.4 The impact of altitude in survival and height of cladode

The altitudinal gradient does not significantly affect the height of the mother cladode ($p = 0.668$) or the height after survival ($p = 0.454$). However, altitude significantly influences the height of the first, second, and third cladodes, as well as flowering time,

with significant values of 0.045, 0.027, 0.004, and 0.001, respectively (Table 2). The average height of cladodes shows the highest mean square (114.311) in the lower altitude class (2,600 m), followed by the middle altitude class (2,750 m). In contrast, the higher altitude class (2,900 m) exhibits a relatively lower mean square (62.178) in height compared to the other altitudinal classes.

Table 2. Results of ANOVA analysis regarding the effects of altitude on the height of cladodes

	Altitudinal class	ANOVA				
		Sum of Squares	df	Mean square \pm SD	F	Sig.
Primary height	Lower	114.311	44	3.09 \pm 2.1	0.41	0.67
	Middle	112.133	42	2.67 \pm 1.78		
	Higher	62.178	24	1.81 \pm 1.1		
Height after survive	Lower	101.2	22	1.87 \pm 1.1	0.8	0.45
	Middle	97.467	42	2.321 \pm 2.04		
	Higher	58.733	44	4.00 \pm 2.6		
Height of 1 st cladode	Lower	80.578	38	4.62 \pm 2.8	2.72	0.05
	Middle	61.333	18	1.70 \pm 0.33		
	Higher	19.244	14	0.88 \pm 0.25		
Height of 2 nd cladode	Lower	134.978	42	10.69 \pm 3.01	3.95	0.03
	Middle	103.6	22	2.71 \pm 0.2.05		
	Higher	21.378	14	1.23 \pm 0.66		
Height of 3 rd cladode	Lower	32.844	44	16.422 \pm 3.7	6.44	0
	Middle	107.067	12	2.549 \pm 2.1		
	Higher	139.911	2	1.12 \pm 0.12		
Flowering time	Lower	124.061	24	0.422 \pm 0.1	6.44	0
	Middle	42.184	12	0 \pm 0.05		
	Higher	38.311	2	0 \pm 001		

NB: Lower altitude= 2600 meters above sea level; Middle altitude =2750 meters above sea level

The ANOVA results indicated that altitude significantly affected the heights of the first, second, and third cladodes, as well as flowering time ($p < 0.05$), but not the initial or post-survival height of the mother cladode (Table 2). The greatest cladode heights were observed at lower altitudes, suggesting that the environmental conditions in these areas were more favorable for robust growth compared to higher altitudes. The decline in size with increasing altitude may be attributed to decreasing temperatures and shorter growing seasons, which influence the amount of biomass accumulation. This finding is consistent with previous observations of altitude-related differences in cactus growth (Gouhis *et al.*, 2017; Naorem *et al.*, 2024).

Interestingly, flowering time was significantly delayed at higher altitudes ($p = 0.001$), likely driven by cooler temperatures and photoperiodic effects. Delayed flowering can impact reproductive success and yield, which should be considered when planning cultivation strategies (Song *et al.*, 2020).

3.5 Implications for Cultivation and Ecological Restoration

The demonstrated adaptability of *Opuntia ficus-indica* across different altitudinal classes suggests potential for cultivation beyond conventional arid environments. The evidence of its resilience, as shown in the study, includes moisture-stress survival rates and overall growth performance at higher elevation sites, which align with observations by Griffith (2004) and Prisa (2023), who noted similar resilience under rocky and resource-scarce conditions. The ability of *Opuntia ficus-indica* to thrive in rocky soils, as seen in the Gullele Botanical Garden, and to withstand adverse conditions highlights its remarkable flexibility. This adaptability reinforces its potential as a candidate for ecological restoration and sustainable agricultural practices in the Ethiopian highlands (Dejene, 2003).

The delayed yet continued growth at higher elevations indicates that environmental constraints, such as lower temperatures, limited oxygen availability, and reduced nutrient levels, initially inhibit faster growth rates. However, once the species adapt, they can exhibit consistent growth processes over time (Ranjan *et al.*, 2016). This evidence supports the

notion that, despite immediate physiological limitations at high elevations, these species may adapt to sustain growth capacity in the long run, emphasizing the importance of acclimatization and evolutionary adaptation (Körner, 2007).

4 Conclusion

This study demonstrated that *Opuntia ficus-indica* is thriving and adapting well across various altitudes in the Gullele Botanical Garden, suggesting it could be an excellent candidate for cultivation in Ethiopia's highland and plateau ecosystems. While initial survival rates were somewhat low in the early planting months, this resilient species rebounded, with survival rates improving over time, particularly in the lower altitude regions. Elevation played a significant role in its growth cycle and physical characteristics, such as the height of the cladodes and the timing of flowering. Lower elevations appeared to promote quicker growth and larger cladodes, while the cooler temperatures and environmental challenges at higher elevations slowed growth, though they did not prevent the plant from surviving and establishing itself.

These findings highlight that *Opuntia ficus-indica* could thrive beyond arid areas, potentially leading the way in ecological restoration, enhancing food security, and promoting sustainable agriculture in the Ethiopian highlands. Its ability to grow in rocky, nutrient-poor soils and withstand environmental stress underscores its potential for revitalizing degraded and drought-affected lands. However, to fully understand its capabilities, further long-term research is needed on its reproductive success, fruiting, and ecological effects.

Limitations and Recommendations

This study is limited to 30 months of activity and the environmental conditions at Gullele Botanical Garden. Long-term monitoring of reproductive performance, fruit yield, and ecological impacts would provide a more comprehensive understanding of the cultivation potential. Additionally, exploring cultivar variability and soil amendments could enhance growth to optimal levels in highland environments.

Based on the study's findings, it is recommended to prioritize the cultivation of *Opuntia ficus-indica* in

lower altitudes (2,600 m), as this zone demonstrated the highest survival rates, faster growth, and larger cladode development. However, with proper management and acclimatization, the species can also be established at middle and higher altitudes, although growth and flowering may be slower.

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Data Availability Statement

Data are contained within the article.

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Conflicts of Interest

The authors declare no conflict of interest.

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