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Adoption of water and soil conservation technologies in Rwenzori region, Western Uganda

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Abstract

Despite investments to combat land degradation in the Rwenzori region of Western Uganda, the adoption of water and soil conservation technologies remains low. This study analyzes the socio-economic, institutional, and geographic factors driving smallholder adoption. Cross sectional data were collected from 385 households in the mountainous Karangura Sub-County, Kabarole district. Descriptive statistics reveal that 23.4%, 16.9%, and 8.1% of the household heads adopted contour bunds, conservation tillage, and a joint integration of both technologies, respectively. A multinomial logit regression model was used to evaluate adoption drivers, anchoring plot-level variables to the primary production parcel to control for land fragmentation. Empirical results indicate that education, farming experience, household income, steep slope gradients, erosion history, social participation, sex, and access to extension significantly increase uptake. Conversely, access to off-farm income significantly reduces the adoption of individual structural practices, highlighting a critical trade-off driven by household labor constraints. To improve uptake, policymakers should strengthen farmer-extension linkages, expand rural credit, and pair income diversification programs with labor saving agronomic tools to support vulnerable hillside farming systems.

Key words: Adoption, farmer groups, marginal effects, multinomial logistic, water and soil conservation

Introduction

Degradation of land is a serious problem across Sub-Saharan Africa, with approximately 67% of the total land affected to varying degrees, from mild to extremely severe degradation (Sileshi *et al*., 2019). Soil loss from agricultural land leads to decreased crop production and lowers surface water quality. Soil erosion has led to an annual loss of 4-12% of Uganda's Gross National Product (Olson *et al*., 2019) and it remains one of the leading environmental challenges limiting agricultural productivity, largely driven by unsustainable practices such as excessive extraction, overuse, and poor management of soil and water resources. Soil erosion not only threatens agricultural productivity but affects biodiversity, water quality and livelihoods of poor farmers, 30% of whom depend on the natural environment for food and survival (Fedele *et al*., 2021).

Uganda's low agricultural productivity remains a significant challenge. A combination of increasing human population, land degradation and realities of climate change brings challenges to farmers by constraining yields. Degradation of land and water resources negatively impacts agricultural output and is a major contributor to both food insecurity and poverty. One effective strategy for combating this challenge and enhancing crop yields is the adoption of improved water and soil conservation technologies (WSCT). These technologies involve the sustainable management of land, implementation of erosion and water control strategies, and use of suitable cropping systems to maintain soil health and curb degradation. Smallholder farmers in Uganda traditionally manage soil degradation using an array of water and soil conservation technologies, notably agroforestry, intercropping, contour bunds, cover cropping, grass strips, and mulching (Nkonya, 2002)

Although water and soil conservation technologies have been emphasized in Uganda's highland areas, it is evident that the slopes still lose tremendous fertile top soil, and the threat of soil loss is increasing (Briggs and Twomlow, 2002). To overcome this problem, the government of Uganda through the Research and Innovation Fund

(RIF), Makerere University, National Environment Management Authority (NEMA) and the Kabarole District Local Government set up demonstrations, study workshops and radio talk shows, among other strategies, to create awareness of these WSCTs. Also, in collaboration with the World Bank, the Global Environment Facility (GEF) and the National Agricultural Research organization (NARO), the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) has undertaken initiatives to promote awareness of improved WSCTs. These include practices such as contour bunds, grass bunds, agroforestry, conservation tillage, mulching, terracing and the establishment of woodlots.

However, despite these collective efforts by the Ugandan government, international donors, researchers and development agencies, land degradation continues to pose a major challenge and the uptake of WSC technologies remains relatively low in the region. Such constrained adoption of conservation technologies is not unique to the Rwenzori area, but is prevalent throughout Sub-Saharan Africa (Barungi *et al*., 2013; Abdul-Hanan *et al*., 2014; Alemayehu *et al*., 2020; Belachew *et al*., 2020). Therefore, it is essential to identify the major barriers that hinder farmers from adopting improved water and soil conservation technologies, as these practices have the potential to enhance agricultural production and productivity. Lack of such understanding will cause failure of other conservation projects. The primary aim of this research was to assess the drivers of adoption of soil water and conservation technologies in Rwenzori Highlands, located in western Uganda. Specifically, the study sought to (i) identify and describe the cause and effects of soil erosion, and (ii) analyze the socio-economic, institutional and geographic determinants that influence the adoption of water and soil conservation practices particularly contour bunds and conservation tillage.

Methodology

Study area

The study was conducted in Kabarole district, western Uganda, which encompasses a total land area of 1,814 km², with over 70% allocated to smallholder cultivation. Agriculture serves as the primary economic anchor for the district's population of 230,368 residents (UBOS, 2024). The region is characterized by a dominant banana-coffee farming system underlain by highly fertile, volcanic black loam soils (90%), which historically incentivized intensive hillside cultivation. While other highland regions in Uganda (such as the Kigezi highlands in the southwest and Mount Elgon in the east) face severe degradation, Kabarole district within the Rwenzori block-mountain system represents a critical agro-ecological zone where extreme population pressure intersects with highly fragile slopes, making it a national priority for soil conservation research (NEMA, 2019).

Within the district, Karangura Sub-County was purposively selected because it represents the absolute typographic extreme of the area, featuring the highest mean altitude and steepest terrain profiles in Kabarole (KDLG, 2021). Unlike the flatter plateau zones of the district, approximately 90% of Karangura's landscape is characterized by rugged, steep hillsides and sheer ridges with slopes ranging from 15% to over 60%. This extreme topography, paired with high intensity rainfall, renders the local topsoil vulnerable to severe sheet and rill erosion.

At the micro-level, Kaisamba and Bukukuru villages were purposively selected because their primary production activities are structurally concentrated on active farming slopes that consistently meet or exceed a critical 30% gradient boundary (NEMA, 2019). Cultivating fields at or above this 30% threshold within the area's intensive perennial banana-coffee systems fundamentally destabilizes the soil matrix, positioning these specific communities at the highest risk of catastrophic topsoil loss and structural farm abandonment during peak rainy seasons.

Sampling strategy and data collection

The data utilized in this paper was obtained through a household survey carried out in September 2022 within the study area. A multi-stage sampling approach was used to select the participating households. In the first stage, Karangura Sub-County in Kabarole district was purposively selected due to the fact that it is the most mountainous Sub-County in the district and is therefore highly prone to soil erosion (KDLG, 2021). In the second stage, two villages Kaisamba and Bukukuru were purposively selected based on their location on active farming slopes exceeding a 30% gradient boundary (NEMA, 2019).

In the third stage, to establish strict statistical randomness and eliminate selection bias, complete and updated household registers were obtained from the respective Local Council I (LCI) administrative chairpersons for both villages, serving as the comprehensive sampling frame. From these registers, a total of 385 households were selected using a simple random sampling technique generated via a computer-based random number allocator. This administrative framework ensured that every smallholder household residing along the hillside topographies of the two villages maintained an equal, non-zero probability of selection. The aggregate sample size was determined using the Cochran (1977) formula as below:

$$n = \frac{(\text{Z-score})^2 \text{x SD x } (1 - \text{SD})}{(\text{margin of error})^2}$$

Taking a confidence level of 95% which corresponds to a Z-score of 1.96, standard deviation of 0.5 and +/- 5% margin of error,

$$n = \frac{(1.96)^2 \text{ x } 0.5 \text{ x } (1 - 0.5)}{(0.05)^2}$$

$$n = \frac{3.8416 \text{ x } 0.25}{0.0025} \qquad n = 385 \text{ farmers}$$

The selected households were interviewed using a semi-structured questionnaire which was designed and pre-tested before the actual survey. The questionnaire explored various aspects aimed at assessing farmer's awareness of soil erosion, and water and soil conservation technologies (WSCTs). It also examined the demographic, socio-economic, geographic and institutional factors that influence the adoption of the WSCTs within the study area.

Although the Southwestern highlands of Uganda feature a diverse array of WSCTs available for potential farmer adoption, evaluating each independently presents significant empirical and practical limitations. Consequently, for the scope of this study, these numerous practices were synthesized and categorized into two primary strategic interventions: conservation tillage and contour bunds. This was directly informed by a prior participatory SWOT-AHP (Strengths, Weaknesses, Opportunities, and Threats - Analytic Hierarchy Process) analysis, which systematically evaluated the regional alternatives against local socioeconomic and biophysical constraints. The SWOT-AHP framework conclusively identified these two specific WSCTs as the "best bet" options, offering the highest institutional viability, structural feasibility, and strategic advantage for sustainable adoption among smallholder farmers in the region.

To account for land fragmentation, all plot-level variables including distance, slope, soil fertility, and erosion history were calibrated exclusively with reference to the household's primary production plot. This primary plot was operationally defined as the parcel contributing the maximum share to household food security or cash-crop income. This single-plot anchoring protocol ensures that household socio-economic traits are paired with the exact physical landscape where core capital and labor resources are concentrated, preventing cross-contamination of plot attributes within the Multinomial logistic (MNL) model.

Data analysis

To assess farmers' awareness of the causes and effects of loss of soil cover, as well as their adoption of WSC technologies, descriptive statistics were employed. In addition, a multinomial logistic regression model was applied to examine how socio-economic, institutional and farm specific geographical factors influence the adoption of WSC technologies i.e. soil conserving tillage practices, contour bunds, and a mix of both. This approach was appropriate since the dependent variables were categorical in nature, unordered, non- overlapping, and limited to a single choice per farmer from a range of independent options (Arumugam *et al*., 2022).

The dependent variable captured adoption categories: Y=0: Non-adoption of both technologies, Y=1: Adoption of contour bunds only (BUNDS), Y=2: Adoption of conservation tillage only (CONTIL), Y=3: Adoption of both technologies (BUNDS+CONTIL). The non-adoption option (Y=0) was used as the reference (base) category and its coefficients were normalized to zero for model identification. Based on random utility maximization, farmers choose the alternative yielding the highest expected utility. The utility derived by farmer L from choosing adoption option J was specified as:

$$U_{LJ} = X_{L,}\beta_J + \varepsilon_{LJ} \quad \text{.........} \quad (2)$$

Where: U_{LJ} is the utility associated with choice J by farmer L, X_L, is a vector of explanatory variables representing socio-economic, institutional and geographical characteristics of farmer L,β_J is a vector of parameters to be estimated for choice J, ε_{LJ} is a stochastic error term capturing unobserved factors.

A household head was assumed to select adoption option J if the utility derived from that option exceeded the utility from all other alternatives. The probability of household head L selecting choice J is:

$$P(Y_L = J|X_L) = \frac{\exp(X_L\beta_J)}{\sum_{k=o}^{J}\exp(X_L\beta_k)}, \; J = 0,1,2,3 \quad \text{.........} \quad (3)$$

Where: $P(Y_L = JlX_L)$ represents adoption of best bet WSC, where J represents the total number of adoption alternatives, β_J parameters measure the influence of the explanatory variables on the likelihood of choosing option J relative to the reference category, X_L are socioeconomic, institutional and geographic explanatory variables which include X_1 = sex, X_2= Marital status, X_3=Age, X_4= Farming experience, X_5= Level of education, X_6= House hold income, X_7= House hold size, X_8= Land size, X_9= Off farm income, X_{10}= Topography, X_{11}= Soil fertility, X_{12}= Soil erosion occurrence, X_{13}= Distance to farmland,, X_{14}= Group membership, X_{15}= Type of land ownership, X_{16}=Access to extension services, X_{17}=Access to credit, ε is the disturbance term representing other factors assumed to be independent of and the household.

The MNL relies on the independence of irrelevant alternatives assumption, where odds of choosing one adoption option over another are independent of the presence or characteristics of other alternatives, a premise supported by earlier water and soil conservation research in Sub-Saharan Africa (Kumar *et al.,* 2021).

Marginal effects of adoption decisions

To facilitate a robust interpretation of the Multinomial Logit results, marginal effects were computed following model estimation. Marginal effects quantify the exact change in the predicted probability of choosing a specific technology alternative resulting from a discrete or continuous shift in an explanatory covariate, keeping all other variables constant (Greene, 2018; Long, 2018). In non-linear probability frameworks, raw regression coefficients do not equal direct changes in absolute probabilities (Mize, 2019). Therefore, for continuous explanatory variables, marginal effects measure the instantaneous rate of change in the predicted probability of adoption associated with a localized one-unit increase in that covariate (Breen *et al.*, 2018). For binary indicator variables, marginal effects reflect the discrete probability shift as the independent variable transitions from 0 to 1: $X_k = Pr(Y = 1|X, X_k = 1) – Pr(Y=1|X, X_k = 0)$ (Williams, 2021).

Consequently, these calculated parameters provide an explicit estimate of the absolute change in the likelihood of selecting a specific soil and water conservation option given a unit change in an independent covariate $X_{k,}$ evaluated at the sample mean (Degfe *et al*., 2023; Williams, 2021). The specific explanatory variables embedded in this structural framework were selected based on well-established theoretical explanations of smallholder agricultural technology adoption alongside contextual knowledge of the Rwenzori region's unique hillside constraints (Alemayehu *et al.,* 2020; Asfaw and Neka, 2023).

Among the socio-demographic characteristics, the model includes the sex, marital status, linear age, farming experience, and formal educational attainment of the household head (Belachew *et al.,* 2020; Zeweld *et al*., 2020). Financial capacity and resource endowment variables comprise the household's monthly income, aggregate family size, and total landholding area (Manda *et al.,* 2021; Mgomezulu *et al.,* 2023). To measure the absolute physical necessity and spatial constraints of implementing specific conservation practices, farm-specific geographical factors are incorporated; these include the primary parcel's land slope gradient, a baseline perception of soil fertility, the documented incidence of visible soil erosion, and the physical distance to the farmland (Degfe *et al.,* 2023; Djillo *et al.,* 2024). Finally, the model accounts for institutional factors, capturing baseline awareness, ease of obtaining general agricultural information, formal land tenure/ownership systems, active social group participation, and targeted access to formal extension and credit services (Kazemba, 2021; Simelton and Ostwald, 2021).

Results

Descriptive statistics for the 385 surveyed smallholders (Table 1) reveal a young and active workforce with a mean age of 37 years and a mean household size of 5 individuals. These households face tight physical resource constraints, operating on a mean farm size of 2.50 acres. Despite this intense land fragmentation, 92.47% of respondents classify their plots as highly fertile. General agricultural information is easily accessible to 96.10% of the sample, driving a universal baseline awareness of the necessity for WSCTs.

Smallholder awareness of the specific physical and management-driven factors causing landscape degradation is detailed but asymmetric (Table 2). Excessive rains register the highest recognition rate at 73.25% of the sample, followed by deforestation at 68.05% and the cultivation of steep slopes at 64.68%. Management-driven triggers are also widely acknowledged, including leaving soil profiles bare and exposed at 62.60% and seasonal bush burning at 61.04%. However, a distinct analytical drop occurs regarding long-term, structural causes, with only 53.25% recognizing a lack of technical conservation training and 50.39% identifying continuous over-cultivation as primary erosion drivers.

Regarding the effects of land degradation, physical manifestations are highly visible to the community, led by field gully development at 73.51% and the depletion of fertile topsoil layers at 70.91%. These physical damages translate into direct economic shocks, with 73.25% of respondents linking erosion to the direct loss of crop and livestock productivity. Ultimately, these shocks trigger macro-level vulnerabilities, with 69.35% associating erosion with household food insecurity and famine, 68.57% noting the down-slope silting of communal water sources, and 68.31% connecting it to poor crop yields (Table 2).

Smallholders exhibit high familiarity with technical mitigation options (Table 2). Traditional, low-input agronomic practices are the most widely recognized, with mulching leading at 98.18%, followed by intercropping at 89.61% and agroforestry setups at 89.09%. Structural and low-disturbance engineering measures also show strong baseline recognition, with runoff-diversion trenches at 88.83%, conservation tillage at 84.94%, contour bunds at 84.68%, and physical terracing systems at 81.82%. However, a severe mismatch exists between technology knowledge and active field uptake (Table 3). Despite high awareness of WSCTs, only 48.31% have

Table 1. Characteristics of Households (hh) used in the Multinomial Logistic model (N= 385)

Variable	Measurement/Unit	Mean	Std. Dev.
Continuous Variables			
Age of the hh head	Years	37	13.212
Household income	Uganda Shillings/Month	182674	143232.36
Household size	Number of individuals	5	2.858
Land area	Total acres owned	2.5	1.318
Categorical Variables			
Variable	Measurement/Unit	Frequencies	Percent
Sex of the hh head	1=Male	234	60.78
Marital status of the head	1=Married	186	48.31
	0=Unmarried	199	51.69
Farming experience	1=<5 years	97	25.19
	2=5-10 years	119	30.91
	3=>10 years	169	43.9
Educational attainment of the hh head	0=None	30	7.79
	1=Primary	226	58.7
	2=Secondary	113	29.35
	3=Certificate	16	4.16
Off-farm income	1=Yes	211	54.81
	0=No	174	45.19
Land slope	1=Flat land	37	9.61
	2=Gentle slope	172	44.68
	3=Steep slope	176	45.71
Fertility of soil	1=Fertile	356	92.47
	0=Infertile	29	7.53
Soil erosion incidence	1=No	15	3.9
	2=Minimal	170	44.16
	3=Extreme	200	51.95
Distance to farmland	1=<2km	362	94.03
	2=2-5km	14	3.64
	3=>5km	9	2.34
Ease of obtaining information	1=Yes	370	96.1
	0=Otherwise	15	3.9
Awareness of WSC measures	1=Yes	385	100
	0=Otherwise	0	0
Group membership	1=Yes	322	83.64
	0=Otherwise	63	16.36
Type of land ownership	0=Communal	22	5.71
	1=Individual	363	94.29
Access to extension services	1=Yes	195	50.65
	0=Otherwise	190	49.35
Access to credit	1=Yes	114	29.61
	0=Otherwise	271	70.39

Table 2. Awareness (%) of soil erosion causes, effects, and mitigation technologies

Causes	Aware (%)
Excessive rains	73.25
Bare soil	62.60
Steep slope	64.68
Deforestation	68.05
Bush burning	61.04
Lack of knowledge	53.25
Over cultivation	50.39
Effects	
Loss of fertile soils	70.91
Silting	68.57
Loss of crops and livestock	73.25
Famine	69.35
Poor yields	68.31
Development of gullies	73.51
Technologies	
Contour bunds (BUNDS)	84.68
Conservation tillage (CONTIL)	84.94
Trenches	88.83
Mulching	98.18
Agroforestry	89.09
Intercropping	89.61
Terraces	81.82
BUNDS+CONTIL	100

actively adopted the target practices contour bunds, conservation tillage, or both leaving a non-adoption baseline of 51.69%.

The sex of the household head significantly influences adoption choices (Table 4), as being male increases the probability of adopting standalone contour bunds by 4.5% and standalone conservation tillage by 7.8% ($p<0.01$), but reduces the probability of simultaneous joint adoption by 1.6% ($p<0.05$). Marital status significantly boosts adoption across all pathways, increasing the probability of choosing standalone contour bunds by 1.2%, standalone conservation tillage by 7.6%, and the combined package by 1.1% ($p<0.01$).

Table 3. Adoption of WSC technologies

WSC Technology	Frequency	Percent (%)
Non-adopters	199	51.69
Adoption of contour embankments	90	23.38
Adoption of conservation tillage	65	16.88
Adoption of both technologies	31	8.05
Total	385	100.00

Table 4. Multinomial Logistic regression results of determinants of adoption of water and soil conservation measures (N=385)

Variables	Contour bunds	Conservation tillage	Both measures
Socio-economic			
Sex (1=Male, 0=Female)	0.045***	0.078***	-0.016**
Marital status (0=Unmarried, 1=Married)	0.012***	0.076***	0.011***
Age (Years)	-0.009	0.007**	0.000**
Age squared	0.000	-0.000***	-0.000
Farming experience (1=<5, 2= 5-10, 3=>10)	0.050***	-0.011*	0.003*
Level of education (0=None, 1=Primary, 2=Secondary, 3=Certificate)	-0.025***	0.051***	0.036***
Log income	0.008***	0.151**	0.020***
HH size	-0.004	-0.005	0.006
Land size (Acres)	-0.028	0.031	-0.003
Off farm income (1=Yes, 0=No)	-0.017*	-0.020*	-0.008
Biophysical factors			
Slope (0=Flat land, 1=Gentle slope, 2=Steep slope)	-0.022**	-0.061***	0.008
Soil fertility (1=Fertile, 0=Infertile)	0.066*	-0.022	0.017
Soil erosion occurrence (1=Yes, 0=No)	0.108***	0.004***	0.003***
Distance to farmland (1=<2km, 2=2-5km, 3=>5km)	0.002	-0.035	0.024
Institutional factors			
Group membership (1=Yes, 0=No)	-0.031	-0.014*	-0.002
Type of land ownership (0=Communal, 1=Individual)	0.179	-0.103	-0.026
Access to extension services (1=Yes, 0=No)	0.051***	0.055***	-0.001**
Access to credit (1=Yes, 0=No)	0.016	-0.002	0.018
Pseudo R-squared	0.6382		
Chi-square	485.65		
Prob>Chi2	0.0000		

*** p<0.01, ** p<0.05, * p<0.1

Age and farming experience display distinct, non-linear parameters within the model. Chronological age displays an inverted-U relationship with conservation tillage, where the linear age term is positive at 0.7% ($p<0.05$), while the quadratic term is negative and significant ($p<0.01$). The linear effect of age also increases joint measures by a minor fraction ($p < 0.05$). Farming experience significantly increases the adoption of standalone contour bunds by 5.0% and the combined package by 0.3% ($p<0.01$), but marginally reduces standalone conservation tillage uptake by (-1.1%, $p<0.1$). Formal education reduces the probability of adopting standalone contour bunds by 2.5% ($p<0.01$), but significantly increases the uptake of standalone conservation tillage by 5.1% and the integrated joint package by 3.6%.

Financial endowments and household labor allocations generate powerful, conflicting structural shifts. A one-unit increase in log household income significantly increases adoption across all paths, boosting standalone contour bunds by 0.8%, conservation tillage by 15.1%, and joint measures by 2.0% ($p<0.01$). Conversely, access to off-farm income streams significantly reduces the individual adoption probabilities of standalone contour bunds by 1.7% and standalone conservation tillage by 2.0% ($p<0.1$). Household size and total land size are statistically non-significant determinants within the model.

Steeper slope gradients significantly restrict individual configurations, reducing the adoption probability of standalone contour bunds by 2.2% ($p<0.05$) and standalone conservation tillage by 6.1% ($p<0.01$). Conversely, households operating on inherently fertile baseline soils are 6.6% more likely to construct standalone contour bunds ($p<0.1$). The active occurrence of soil erosion serves as an overwhelmingly powerful, positive driver across all options ($p<0.01$), increasing standalone contour bund adoption by 10.8%, conservation tillage by 0.4%, and combined measures by 0.3%. Institutionally, group membership shows a marginal negative relationship with standalone conservation tillage, reducing its probability by 1.4% ($p<0.1$). Formal agricultural extension access acts as a powerful catalyst, increasing the adoption probability of standalone contour bunds by 5.1% and standalone conservation tillage by 5.5% ($p<0.01$). However, it significantly reduces joint technology adoption by 0.1% ($p<0.05$) and (Table 4).

Discussion

The demographic profile of a young highly active farming workforce paired with a relatively large mean family size creates a dual-edged economic scenario for the household. On one hand, large families provide a pool of manual labor essential for implementing labor-intensive soil interventions. On the other hand, it places immediate food security pressures on a highly constrained average land holding of just 2.50

acres. This extreme land fragmentation forces intensive over-cultivation and continuous nutrient mining, which threatens long term soil health despite any baseline perceptions of high soil fertility (Miheretu and Yimer, 2017).

Concurrently, institutional exposure within the study area is exceptionally high, with almost the entire sample of the surveyed smallholders reporting that they can easily obtain general agricultural information. Furthermore, there is a universal baseline awareness of the necessity for water and soil conservation measures across the sample. This widespread exposure to information underpins the smallholder farmers' detailed awareness of the immediate physical drivers and symptoms of land degradation within their landscapes. However, it also underscores that the key bottleneck in this production system is not a lack of general information access, but rather the severe structural and resource constraints imposed by land scarcity and high household dependency ratios (Manda *et al.*, 2021).

The descriptive results reveal a clear asymmetry in the types of agricultural information smallholders possess. There was exceptionally high awareness of visible biophysical triggers led by excessive rain followed by the cultivation of steep slopes and anthropogenic accelerators (deforestation, bare soil, seasonal bush burning). However, there is a visible drop in awareness regarding long-term structural issues, such as a general lack of technical conservation knowledge and continuous over-cultivation. This imbalance aligns with broader empirical evidence across Sub-Saharan Africa showing that while farmers easily diagnose acute, visible environmental damage, they often lack information regarding the invisible, creeping process of nutrient mining and structural soil decline (Alemayehu *et al.*, 2020). Consequently, public advisory messaging remains unsystematically skewed toward visible crisis-response triggers rather than successfully building cognitive technical capacity for systemic land management (Simelton and Ostwald, 2021). Smallholder farmers demonstrate a high awareness of effects of unchecked topsoil loss, focusing on visible physical changes and direct threats to their livelihoods. The physical manifestations of erosion are highly visible to the community (development of deep field gullies and direct loss of fertile topsoil layers), to severe household economic shocks (crop and livestock productivity, chronic yield deficits, and food insecurity). This shows that farmers view soil erosion as a direct shock to household survival. This seamless cognitive mapping from physical landscape damage to household food crises aligns with regional empirical evidence demonstrating that for resource-poor smallholders, soil erosion functions as a primary driver of structural poverty and immediate welfare shocks (Tsegaye *et al.*, 2021).

Traditional agronomic practices are the most widely recognized, led by mulching, intercropping and agroforestry. These practices are popular and well-known because they fit smoothly into existing banana-coffee farming systems without requiring extra capital or specialized tools. Similarly, high levels of awareness baselines are recorded for structural setups and low disturbance agronomic methods (runoff-diversion trenches, conservation tillage, contour bunds and terracing).

It is important to note the sharp mismatch between technology awareness and actual field uptake. While 100% of the smallholder farmers are aware of WSC technologies, only 48.31% have actively adopted contour bunds or conservation tillage, either singly or in combination. While awareness is a vital precursor to technology use (Kazemba, 2021), this divergence shows that high knowledge exposure does not automatically drive behavioral change. This mismatch extends beyond a simple technical "knowing-doing gap" (Pfeffer and Sutton, 2000). Framed within expected utility theory, non-adoption is a rational response to binding household labor constraints and competing economic opportunities (Edeh *et al*., 2023; Mulokozi *et al*., 2024).

Constructing and maintaining physical earthworks on steep mountain faces requires massive manual labor investments (Sserunkuuma *et al*., 2021). Because more than half of the surveyed households earn off-farm income, available family labor is split between field maintenance and external employment. When off-farm work offers higher, immediate financial returns than the delayed benefits of soil conservation, the opportunity cost of farm labor becomes unsustainably high (Kassie *et al*., 2020; Lwasa *et al*., 2022). Consequently, smallholders reject these labor-intensive practices not due to a lack of technical capacity, but because limited household labor yields higher utility through off-farm diversification.

Driving factors for adoption of water and soil conservation technologies

Socio-Economic Factors

Sex of the household head significantly influences adoption pathway choices. Being a male head of household increases the probability of adopting standalone contour bunds and conservation tillage. In Sub-Saharan smallholder systems, male heads traditionally command greater control over institutional resources, secure land tenure, and family labor allocation, thereby lowering the physical entry barriers for individual technologies (Belachew *et al*., 2020; Belayneh, 2023). Conversely, male-headed households see a decrease in the probability of adopting both measures simultaneously. This indicates that female-headed households, when they do adopt, are more inclined to pursue intensive, fully integrated risk-diversification strategies as they cannot afford the risk of piecemeal intervention failure so as to maximize structural and agronomic resilience, leveraging their close management of specific plots (Alemayehu *et al*., 2020a; Fisher and Carr, 2025). This clear divergence highlights that gender does not merely influence whether a farmer adopts, but structurally alters the strategic configuration of their land conservation choices.

Marital status exerts a consistently positive and highly significant influence across all three adoption pathways. This uniform statistical significance across both individual and bundled choices implies that marriage is not merely a descriptive demographic state, but a structural conduit for resource mobilization and unified strategic choice. From an intra-household decision-making perspective, marriage serves as a framework for cooperative bargaining and joint utility maximization. Rather than reflecting isolated preferences, the choice to invest in sustainable technologies under a marital structure represents a coordinated household strategy that mitigates individual risk aversion. Marriage typically expands household social capital, clusters extended family networks, and mitigates the severe bottlenecks that typically cripple resource-poor smallholders. By establishing a shared domestic economic unit, married households can pool kinship labor to execute physically demanding earthworks like contour bunds while simultaneously managing the precise seasonal timelines required for minimum-tillage regimes. Furthermore, marital bonds often reinforce secure, stable, long-term residential investment in farm plots, which naturally incentivizes long-term soil investments (Teshome *et al*., 2016).

The model confirms a non-linear, quadratic relationship between age and conservation tillage adoption, as indicated by a highly microscopic yet statistically significant negative coefficient for age squared. This confirms an inverted-U relationship where adoption increases with age up to a threshold, after which physical labor constraints and shorter planning horizons cause the probability of adoption to decline (Zeweld *et al*., 2020). Conversely, the linear effect of age significantly increases the probability of adopting conservation tillage and joint measures by a minor fraction. This reflects an accumulation of experiential human capital, as older farmers possess deeper historical wisdom regarding localized weather volatility and degradation patterns, driving them toward conservation tillage and multi-layered strategies to protect base yields (Zeweld *et al*., 2020). However, the eventual downturn proves that even the highest levels of historical wisdom eventually succumb to the binding physical labor requirements of these technologies, emphasizing that technical knowledge must be backed by institutional labor-saving innovations as a farming population ages.

Each additional year of farming experience significantly increases the probability of adopting standalone contour bunds and joint measures. Decades spent working localized plots give smallholders a precise historical memory of rainfall impacts and runoff directions, enabling effective risk assessment. This drives them to implement heavy physical structures like contour bunds to arrest visible topsoil loss. Conversely, experience has a marginal negative impact on standalone conservation tillage, suggesting that long-time traditional farmers can exhibit an operational attachment to conventional, deep-plowing methods, making them resistant to minimum-tillage modifications. Crucially, however, because experience positively influences the joint pathway, it indicates that this traditional inertia can be systematically overcome if conservation tillage is not preached in isolation, but packaged inside a wider setup (Alemu *et al*., 2022; Mujuyi and Mugisha, 2022).

Formal education acts as a transformative socio-economic driver, significantly scaling up the probability of adopting conservation tillage and the integrated framework. This aligns with findings that education enhances farmers' capacity to understand technical information, assess long-term benefits, and implement complex techniques (Miheretu and Yimer, 2017; Belachew *et al*., 2020). Conversely, education reduces standalone contour bund adoption. This indicates that educated household heads intentionally look past isolated, traditional structural earthworks which are notoriously labor-intensive and yield lower immediate agronomic returns viewing them as economically inefficient in isolation. Instead they favor integrated combinations and knowledge-intensive practices that offer superior joint returns in both soil stabilization and moisture retention, highlighting how education actively alters the strategic sophistication of household land management choices (Abid *et al*., 2020).

Financial capacity yields powerful, positive, and highly significant influences across the board, increasing the probability of adopting standalone contour bunds, conservation tillage and joint technologies. This strongly confirms that transitioning to soil conservation regimes is a capital-intensive venture requiring cash reserves to absorb upfront costs, procure specialized tools, or hire external casual labor (Teshome *et al*., 2016; Manda *et al*., 2021). In contrast, access to off-farm income streams significantly reduces the probability of adopting standalone contour bunds and conservation tillage. This represents a clear labor constraint where off-farm work competes directly with the heavy on-farm labor required for physical implementation (Fontes, 2019). This direct competition for labor hours effectively prevents smallholders from executing labor-intensive standalone conservation measures, unless those measures can be mechanically automated or subsidized to reduce the operational burden on the family unit.

Biophysical factors

Topographic constraints significantly restrict standalone configurations, decreasing the probability of adopting conservation tillage and contour bunds on steeper gradients. On highly rugged terrains, single conservation measures are frequently rendered economically unviable due to extreme manual labor requirements. Furthermore contour bunds bear an immense physical burden on steep inclines, making them highly susceptible to being physically washed away by torrential rains unless supported by integrated setups (Asfaw and Neka, 2023; Dash *et al*., 2023). Consequently, extreme terrain imposes a physical threshold where piecemeal configurations fail, structurally forcing smallholders to either abandon conservation entirely or transition toward comprehensive, joint technology packages to withstand local environmental pressures. Farms characterized by inherently fertile soil baselines exhibit a higher probability of adopting contour bunds. This reveals an asset-protection management pattern where smallholders intentionally prioritize heavy physical investments on their most productive plots. Rather than using contour bunds as a remedy for completely exhausted land, farmers deploy them as a preventative mechanism to protect and lock in highly valuable baseline nutrients that yield immediate, high returns, rather than sinking scarce capital and manual labor into reclaiming marginalized soils (Dejene and Belay, 2022). Deploying earthworks in this preventive manner allows smallholders to insulate their primary income generating plots against irreversible topsoil erosion and subsequent yield collapse, demonstrating that baseline environmental quality actively guides the efficiency and location of household land investments.

This crisis-driven response is further proved by soil erosion occurrence, which acts as a powerful biophysical trigger across all adoption paths. The substantial spike in contour bund construction isolates a highly reactive, shock-driven management pattern within the farming community. Rather than practicing preventative land management, resource-constrained farmers respond directly to visible environmental shocks such as rills and gullies that pose an immediate, existential threat to household food security (Dagne *et al*., 2023; Djillo *et al*., 2024). Smallholders only alter their baseline practices when driven by a visible landscape crisis, highlighting that physical land degradation functions as the primary mechanism overriding household inertia and forcing adoption out of absolute necessity.

Institutional factors

Active involvement in local community groups shows a marginal negative relationship with standalone conservation tillage. This negative coefficient explicitly challenges standard assumptions regarding the universally positive role of social networks in technology diffusion. This counter-intuitive finding suggests that general social networks within this specific region may lack targeted information sharing regarding conservation tillage benefits, or that group dynamics prioritize alternative communal marketing and credit activities over specific agronomic adjustments (Bonabana *et al*., 2016). Consequently, participation in these groups diverts a smallholder's attention and limited farm investments toward market-oriented activities rather than specific agronomic or conservation adjustments. This highlights that unless social capital networks are explicitly structured around dedicated agricultural extensions, general group dynamics can inadvertently act as a barrier to the adoption of knowledge-intensive conservation practices.

Conversely, agricultural extension service delivery emerged as a powerful institutional catalyst, increasing the probability of adopting standalone contour bunds and conservation tillage. This highlights the critical role of extension services in disseminating technical knowledge and enhancing farmers' confidence in implementing new techniques (Belachew *et al*., 2020; Belayneh, 2023). However, the negative marginal effect on the joint adoption category highlights an institutional fragmentation in advisory packages. Public advisory messaging remains heavily structured around isolated technical modules rather than promoting holistic, integrated conservation systems (Simelton and Ostwald, 2021).

Conclusion

Implementation of physical water and soil conservation (WSC) technologies is essential for rehabilitating degraded lands and mitigating severe soil loss in mountainous smallholder ecosystems. This study demonstrates that the adoption of contour bunds, conservation tillage, or their joint integration is driven by a complex interplay of socio-economic, biophysical, and institutional factors. Specifically, empirical evidence indicates that the gender, marital status, linear age, and accumulated farming experience of the household head, alongside household income, land slope gradient, historical soil erosion occurrence, social group participation, and access to extension and credit services, significantly shape technology adoption pathways.

Recommendations

Public authorities and agricultural policymakers must prioritize strengthening the linkage between smallholder farmers and extension systems. Because exposure to technical advisory services significantly increases the probability of adopting water and soil conservation practices, interventions should focus on increasing agent-to-farmer contact, establishing localized demonstration plots, and providing practical, hands-on training directly on smallholders' primary production parcels to maximize technology adoption.

Providing farmers with access to credit services reduces the financial burden of implementing water and soil conservation measures. As such, this study recommends improving credit access by extending the reach of credit-granting facilities within the area in order to address barriers that prevent farmers from obtaining the necessary resources to construct contour embankments and practice conservation tillage.

Creation of social groups and encouraging farmers to join these groups will improve adoption. In group settings, farmers can obtain training on how to implement various water and soil conservation techniques and also easily receive social support.

Moreover, through these social groupings, farmers can learn the value of investing in multiple methods, particularly if one method is ineffective on their farms.

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