Heliyon 10 (2024) e37786

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Multi-Scale analysis of the impacts of soil and water conservation practices and landscape on grain yield and return on investment in the sub-humid ethiopian highlands

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ARTICLE INFO

Keywords:
Soil and water conservation
Economic return
Food security
Sustainable development
Community-based cost-sharing
Livelihood

ABSTRACT

Ethiopia's sub-humid highlands face a critical challenge in balancing agricultural productivity with land degradation. This study explores the effectiveness of soil and water conservation practices (SWCPs) in addressing this challenge. We investigated the interaction effects of types of SWCPs, landscape positions, and location on *Teff* (*Eragrostis teff*) and wheat (*Triticum aestivum*) yield. In addition, we assessed the economic viability of SWCPs using cost-benefit analysis with farmer-funded and cost-sharing scenarios. The results indicated that yield was significantly affected by the interactions between factors like SWCP type and landscape position. Soil bunds consistently increased crop yield across diverse locations and landscapes, indicating superior erosion control benefits. Lower landscape positions on foot slopes benefited most from SWCP implementation. *Teff* yield increased by 188 % and wheat yield by 181 % under soil bunds. The cost-benefit analysis confirmed the financial viability of SWCPs, particularly for *Teff* (NPV = 4499.35 USD, IRR = 50 %, and BCR = 1.51) and wheat (NPV = 544.35 USD, IRR = 16 %, and BCR = 1.06) grown on lower landscapes with farmer-funded investment scenarios. Positive return on investment was observed in both scenarios, with cost-sharing offering greater economic benefits for farmers. These findings highlight the importance of an integrated approach to SWC implementation for achieving multiple Sustainable Development Goals (SDGs) by enhancing food security, improving farmer incomes, and promoting sustainable and productive landscape management practices. Future research should explore the long-term sustainability of SWCPs, their adaptation across diverse agroecological zones and landscapes, the incorporation of various crops, the broader socioeconomic impacts, and the development of effective extension programs for wider adoption by farmers.

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https://doi.org/10.1016/j.heliyon.2024.e37786
Received 1 June 2024; Received in revised form 28 August 2024; Accepted 10 September 2024

1. Introduction

Soil erosion is a critical environmental and agricultural challenge across the globe, particularly in sub-humid ecosystems like those found in East Africa such as Ethiopia [1–3]. This erosion reduces land productivity and negatively impacts downstream ecosystems and infrastructure [4]. Implementing SWC practices has been demonstrated as a powerful tool for mitigating soil erosion in some regions of the world. Studies in Ethiopia [5,6] have shown that SWC practices like terracing, mulching, and stone bunds significantly reduce soil erosion rates, improve soil moisture content, and enhance agricultural productivity.

Ethiopia's subhumid highlands are a critical agricultural region facing a significant threat from severe soil erosion. This vulnerability arises from various factors, including high and concentrated population, high annual rainfall, steep terrain, and inappropriate land management methods [7]. Estimates of annual soil loss under various land use patterns range from 30.4 to 122.3 t ha^{-1} yr^{-1} [8], exceeding established sustainable limits for Ethiopia, varying from 2 to 18 t ha^{-1} yr^{-1} [9]. This erosion significantly degrades soil fertility, reduces crop yield, and negatively impacts agricultural productivity and ecosystem services [10].

Soil and water conservation practices (SWCPs) have emerged as a promising strategy to address soil erosion and enhance agricultural sustainability [7]. Existing research demonstrates a positive impact of SWCPs on soil fertility and crop yields. Studies have shown improvements of soil quality [11,12], with a notable example from Debre Mawi reporting a 32.15 % improvement of soil quality due to SWCP implementation [13]. Similarly, significant yield enhancements have been observed, with terraced farms in the Anjenie watershed achieving yield increases of 94 %, 205 %, and 125 % for *Teff*, barley, and maize, respectively, compared to non-terraced fields [14]. However, the effectiveness of SWCPs is known to vary depending on several factors, including geographic location [15,16], the specific type of SWCP implemented [17,18], landscape position, and the type of crop being cultivated [15,16]. Although landscape position plays a crucial role in Ethiopian agriculture, its influence on SWCP efficacy remains understudied [5,19].

While existing research highlights the negative economic impact of soil erosion and the benefits of SWCPs, a deeper understanding of the interactions between geographic location, SWCPs, landscape position, and economic outcomes is needed. This knowledge gap hinders the optimization of these practices for local contexts and advances to better soil and water conservation technologies based on their impacts on yield. This research aims to bridge this knowledge gap by examining interactions between location, types of SWCP,

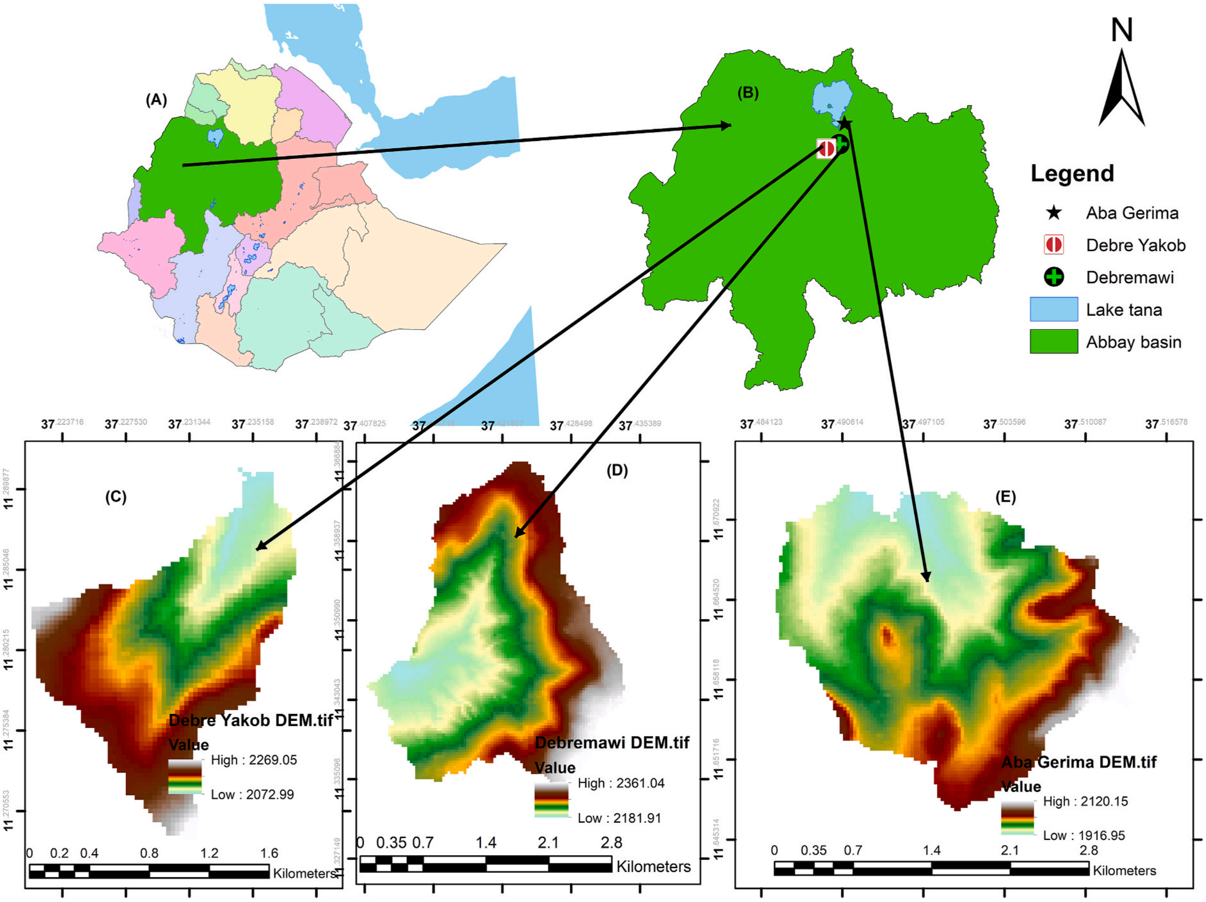

Fig. 1. Location map of project sites, Ethiopia and 12 river basins (A), Abbay basin, Lake Tana and study watersheds (B), Debre Yakob (C), Debre Mawi (D) and Aba Gerima (E).

and landscape position on crop productivity and profitability within the subhumid ecosystem, contributing to a more comprehensive understanding of SWCPs in a landscape context.

Therefore, this study investigates the impact of soil and water conservation practices (SWCP) on grain yield, profitability, and/or return on investment (ROI) in the subhumid tropical highland ecosystem of Ethiopia. Recognizing the potential variability in productivity gains due to crop type, landscape position, and specific SWC structures, the research aims to: 1) quantify the effects of SWCPs on *Teff* and wheat grain yield; 2) analyze the economic gain variation of SWCPs (e.g. cost-benefit analysis); and 3) identify existing impacts of interactions between SWCP type, landscape position, and location on grain yield and economic outcomes.

By considering both agronomic and economic factors, this study provides valuable insights for optimizing soil and water conservation strategies and promoting sustainable land management practices in the subhumid ecosystem, ultimately contributing to rural livelihoods and economic viability and agrifood systems improvement in the region in general and the study area in particular.

2. Methods

2.1. Study area description

This research was conducted in three watersheds of the northwestern Ethiopian highlands. This zone is characterized by tepid thermal regimes (mean annual temperature of 16–21 °C) and moist moisture regimes (average growing season length of 121–180 days). The watersheds are Aba Gerima (582 ha), Debre Mawi (597 ha), and Debre Yakob (299 ha) (Fig. 1(A–E)). A table summarizing each watershed's major climatic data is presented in Table 1.

All three watersheds share several key common characteristics. They exhibit a similar range of slope gradients, with the dominant slopes falling within the 2–15 % range. Also, all watersheds cultivate wheat and *Teff* as primary crops, and Nitisols and Vertisols are the most dominant soil types, although their proportions vary. Notably, soil and water conservation structures in the form of stone and soil bunds were implemented in all three watersheds between 2013 and 2014 under the Water and Land Resource Center supporting program.

On the other hand, the watersheds also exhibit some key differences. The topographic orientation and coverage of landscape positions (upper, middle, and foot slopes) differ across the watersheds. Aba Gerima has the greatest proportion of the lower landscape, while Debre Yakob has the most extensive middle landscape. Upper landscape coverage is also most significant in the south and southwest areas of Debre Yakob. The specific proportions of Nitisols and Vertisols vary. Debre Yakob has the most diverse soil composition, with Nitisols (28 %), Luvisols (38 %), Regosols (33 %), and Vertisols (1 %). In contrast, the upper parts of Debre Mawi and Aba Gerima are dominated by Nitisols, with increasing Vertisol presence in the lower landscapes.

2.2. Methodology

2.2.1. Treatments and crop selection

This study examined the combined effects of location, soil and water conservation practices (SWCPs), and landscape units on the grain yield of two dominant crops, *Teff* (*Eragrostis teff*) and wheat (*Triticum aestivum*) in a tepid sub-humid ecosystem. A pre-experiment survey identified dominant crops and soil and water conservation practices (SWCPs) within the three watersheds. *Teff* and bread wheat, the most dominantly grown crops, were chosen for a landscape yield response study. The soil and water conservation structures were extracted from Google Images, verified on the ground, and categorized into three management conditions. These include non-conserved, soil bund, and stone bund areas. The soil and stone bunds were constructed 10 years ago. Fig. 2(A–D) illustrates the appearance of soil and water conservation structures during and after that period.

The landscape units of the watersheds were derived from the landscape map of Ethiopia [20], derived basically from the geomorphology map produced by the International Soil Research Center (ISRC) at 50m resolution in 2019. The classification considers relief intensity, elevation difference, topographic index, slope gradient, and position in the landscape. Using these thematic layers, the study sites were classified into three distinct landscape units: upper, middle, and lower positions. This classification was verified through a field survey and adjusted to align with the actual field conditions and the proposed experimental design. The spatial distribution of these three landscape positions across the three study watersheds is illustrated in Fig. 3(A–C), which was used to guide the selection of experimental plots.

Therefore, experimental treatments were formed from a combination of location, SWC practices, and landscape units to assess their effects on the yield of two major crops. In the three study watersheds (Aba Gerima, Debre Mawi, and Debre Yakob), three SWCP

Table 1
Climatic data of the study watersheds.

Watershed	Area (ha)	Elevation (masl)	Mean annual rainfall (mm)	Mean annual temperature (°C)	Annual mean minimum temperature (°C)	Annual mean maximum temperature (°C)
Aba Gerima	582	1917–2120	1397	19.6	12.6	26.7
Debre Mawi	597	2182–2361	1248	17.9	9.79	26.03
Debre Yakob	299	2073–2269	1347	19.1	10.9	27.3

Fig. 2. Photos depicting soil and water conservation practices (SWCPs) in the study area: (a) Newly constructed soil bund in the Debre Mawi watershed (January 2014, photo by Dr. Gizaw Desta); (b) Stabilized soil bund in the Debre Mawi watershed (November 2023, photo by Aschalew Kassie); (c) Newly constructed stone bund in the Abaa Gerima watershed (January 2014, photo by Dr. Gizaw Desta); (d) Stabilized stone bund in the Abaa Gerima watershed (November 2023, photo by Aschalew Kassie).

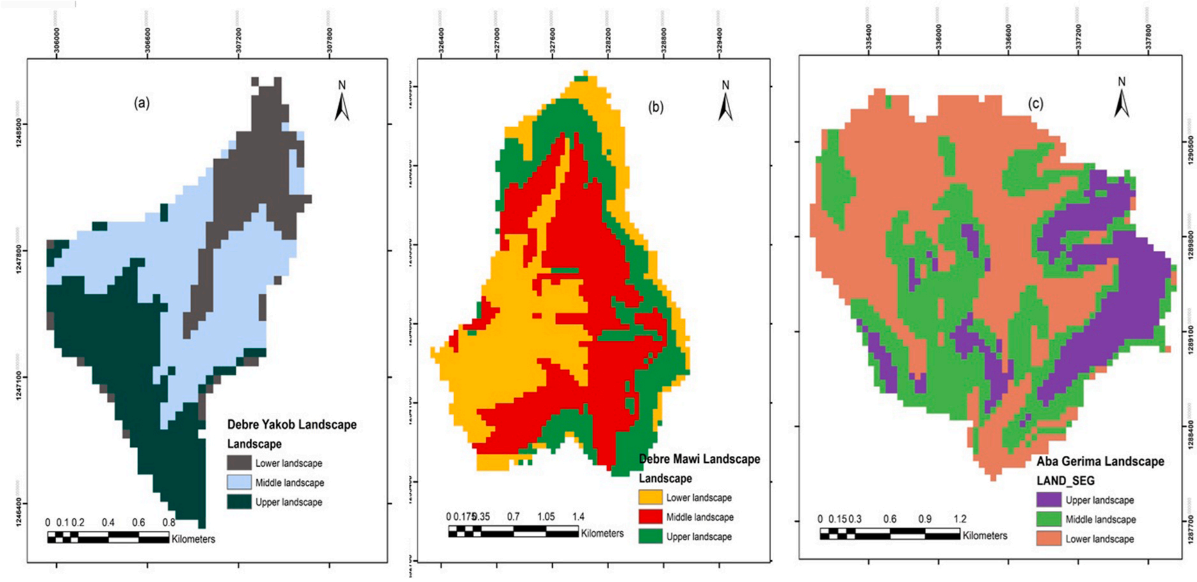

Fig. 3. Spatial distribution of three landscape positions across three study watersheds, (a) Debre Yakob, (b) Debre Mawi, and (c) Aba Gerima.

categories (non-conserved, soil bunds, and stone bunds) were applied across three landscape units (upper, middle, and lower landscape positions), resulting in unique treatment combinations for two experimental crops.

2.2.2. Experimental setup and design

The experimental setup was designed to assess the impact of various factors on crop productivity in the context of the three watersheds. As mentioned, the study incorporated soil and water conservation practices (non-conserved, stone bund, and soil bund), serving as key independent variables. The topographic diversity of the landscape positions i.e. upper, middle, and lower landscape positions was integrated as a second factor. Additionally, two major crops, *Teff* and wheat were included as test crops to represent crop production scenarios.

A three-way factorial design with nested replicates was employed to evaluate the combined effects of location, SWCPs, and landscape position on crop yields. Each watershed served as a spatial location ($n = 3$). Three landscape units (upper, middle, and lower landscape positions) were identified within each watershed. Three SWC practices (non-conserved, soil bunds, and stone bunds) were implemented within each landscape unit. Plots were randomly assigned within the study watersheds to receive one of the nine treatment combinations (3 SWCPs x 3 landscape units). Each treatment combination was replicated three times, resulting in a total of 27 potential treatment plots per watershed. However, due to the absence of certain treatment combinations in specific watersheds on the ground, a total of 114 data plots were established (Table 2). The treatment combinations that appeared on the ground were 14, 16, and 8 for Aba Gerima, Debre Mawi, and Debre Yakob respectively with 3 replications (Table 2). The landscape units and types of SWCPs were mapped in the ArcGIS environment. However, the crop plots were selected at the farm level through a ground survey. The relevant response variable (crop yield) was collected at the end of the growing season and analyzed using three-way ANOVA to assess the main and interaction effects.

2.3. *Yield data collection and main assumptions*

To facilitate statistical analysis and interpretation, 17 and 21 treatment combinations were used for *Teff* and wheat respectively, resulting in a total of 38 unique treatments each replicated three times. Among these, 22 treatments represented treated fields with soil and water conservation practices (SWCPs), whereas 16 represented untreated control fields.

For each treatment within SWCP-implemented fields, a 4 m^2 steel quadrant was cast at three distinct positions: base (lower part of the area between two bunds), middle, and upper section (upper part of the area between two bunds) within the bunds. These positions were marked and delineated using wooden pegs and nylon ropes to ensure precise sampling area demarcation. To account for potential land area loss due to SWCP structures, harvests from the three bund positions were combined and extrapolated to represent a standard 12 m^2 area, replicating this process three times per treatment. By adopting this strategy, the collected data accurately reflects yield within bunded fields. Considering an estimated 7 % land loss (or effective cropped area of 0.93 ha per 1 ha) due to SWCPs [16,21], all results were converted and reported directly as tone per hectare for consistent analysis and interpretation.

2.4. *Financial viability of soil and water conservation investments*

The central hypothesis we aim to test here is whether the costs outweigh the benefits when investing in soil conservation measures, as often is suggested, but about which the empirical evidence base is ambiguous. This study investigated the 10 years (2014–2023) impacts of soil and water conservation (SWC) practices on *Teff* and wheat yields and economic returns. We focused on two common SWC interventions, soil and stone bunds, implemented across the three identified landscape units. The study aims to provide comprehensive insights into their effectiveness over 10 years, from a period when the watersheds were treated with soil and water conservation practices through the project implemented by the Water and Land Resource Center (WLRC) and the local agriculture departments up to 2023.

Yield data were estimated for the entire study period (2014–2023) based on certain assumptions as described by Tesfaye, Brouwer [22]. The year 2014 was considered as the baseline, representing a non-conserved scenario for the entire watershed. Control plots were

Table 2
Distribution of experimental variables, treatments, and number of plots of *Teff* and wheat in the three watersheds.

Watersheds	Landscape unit	Type of conservation practices	Crop type	# of replicated plots
Aba Gerima	Upper	Non-conserved	*Teff* and wheat	6
		Soil Bund	*Teff* and wheat	6
	Middle	Non-conserved	*Teff* and wheat	6
		Stone bund	*Teff* and wheat	6
	Lower	Non-conserved	*Teff* and wheat	6
		Soil Bund	*Teff* and wheat	6
		Stone bund	*Teff* and wheat	6
Debre Mawi	Upper	Non-conserved	*Teff* and wheat	6
		Soil Bund	*Teff* and wheat	6
		Stone bund	*Teff* and wheat	6
	Middle	Non-conserved	*Teff* and wheat	6
		Stone bund	*Teff* and wheat	6
	Lower	Non-conserved	*Teff* and wheat	6
		Soil Bund	*Teff* and wheat	6
		Stone bund	*Teff* and wheat	6
Debre Yakob	Upper	Non-conserved	Wheat	3
		Soil Bund	Wheat	3
	Middle	Non-conserved	Wheat	3
		Stone bund	Wheat	3
	Lower	Non-conserved	*Teff* and wheat	6
		Soil Bund	*Teff* and wheat	6

assumed to remain non-conserved throughout the study period (2014–2023); thus the estimation assumed control treatments obtained the same yield for the previous 10-year cropping seasons regardless of variation in weather changes, and impacts of pests, etc., and accounted with their 2023 yield estimates. For conserved plots, yield data for 2014 was obtained by averaging the respective control plot yield based on landscape position. Subsequently, yield differences observed in 2023 were linearly interpolated to estimate yield for the intervening years (2015–2022) in conserved plots [22]. The annual income was calculated by annual yield gain multiplied by the respective market price (Table 3). The sum of the 10-year annual income from each treatment was used for income calculations.

The financial study uses the current price discounted based on the average discount rate. Economic data at the farm level were collected using farmer interviews, and market surveys (Table 3). This data encompassed SWC implementation costs, crop production expenses, and prevailing market prices for *Teff* and wheat. Specific assumptions were made to maintain consistency across treatments: an average of 1 Km SWC structure per hectare of land, established work norms for SWC practices (150 and 250 person-days per hectare or 6 m for soil bund and 4 m for stone bund per person day) for constructing soil bunds and stone bunds, respectively) [23]. Fertilizer and seed rates were estimated based on local extension recommendations.

A comprehensive cost-benefit analysis (CBA) was conducted to assess the financial implications of implementing the two main SWC measures in three landscape units compared with no conservation efforts. The financial viability of each approach was evaluated using economic parameters like Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR), considering an average discount rate of 11.50 % [24] to overcome inflation.

The economic benefits of different soil and water conservation (SWC) practices were assessed using gross margin analysis. This analysis considers crop yield data, production costs, and market prices (Table 3) to calculate the gross margin for each SWC practice. Return on investment (ROI) was then estimated by dividing the net gain (gross margin minus the cost of implementing the SWC practice) by the initial investment cost. To explore the economic feasibility under different financial circumstances, two scenarios were considered. The first scenario assumes that farmers or the community have already implemented all SWC measures. This might involve community mobilization efforts where farmers collaborate to build bunds on each other's fields, contributing labor in exchange for reciprocal help. The second scenario assumes that farmers only cover 10 % of the total SWC investment, with the remaining 90 % subsidized through programs like food-for-work (FFW) or cash-for-work (CFW). Regardless of the scenario, the long-term maintenance of the SWC practices remains the responsibility of the farm owner.

2.5. *Statistical analysis*

The R statistical software package [25] was employed for all data analyses. Crop yield data from the three-way factorial experiment (location × SWC practice × landscape unit) were subjected to normality tests (e.g., Shapiro-Wilk test) to confirm adherence to a normal distribution [26,27]. The data satisfied the normality assumption, and subsequent analyses proceeded with a three-way analysis of variance (ANOVA) using the general linear model (GLM) procedure at a 5 % significance level (($\alpha = 0.05$). The Least Significant Difference (LSD) post-hoc comparisons were used to separate means and identify significant differences among treatment combinations for each measured response variable (e.g., crop yield).

For comparisons between treated and untreated farmlands, a one-way ANOVA was conducted [25] to assess statistical differences. Inter-bund variability in crop yield at the base, middle, and upper sections between successive bunds was analyzed using descriptive statistics, including means, standard deviation, and coefficients of variation (CV). Similar statistical comparisons using appropriate tests were performed to evaluate economic parameters such as Net Present Value (NPV) and Benefit-Cost Ratio (BCR).

3. Results

3.1. *Overall analysis of variance (ANOVA) results*

The results indicated statistically significant main effects ($p < 0.01$) for all factors (watersheds location, landscape units, and types of soil and water conservation practices) on both wheat and *Teff* yields (Table 4). Additionally, various interaction effects significantly modulated yield responses ($p < 0.01$), highlighting the complex interplay between these factors.

Table 3
Input data used for estimation of costs and benefits of soil and water conservation measures.

Inputs	Teff		Wheat	
	Amount	Unit rate	Amount	Unit rate
Seed	30 kg/ha	2365 USD/t	175 kg/ha	1454.5 USD/t
Fertilizer	150 kg/ha	765 USD/t	150 kg/ha	765 USD/t
Soil bund	1 Km/ha	150 PD/ha (5.45 USD/PD/day)	1 Km/ha	150 PD/day (5.45 USD/PD/day)
Stone bund	1 Km/ha	250 PD/ha (5.45 USD/PD/day)	1 Km/ha	250 PD/ha (5.45 USD/PD/day)
Soil bund maintenances	18 % of the total investment/year			
Stone bund maintenances	5 % of the total investment/year			
Labor requirement	160 PD/year	5.45 USD/PD	108 PD/year	5.45 USD/PD
Oxen requirement	18 OD/year	10.9 USD/OD	40 OD/year	10.9 USD/OD
Sales price		2182 USD/t		1091 USD/t

OD= Oxen day; PD = person day; and USD= US dollar.

While several interactions significantly influenced yields ($p < 0.01$), the three-way interaction encompassing the three factors did not show a significant interaction effect on wheat yield ($p = 0.96$). This suggests that the combined influence of all three factors does not consistently explain wheat yield variations across the study area. However, the interaction between location and SWC practices significantly affected wheat yield ($p = 0.03$). This finding implies that the effectiveness of specific SWC strategies varies spatially within the investigated watersheds.

A one-way ANOVA comparing wheat and *Teff* yields from treated and untreated fields revealed a statistically significant difference ($p < 0.001$). This finding strongly suggests that SWC practices significantly influence wheat and *Teff* yields.

3.2. *Effects of soil and water conservation (SWC) on teff and wheat yield*

There was a significant ($p < 0.01$) difference in the yield of *Teff* and wheat crops grown in treated (soil bund and stone bund) and untreated plots within a sub-humid ecosystem (Table 5), irrespective of the type of structures and landscape units. The results revealed a significant increase ($p < 0.01$) in mean *Teff* yield (188 %) and mean wheat yield (181 %) for plots with SWC practices compared to untreated controls. This finding suggests that SWC practices in general can substantially enhance crop yields regardless of the specific structure type or landscape unit within this ecosystem.

3.3. *Effects on teff yield*

3.3.1. *Main effects of location, landscape, and SWCPs*

Significant differences in *Teff* yield were observed among locations, landscape units, and types of SWCPs ($p < 0.001$) (Table 4). The highest average Teff yield (1.73 t/ha) was recorded for Debre Yakob, followed by Debre Mawi (1.46 t/ha). The lowest yield (0.85 t/ha) was observed in Aba Gerima, highlighting potential spatial variations in environmental factors impacting *Teff* production. Among the three landscape positions, the lower landscape position recorded the highest average yield (1.44 t/ha), followed by the upper position (1.17 t/ha). The middle landscape position exhibited the lowest yield (0.93 t/ha), where this unit is dominated by steeper terrain as compared to other landscape units. These findings dictate the importance of considering topographic variations within fields for optimizing *Teff* management. In the same manner, the yield of *Teff* varied based on the types of SWCPs. Soil bunds offered the highest average yield (2.07 t/ha), followed by stone bunds (1.33 t/ha). Untreated fields recorded the lowest average yield (0.58 t/ha) (Fig. 4). This highlights the significant potential of SWC practices, particularly soil bunds, in enhancing *Teff* productivity.

3.3.2. *Interaction effects of location, landscape position, and SWCP*

A significant ($p < 0.001$) three-way interaction effect of location, landscape position, and SWCP on Teff yield was observed (Table 4). This finding suggests that the impact of SWC practices on *Teff* yield depends on both the spatial location and the specific landscape unit within a particular watershed.

Soil bunds enhance *Teff* yield across landscapes. The highest mean *Teff* yields were obtained in the lower landscapes treated with soil bunds at Debre Mawi (2.98 t/ha) and Debre Yakob (2.78 t/ha) (Table 6). These yields were statistically superior to all other treatment combinations but statistically similar to each other. This finding highlights the potential of soil bunds for enhancing *Teff* yield regardless of the specific landscape position within these watersheds. For Aba Gerima watershed, the highest Teff yield (1.22 t/ha) was obtained at the lower landscape with a stone bund.

Further analysis of Table 6 reveals variations in *Teff* yield across different landscapes and SWC practices. The second-highest yield (2.46 t/ha) was recorded in the upper landscape of the Debre Mawi watershed with soil bunds. This was followed by the middle landscape at Debre Mawi with stone bunds (1.93 t/ha). These results suggest that soil bunds outperform stone bunds, but the specific yield benefit may vary depending on the landscape units.

Untreated plots exhibited the lowest yields. Consistently across all landscapes within each watershed, the lowest *Teff* yields were observed in untreated plots (Table 6). For example, in Debre Mawi, untreated plots in the middle and upper slopes yielded only 0.43 t/ha and 0.59 t/ha, respectively. Similarly, low yields were observed in untreated plots at Aba Gerima and Debre Yakob. This emphasizes the importance of implementing SWC practices for improving *Teff* yield.

Table 4

The significance level of environmental factors and their interaction.

Factors	*Teff*		Wheat	
	Df	P value	Df	P value
Location	2	***	2	***
Landscape	2	***	2	***
SWCP	2	***	2	***
Location* Landscape	2	***	4	***
Location*SWCP	3	***	4	0.03
Landscape* SWCP	3	***	3	***
Location*Landscape*SWCP	2	***	3	0.96
Untreated visa-a-visa Treated	1	***	1	***

Df = degree of freedom, *** indicates $p < 0.001$.

Table 5
Summary of the effect of soil and water conservation on *Teff* and wheat yield.

Crop type	Mean grain yield (t/ha)		Grand mean
	Untreated	Treated	
Teff	0.58^{a}	1.67^{b}	1.14
Wheat	0.94^{a}	2.64^{b}	1.79

Means represented by the same letter across a row are significantly different ($p < 0.05$).

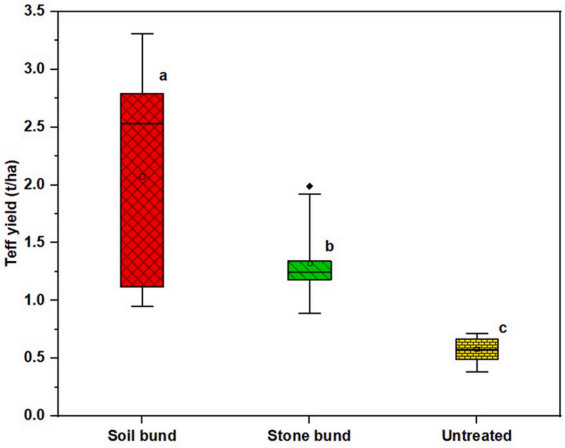

Fig. 4. Teff (Eragrostis teff) grain yield for non-conserved, soil bund, and stone bund treated farm plots (means represented by the same letter are not significant at $p < 0.05$).

Table 6
Mean separation on the interaction effects of location, landscape unit, and types of conservation practices on *Teff* yield.

Location	Landscape unit	Grain yield under different SWCPs (t/ha)			Mean	Overall mean
		Untreated	Soil bund	Stone bund		
Aba Gerima	Upper	0.56^{ab}	0.98^{de}	–	0.77	0.85
	Middle	0.47^{ab}	–	0.91^{cd}	0.69	
	Lower	0.66^{ab}	1.17^{ef}	1.22^{f}	1.02	
	Mean	**0.56**	**1.08**	**1.06**		
Debre Mawi	Upper	0.59^{ab}	2.46^{h}	1.26^{f}	1.43	1.46
	Middle	0.43^{a}	–	1.93^{g}	1.18	
	Lower	0.69^{bc}	2.98^{i}	1.31^{f}	1.66	
	Mean	**0.57**	**2.72**	**1.50**		
Debre Yakob	Upper	–	–	–	–	1.73
	Middle	–	–	–	–	
	Lower	0.67^{ab}	2.78^{i}	–	1.73	
	Overall mean	**0.58**	**2.07**	**1.33**		
Combined over location	Upper	0.57	1.72	1.26	1.17^{b}	
	Middle	0.45	–	1.42	0.93^{a}	
	Lower	0.67	2.31	1.26	1.44^{c}	

3.4. *Effects on wheat yield*

3.4.1. *Main effects of location, landscape, and SWCP*

The effect of location, landscape, and SWCP on wheat yield was significant ($p < 0.01$) (Table 4). Significant differences in wheat yield were observed among the three locations ($p < 0.01$) (Table 4). Aba Gerima recorded the highest average yield (1.93 t/ha), followed by Debre Mawi (1.95 t/ha) (Table 7). Notably, there was no statistically significant difference between these two watersheds. Conversely, Debre Yakob exhibited the lowest yield (1.83 t/ha) and a statistically significant difference compared to the other two locations. This spatial variation suggests potential differences in environmental factors impacting wheat production across these regions.

Landscape units within a location also significantly influenced wheat yield ($p < 0.01$) (Table 4). The lower slope recorded the highest average wheat yield (2.32 t/ha), followed by the upper slope (1.86 t/ha). The middle slope exhibited the lowest yield (1.43 t/

Table 7
Mean wheat yield comparison affected by the main and interaction effects of location, landscape unit, and types of SWCPs, Means in the same column (color) represented by the same letter are not statistically significant.

		Grain yield under different SWCPs (t/ha)				Overall
Location	**Landscape unit**	**Untreated**	**Soil bund**	**Stone bund**	**Mean**	**mean**
Aba Gerima	Upper	0.95	2.46	-	1.70^{a}	1.93^{b}
	Middle	0.65	-	1.93	1.29^{a}	
	Lower	1.28	2.98	3.24	2.50^{b}	
	Mean	**0.96^{a}**	**2.72^{b}**	**2.59^{b}**		
Debre Mawi	Upper	0.90	2.49	2.28	1.89^{a}	1.95^{b}
	Middle	0.73	-	2.13	1.43^{a}	
	Lower	1.04	2.93	3.14	2.37^{b}	
	Mean	**0.89^{a}**	**2.71^{b}**	**2.52^{b}**		
Debre Yakob	Upper	1.09	2.83	-	1.96^{a}	1.83^{a}
	Middle	0.80	-	2.32	1.56^{a}	
	Lower	0.99	2.98	-	1.99^{a}	
	Mean	**0.96^{a}**	**2.90^{b}**	**2.32^{b}**		
	Overall mean	**0.94^{a}**	**2.78^{c}**	**2.51^{b}**		
Combined over location	Upper	0.98^{b}	2.59^{d}	2.28^{c}	1.86^{b}	
	Middle	0.73^{a}	-	2.13^{c}	1.42^{a}	
	Lower	1.10^{b}	2.96^{e}	3.19^{e}	2.32^{c}	

ha). These findings highlight the importance of considering topographic variations within fields for optimizing wheat management practices. Tailoring strategies based on the specific landscape position within a field can potentially improve overall wheat production.

The type of SWC practice significantly affected mean wheat grain yield ($p < 0.01$). Soil bunds offered the highest average yield (2.78 t/ha), followed by stone bunds (2.51 t/ha) (Fig. 5). Untreated fields recorded the lowest average yield (0.94 t/ha). This demonstrates the substantial yield improvement potential of SWC practices, particularly soil bunds, compared to untreated fields. Implementing these conservation strategies can significantly enhance wheat production.

The substantial yield increase observed with soil bunds compared to untreated fields highlights their effectiveness as a conservation strategy. Additionally, the spatial and topographic variations in yield emphasize the need for location-specific and landscape-sensitive wheat management practices for optimal production.

3.4.2. Effects of location and landscape unit

This study investigated the interactive effects of spatial location, landscape position, and soil and water conservation practices (SWC) on wheat yield in a sub-humid ecosystem. A three-way ANOVA (details in Table 4) revealed a statistically non-significant three-way interaction ($p = 0.96$). However, significant two-way interactions were identified, suggesting that the impact of one factor on yield depends on the levels of another factor.

The interaction between location and landscape unit significantly affected mean wheat yield ($p < 0.01$). The lower landscape position within the Aba Gerima watershed exhibited the highest yield (2.50 t/ha), followed by the lower landscape position of the

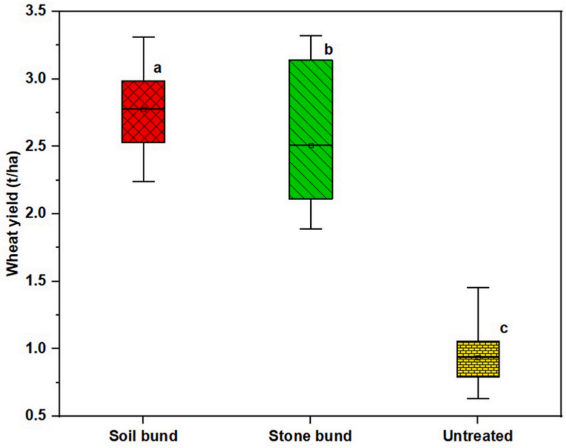

Fig. 5. Wheat grain yield for non-conserved, soil bund, and stone bund treated farm plots (means represented by the same letter are not significant at $p < 0.05$).

Debre Mawi watershed (2.37 t/ha) (Table 7). These findings indicate that spatial variations, potentially due to environmental factors, can influence wheat yield. Notably, despite slight differences in yield, these results were statistically similar. Other treatment combinations fall within a lower and statistically similar range based on mean separation. The lowest yield (1.29 t/ha) was observed in the middle landscape position of the Aba Gerima watershed. This highlights the importance of considering both spatial location and landscape position when managing wheat production.

3.4.3. *Effects of landscape unit and types of SWCPs*

The interaction between landscape unit and type of SWC practice also had a significant effect on wheat yield ($p < 0.01$). Stone bunds (3.19 t/ha) and soil bunds (2.96 t/ha) applied at the lower landscape position produced superior wheat yields compared to other combinations, although statistically similar to each other. Conversely, untreated fields on the middle landscape position exhibited the lowest and statistically different mean yield (0.73 t/ha) from all other treatments. This finding emphasizes the potential of soil bunds and stone bunds for enhancing wheat yield, particularly in lower landscapes within these watersheds. While SWC practices benefit yield, the specific benefit may vary depending on the landscape.

3.4.4. *Effects of location and types of SWCPs*

The interaction effect of spatial location and types of SWCPs on mean wheat yield were significant ($P = 0.03$). Further analysis of Table 7 revealed that untreated plots consistently exhibited the lowest yields across all three locations (Debre Mawi: 0.89 t/ha, Aba Gerima: 0.96 t/ha, Debre Yakob: 0.96 t/ha), with statistically similar results. Conversely, conserved fields at each location produced significantly higher mean wheat yields compared to untreated fields within the respective watersheds. Recorded yield values for conserved fields ranged from 2.32 t/ha (soil bund at Debre Yakob) to 2.90 t/ha (soil bund at Debre Yakob). This finding underscores the critical role of SWC practices in improving wheat yield within sub-humid ecosystems and provides valuable insights for optimizing SWC strategies to maximize wheat yield in different geographical locations and landscape settings.

3.5. *Interbund yield variability*

Soil and water conservation practices (SWCPs) significantly influenced Teff and wheat yields across different landscape positions

Table 8
Interbund Teff and wheat mean yield variability, standard deviation and coefficient of variation in the upper, middle, and lower landscape positions.

Landscape position	Interbund mean grain yield (t/ha) and standard deviation			Overall Mean (t/ha) and CV (%)
	Base	Middle	Upper	
Teff				
Upper	1.88 ± 0.78	1.17 ± 0.49	1.64 ± 0.68	1.57 ± 0.29 (19 %)
Middle	1.53 ± 0.56	1.21 ± 0.44	1.52 ± 0.55	1.31 ± 0.15 (12 %)
Lower	2.03 ± 0.88	1.48 ± 0.64	2.18 ± 0.94	1.89 ± 0.30 (16 %)
Wheat				
Upper	2.96 ± 0.27	1.88 ± 0.17	2.69 ± 0.25	2.51 ± 0.46 (18 %)
Middle	2.30 ± 0.18	1.79 ± 0.14	2.30 ± 0.18	2.13 ± 0.24 (11 %)
Lower	3.21 ± 0.18	2.44 ± 0.13	3.51 ± 0.19	3.05 ± 0.45 (15 %)

CV = coefficient of variations.

relative to the conservation structures (bunds). Within the upper landscape position (closest to the ridge), the highest mean yields were recorded at the base (downstream end) of the bund (Teff: 1.88 t/ha, wheat: 2.96 t/ha), followed by the upper section (upstream end). Conversely, the lowest yield for both crops occurred in the middle section between successive bunds.

The middle landscape position exhibited similar yields at the base and upper sections of the bunds. However, the middle section consistently produced the lowest yield compared to the other two. This pattern contrasted with the lower landscape position (closest to the valley bottom), where the highest mean yields for both Teff (2.18 t/ha) and wheat (3.51 t/ha) were observed in the lower section (upstream end) of the bunds. Notably, plots located between successive bunds in all landscape positions consistently produced lower yields compared to the base and upper sections (detailed data in Table 8).

These spatial yield variations can be attributed to the alternative effects of SWCPs on soil moisture and erosion/deposition processes within the space between bunds.

3.6. Financial return on SWC investments

This section discusses the financial analysis of SWC investment under farmer-funded and cost-sharing scenarios.

3.6.1. Scenario one: farmers incurred costs of investment in SWCP

This study investigated the financial implications of implementing Soil and Water Conservation Practices (SWCPs) on *Teff* and wheat production in the Ethiopian highlands. Table 9 presents the cost and benefit analysis of SWC investment by farmers.

The cost-benefit analysis results revealed that stone bunds had a 20 % ROI, while soil bunds offered a 50 % ROI for *Teff*. However, ROI decreased for both SWCPs when applied to wheat. Untreated and fields treated with stone bunds had negative NPV, potentially due to lower net present benefits from untreated plots and high investment costs for constructing stone bunds. Conversely, both soil bunds and stone bunds on *Teff* and soil bunds on wheat exhibited positive NPV, indicating their economic viability with different magnitudes.

Furthermore, the analysis explored the interaction between SWCP type and landscape position. Statistically significant differences ($p < 0.01$) were observed between the financial performance of different SWCP types and their interaction with landscape units. As indicated in Supplementary Table S1, soil bunds constructed at lower landscapes demonstrated superior financial performance for *Teff* cultivation, with the highest IRR (63 %) and B-C ratio (1.66). For wheat, stone bunds at lower landscape yielded the highest IRR (27 %) and B-C ratio (1.21), followed by soil bunds at lower landscape position (IRR: 22 % and B-C ratio: 1.1).

This study demonstrates that implementing SWCPs, particularly soil bunds, and stone bunds at lower landscape positions, leads to significant financial benefits for *Teff* and wheat productivity in the Ethiopian highlands under the situation that farmers incur all costs of SWC construction. The selection of SWCP type and its placement within the landscape play a crucial role in maximizing economic returns. These findings can inform both farmers and policymakers in optimizing SWCP implementation strategies for enhanced agricultural productivity and economic sustainability.

3.6.2. Scenario two: SWC investments with 10 % farmers' contribution

In the Ethiopian highlands, soil and water conservation practices (SWCPs) are constructed through community mobilization and food for work (FFW) and cash-for-work approaches. Often, the initial investment burden is shared by projects, 10 % community contribution is commonly expected. To assess the financial implications under this scenario, an alternative analysis was conducted assuming a 10 % contribution from the farmers towards the initial SWCP investment costs (Table 10).

This approach significantly improves the return on investment (ROI) for both SWCP types. Soil bunds exhibited the highest ROI for *Teff* at 127 % (per hectare), followed by stone bunds at 80 % (Table 10). As compared to *Teff*, ROI decreased for both SWCPs when applied to wheat. Untreated fields continued to show negative net present value (NPV), likely due to lower yields compared to fields with SWCPs. However, both soil bunds and stone bunds on *Teff* and wheat maintained positive NPVs, with varying magnitudes, indicating their economic viability under this investment assumption.

Statistically significant differences ($p < 0.01$) were observed between the financial performance of different SWCP types and their interaction with landscape units. As presented in Supplementary Table S1, Soil bunds constructed on lower landscape demonstrated superior financial performance for *Teff* cultivation, with the highest recorded NPV (6509.95 US dollars), internal rate of return (IRR) of

Table 9

Summary results of cost-benefit analysis of soil and water conservation measures when constructed by the community (100 % farmer-owned investment).

Cost-benefit variables	*Teff*			Wheat		
	Untreated	Soil bund	Stone bund	Untreated	Soil bund	Stone bund
Present value benefit	6696.10	13,318.50	9845.40	5892.45	10,171.00	9488.35
Present value cost	7235.95	8819.15	8852.20	8043.40	9626.65	9659.65
NPV	(539.85)	4499.35	993.20	(2150.95)	544.35	(171.30)
IRR	–	50 %	20 %	–	16 %	9 %
B-C ratio	0.93	1.51	1.11	0.73	1.06	0.98

The discount rate is 11.5 %, NPV is the net present value, IRR is the internal rate of return, B-C ratio is the discounted cost-benefit ratio, and the lifetime of conservation measures is 10 years, with costs and benefits being in US dollars.

Table 10
Summary results of cost-benefit analysis of soil and water conservation measures when constructed by 10 % community contributions.

Cost-benefit variables	*Teff*			Wheat		
	Untreated	Soil bund	Stone bund	Untreated	Soil bund	Stone bund
Present value Benefit	6696.10	13,318.50	9845.40	5892.45	10,171.00	9488.35
Present value cost	7235.95	8158.75	7751.50	8043.40	8966.25	8516.45
NPV	(539.85)	5159.75	2093.90	(2150.95)	1204.75	971.90
IRR	–	127 %	80 %	–	27 %	23 %
B-C ratio	0.93	1.63	1.27	0.73	1.13	1.10

The discount rate is 11.5 %, NPV is the net present value, IRR is the internal rate of return, B-C ratio is the discounted benefit-cost ratio, and the lifetime of conservation measures is 10 years, with costs and benefits being in US dollars.

171 %, and benefit-cost ratio (B-C) of 1.80. For wheat, stone bunds at lower landscape positions yielded the highest NPV (3161.20 US dollars), IRR (55 %), and B-C ratio (1.37).

4. Discussions

4.1. Effects of SWC on yield

Our findings reveal a significant three-way interaction effect of location, landscape position and type of SWCP on crop yield, aligning with previous research by Adgo, Teshome [14] and Tesfaye, Brouwer [22] who observed similar variations in crop response to SWC practices.

Conserved plots had significantly higher yields as compared to non-conserved plots for both teff and wheat crops. This means soil and water conservation need to be sought of any cropping system regardless of the types of conservation structures. So, SWCPs are essential for sustainable agriculture at any occasion, as they offer numerous benefits, including improved soil quality, increased water infiltration and storage, and enhanced crop yields. Adopting these practices is crucial for ensuring continuous and productive farming activities. This finding is in agreement with the investigations made by Kumawat, Yadav [28].

Soil bunds consistently resulted in the highest *Teff* and wheat yields across diverse locations and landscapes. This supports the effectiveness of these structures in preventing soil erosion and enhancing soil fertility, as documented by Bayle and Muluye [29] and Hishe, Lyimo [30]. The results of this study showed soil bunds outperformed stone bunds, although stone bunds offer advantages in durability (long-term sustainability) and lower maintenance costs compared to soil bunds. This aligns with the observations of Ebabu, Tsunekawa [31], Gelaw, Tsunekawa [32], and Moges and Taye [33] who highlighted the influence of types of SWCPs on the effectiveness of SWC interventions.

Our study revealed a significant influence of landscape position on crop yield. Lower landscapes with SWC practices consistently produced higher *Teff* and wheat yields compared to middle or upper landscape positions. This finding aligns with previous research by Tebeje, Abebe [13], Bojago, Delango [34], and Guadie, Molla [35], who reported the dominant effect of landscape units on soil formation, fertility, and its subsequent crop yield in Ethiopia. These studies suggest that SWCPs, particularly in lower landscapes, promote the accumulation of nutrients and moisture in the soil, leading to enhanced crop productivity.

The observed spatial variation in the effectiveness of SWC practices highlights the need for location-specific recommendations. This aligns with the findings of Amsalu and Mengaw [8] who reported variations in the impact of soil bunds on runoff, soil and nutrient losses, and crop yield improvement across different regions within the Ethiopian central highlands.

This study demonstrates a significant interaction effect between SWC type, landscape position, and spatial location on Teff and a significant interaction effect between spatial location and SWCP; SWCP and landscape; and spatial location with landscape on wheat yields in Ethiopia. These interactions highlight the importance of tailoring SWC practices to specific landscapes and locations for optimal crop production. Consistent with this finding, Bitew, Mekonnen [19] and Mekonnen, Fisseh [36] reported similar observations regarding the influence of landscape and locations on the effectiveness of SWC interventions in Ethiopian contexts. Soil bunds in lower landscapes and soil and stone bunds in lower landscapes resulted the highest grain yield for teff and wheat crops respectively, emphasizing the crucial role of landscape-specific SWC strategies. This finding aligns with the documented benefits of soil bunds in controlling soil erosion and potentially enhancing soil fertility, as reported by Addis, Abera [37] and Demissie, Meshesha [38]. The observed accumulation of nutrients and moisture in lower landscape positions facilitated by SWC practices likely contributes to these yield improvements.

4.2. Interbund yield variability

Soil and water conservation structures (SWCS) can significantly influence the distribution of soil moisture content and nutrients within a field. This generally increases overall soil moisture content and nutrients compared to non-conserved fields. However, the distribution within the field might not be uniform [39]. This study revealed significant yield variations across different landscape positions within bunded areas. The highest mean yields for both *Teff* and wheat were observed at the base (downstream end) and upper section (upstream end) of the bunds, aligning with established knowledge on the influence of SWCPs on soil moisture and erosion/deposition processes [40]. Bunds effectively reduce surface runoff, leading to increased water infiltration and soil moisture content at the base and upper sections. Conversely, the middle sections between bunds experience less water infiltration and potentially higher erosion rates, resulting in the lowest crop yields. This implies more bunds required between the present bund or careful bund spacing would be considered to ensure sustainable and productive land management in Ethiopia. Demissie, Meshesha [41] and Alemu and Kidane [42] reported poor performance of soil and water conservation structures in runoff and ersoion control and crop yield improvement in ethiopian highlands.

The contrasting pattern observed in the lower landscape position, where the highest yields were recorded in the lower (upstream) section of the bunds, suggests additional factors at play. This could be attributed to the combined effect of reduced erosion and potentially higher deposition of fertile topsoil from upslope areas, creating a more favorable soil environment for crop growth. Additionally, piezometric measurements at one site [43] indicated a near-surface groundwater table near the upstream section of the bunds, potentially further contributing to favorable moisture conditions in this area. Understanding these spatial variations is crucial for optimizing the placement and design of SWCP interventions to maximize agricultural productivity within the context of mountainous landscapes.

4.3. Return on investment (ROI)

The economic analysis demonstrated the financial viability of SWC practices, particularly soil bunds implemented on lower landscapes for *Teff* and wheat production. This supports the economic benefits reported in previous studies [15,44]. Furthermore, the study underlines the potential cost-sharing mechanisms (Scenario 2) to enhance the economic attractiveness of SWC practices for farmers by lowering individual financial burdens [22]. This analysis highlights the economic benefits of SWCPs for *Teff* and wheat production in the Ethiopian highlands, particularly when considering a subsidy approach to construction. This approach reduces the individual farmer's financial burden, significantly improving the economic viability of SWCP implementation. These findings can inform farmers and policymakers in optimizing SWCP implementation strategies, considering both community- and subsidy-based construction approaches, to enhance agricultural productivity and economic sustainability. This approach aligns with the principles of sustainable livelihood promotion, as discussed by Jacobs, Santos-Martín [45] and Scoones, Stirling [46] who emphasize the importance of collective action and social capital in supporting resource-poor farmers. Tesfaye, Brouwer [22] highlight potential benefits such as reduced soil runoff, associated sedimentation, and flood risks. Beyond crop yield and income improvements, SWC practices offer broader socio-economic benefits and hold promise for promoting sustainable livelihoods [47,48].

4.4. Relevance and implications for intensification, food security, livelihood improvement, and sustainable development

The interaction of SWC and landscape positions revealed the need for landscape-segmented land management and intensification strategies and practices guided by a cost-benefit analysis of investments. The relative lower yield benefits/responses on the upper landscape should be optimized using sustainable intensification practices and technologies, where integrated land management and cropping systems can be applied. The positive yield and economic impacts of SWC practices demonstrated in this study have significant implications for food security, livelihood improvement, and sustainable development in Ethiopia. Improved crop yields contribute directly to enhanced food availability and dietary diversification, addressing a critical challenge for food security in the region, as highlighted by Unicef [49] and Tas and El [50]. Additionally, the increased profitability associated with SWC practices translates to higher incomes for farmers, enabling them to invest in better nutrition, healthcare, and education, all crucial aspects of livelihood improvement as highlighted by Poverty [51]. Furthermore, by promoting soil and water conservation, these practices contribute to sustainable land management practices. This not only ensures long-term agricultural productivity but also asserts the optimization of resource use efficiencies such as soil, water, nutrients, and carbon across landscape positions and protects vital ecosystem services essential for maintaining a healthy environment [52]. This aligns with the goals of sustainable development, as outlined in the United Nations Sustainable Development Goals (SDGs) [53]. Specifically, SWC practices can contribute to achieving SDG 2 (Zero Hunger), SDG 1 (No Poverty), SDG 13 (Climate Action), and SDG 15 (Life on Land). In brief, this study provides compelling evidence for the effectiveness of SWC practices in enhancing crop yields, and economic returns, and promoting food security, livelihood improvement, and sustainable development in Ethiopia.

5. Conclusions

This study investigated the effects of soil and water conservation (SWC) practices on crop yields and their economic viability for *Teff* and wheat production in Ethiopia. Our findings demonstrate significant positive impacts of SWC practices on both agronomic and economic outcomes, with implications for food security, livelihood improvement, and sustainable development. However, the current study is limited to two major crops (*Teff* and wheat). To gain a more comprehensive understanding of SWCP effectiveness, our findings highlight the need for further research on wider applicability across diverse agroecological zones, and considering a wider range of crop types and soil conditions. Further research on the quantification of broader socioeconomic consequences of SWCP should also be considered in the future.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

CRediT authorship contribution statement

Aschalew K. Tebeje: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gizaw Desta:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Misbah A. Hussein:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tewodros T. Assefa:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation, Conceptualization. **Yonas L. Tsegaw:** Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Fasikaw A. Zimale:** Writing – review & editing, Supervision. **Mohammed A. Ahmed:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Aschalew Kassie Tebeje reports a relationship with Lihiket Design and Supervision Corporation that includes: employment. Aschalew K. Tebeje, and Yonas L. Tsegaw, were employed by Lihiket Design and Supervision Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e37786.

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