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Using local knowledge and scientific assessment for inclusive land restoration in Halaba, Central Ethiopia

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Abstract
This study used Halaba, Ethiopia, as a case study and employed a mixed approach to examine societal challenges and evaluate the benefits of adopting sustainable land management (SLM) practices. Qualitative data analysis applied the drivers-pressures-state-impact-responses framework to capture farmers' perspectives on land degradation and restoration, while quantitative analysis assessed land use and land cover and land degradation neutrality trends, as well as the resulting changes in ecosystem service values (ESVs). The results revealed significant variations in resource access and land use needs among the different groups, shaped by gender, wealth, and seasonal patterns, highlighting the need for gender-sensitive and inclusive interventions. Insights from scientific knowledge indicate substantial landscape transformation between 1994 and 2024. From 1994 to 2014, natural ecosystems declined markedly, including forestlands (− 9.9%), shrublands (− 9.5%), and grasslands (− 6.5%), alongside an expansion of degraded areas from 27 to 40%. However, the period from 2014 to 2024 shows signs of recovery in both natural ecosystems and degraded lands. Insights from local and scientific knowledge highlight significant environmental, economic, and social benefits of adopted SLM interventions. Specifically, the scientific knowledge indicated that the post-2014 period showed recovery reflected in rising ESVs from natural ecosystems, ranging from 20 to 30%, translated to increases in ESVs by 0.9 to 16.9 million US$. Ensuring community engagement and social inclusivity, and bundling conservation measures when planning future SLM practices are crucial. Prioritizing affordable and user-friendly technologies; maintaining consistent follow-up; and scaling successful practices with long-term investment will enhance ecological restoration and livelihood resilience.

Keywords Community-driven interventions, DPSIR framework, Land degradation, Land resources, Ecosystem services, Gender and social inclusion

1 Introduction

The world's population is projected to cross 9.7 billion by the year 2050 [90], requiring a 60% increase in agricultural production compared to 2005–2007 levels [92]. Achieving this goal is increasingly constrained by widespread land degradation driven by social, economic, and environmental factors, which undermine agricultural productivity and ecosystem services [19, 22, 48, 88]. Approximately one-quarter of the Earth's land surface is already degraded, with diverse impacts on food, water, and climate regulation services [32]. In addition, evidence from global and regional studies shows that land use and land cover (LULC) changes substantially affect ecosystem services, biodiversity, and food and water security, particularly for poor rural communities [1, 26, 43, 54, 61, 96]. Globally, LULC changes caused annual ecosystem service value losses of 4.3–20.2 trillion USD between 1997 and 2011 [26], with significant declines also reported at national and landscape scales, including Nepal, Germany, and China (Li et al., 2010; [56]; Sharma 2019; [87]).

Like other parts of the world, Sub-Saharan African (SSA) countries are severely affected by land degradation induced by LULC changes [22], resulting in reduced economic growth [67]. Fenta et al. [34] indicate that land degradation hotspots covered about 5% of SSA, resulting in a total ESV loss of about US\$56 billion year^{-1}, of which nearly 65% is due to the degradation of forests and croplands.

Ethiopia, the case study country, is a SSA country affected by land degradation and climate change ([37];; [12]). This has resulted in the degradation of diverse ecosystems, including forests, agricultural lands, grazing lands, and water, alongside reduced ecosystem services ([12]. In line with this, a study in Ethiopia [18] estimated a loss of 85 billion USD of ESVs due to land degradation caused by LULC changes. Other case studies in Ethiopia (e.g.[44], [63] reported considerable losses of ESVs due to LULC changes. For example, [63] reported a total loss of ESVs of 1.6 to 24 million USD over 41 years in two highly eroded watersheds in the Lake Abaya Chamo Sub-basin, Ethiopia.

Studies (e.g., [63, 66, 70]) consistently show that timely action to prevent, mitigate, and reverse land degradation can enhance food and water security, significantly contributing to climate change adaptation and mitigation, while helping to prevent conflict and migration. Recognizing this, multiple global and regional efforts, including the global initiative of the UN Decade on Ecosystem Restoration [3], the United Nations Convention to Combat Desertification (UNCCD), and UNCCD's Land Degradation Neutrality Initiative [23], the AFR100 initiative [71], alongside various national and local projects focused on sustainable land management and restoration techniques [57].

Specifically, the Ethiopian government, in collaboration with local communities and international donors, has been implementing diverse sustainable land management (SLM) practices to address the challenges of land degradation and climate change. The efforts are designed to achieve multiple goals, including increasing agricultural productivity, restoring degraded ecosystems, and improving rural livelihoods [6]. The SLM practices included physical and biological landscape management measures, such as terraces, bunds, trenches, check-dams, afforestation and reforestation practices, participatory forest and rangeland management, as well as the establishment of exclosures [62]. The meaningful participation of local communities and the consideration of local knowledge during the entire project phases by the Ethiopian government through community-based watershed development activities enabled the sustainability of SLM practices and the restoration of degraded agricultural landscapes [38, 74].

In line with this, [74] demonstrated that considering local knowledge during the entire project phases helps sustain SLM interventions through tailoring measures to the local context. Adade et al. [4] and [81] also argue that local knowledge plays a critical role in sustainable land management because it captures context-specific understanding of landscapes, livelihoods, and resource use that is often overlooked by purely technical assessments. In this study, local knowledge is understood in a broad sense, encompassing insights held by long-term residents, non-indigenous groups, and migrant communities who interact with and manage the land. Using a mixed approach (i.e., integrating local knowledge with scientific knowledge) in assessment studies, the case in this study is essential for accurately identifying both the benefits and disbenefits of land management interventions, as it enables capturing the lived experiences of trade-offs, risks, and unintended consequences of interventions [14]. It also enhances the relevance, feasibility, and social acceptance of interventions, ultimately leading to more effective, equitable, and sustainable outcomes [76].

SLM practices in Ethiopia have generated documented environmental benefits, including erosion control, vegetation restoration, increase in biodiversity [63, 86], alongside economic gains such as improved agricultural productivity and crop diversification [7, 61], and social benefits including enhanced social interaction and access to drinking water [94]. However, most studies exhibit critical gaps, notably the lack of comprehensive assessments capturing environmental, economic, and social benefits and disbenefits simultaneously [80]; and limited incorporation of farmers' perspectives and local knowledge [11, 86]. Consequently, existing research often overlooks the full spectrum of SLM impacts and the integration of local and scientific knowledge.

We argue that fragmented studies focusing on single aspects risk overlooking the inter- and trans-disciplinary nature of landscape management, thereby limiting their usefulness for improving the planning and implementation of SLM practices. Recent studies emphasize the need to combine local knowledge with scientific evidence when assessing the benefits and disbenefits of SLM practices. Such integration enables a more comprehensive understanding of the biophysical and socio-economic context, helps identify synergies and trade-offs that may otherwise be missed [73], and supports the design of context-specific and socially acceptable interventions [61].

Against this background, this study aims to answer four broad research questions: (i) What societal challenges do local communities face due to land degradation, and how do these affect their livelihoods?; (ii) what are the main drivers and impacts of land degradation, and how do these affect land use systems?; (iii) How does the integration of local knowledge and scientific insights improve the understanding of benefits and disbenefits associated with SLM practices? and (iv) what benefits do local farmers perceive from SLM practices and how do these align with scientific assessments of their effectiveness? Therefore, we used the Halaba zone in Ethiopia as a case study, combining local and scientific knowledge to (i) investigate societal challenges; (ii) assess the drivers, pressures, state, impact, and responses to land degradation; and (iii) evaluate the benefits and disbenefits of adopted SLM practices.

Unlike previous SLM studies in Ethiopia that assess isolated environmental, economic, or social outcomes, this study offers an integrated, trans-disciplinary assessment that simultaneously captures benefits and disbenefits of SLM practices by systematically combining farmers' local knowledge with scientific evidence, thereby revealing context-specific synergies, trade-offs, and planning insights that fragmented approaches overlook. In this study, communities were engaged through key informant interviews, focus group discussions and participatory transect walks. The findings from these community engagement research activities are referred to as local knowledge. Findings from GIS and remote sensing technologies, as well as ecosystem service valuation, are referred to as *scientific knowledge*. Such a deliberate integration of local and scientific knowledge was employed to generate a holistic evidence base that informs policy and decision-makers and to support more effective and context-appropriate implementation of SLM practices. This, in turn, supports sustaining the benefits of SLM practices, enhancing the resilience of farming communities while promoting environmental sustainability in the long run.

2 Materials and methods

2.1 Study area

This study was conducted in the Halaba zone, the Central Ethiopia regional state, which is situated in the Bilate catchment, Abaya Chamo sub-basin of the Ethiopian Rift Valley Lakes Basin (RVLB) (Fig. 1). The topography is characterized by hilly terrain in the central and western parts that gradually descends to an undulating plain in the northeast (Fig. 1). The area receives an average annual rainfall between 544 and 1271 mm. The mean monthly temperature varies between 12.8 °C and 26.8 °C, while the agroecology is mainly classified as Weyina Dega [40].

The population in the study area is mainly rural (~ 88%), and the local economy mainly relies on subsistence mixed crop-livestock farming; irrigation is practiced in certain areas along the Bilate River [2]. The study area faces significant environmental and socio-economic challenges, such as severe soil erosion, flooding, declining soil fertility, and food and water insecurity [61, 98]. These challenges are attributed to diverse environmental, social, and economic factors. Specifically, deforestation in upstream areas and the high erodibility of soils aggravated land resource degradation [2, 63]. Additionally, the transition from livestock-based to crop-based agriculture [63], coupled with limited community awareness of low-cost land management practices, aggravated the degradation of land resources and their impact on people's livelihoods [61].

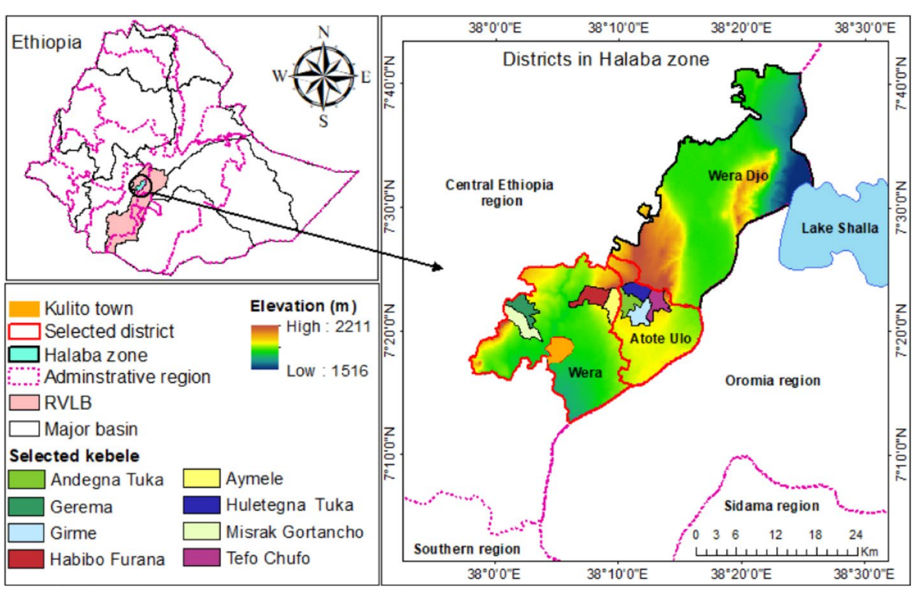

Fig. 1 Location map of the Halaba zone and the study Kebeles. Kebele is the lowest administrative district within Ethiopia. RVLB refers to the Rift Valley Lakes Basin. Source: Author's creation using ArcGIS 10.8.

2.2 Study site selection

We used a multi-stage approach to select specific study Kebeles within the Halaba zone. The multi-stage approach comprised three key stages, namely district selection, initial kebele screening, and final kebele prioritization (Table 1). Activities, criteria used, and the final output of each stage are summarized in Table 1. Nevertheless, to assess LULC changes and investigate land degradation neutrality (LDN) trends, we used the entire zone as a study site. The inclusion of agricultural office preferences as one criterion in the multi-stage site selection aimed to align the study with local landscape management and development priorities, without overriding biophysical or methodological selection criteria.

2.3 Data collection

2.3.1 Data collection framework

The study employed diverse methods to gather qualitative and quantitative data. The methods include reconnaissance surveys, key informant interviews (KIIs), focus group discussions (FGDs), GIS and remote sensing techniques, as well as ecosystem service valuation (Fig. 2). Reconnaissance surveys were undertaken primarily to prepare for subsequent KIIs and FGDs and support site characterization and ground-truthing (Fig. 2). Then, we conducted 22 key informant interviews (KIIs) and 10 focus group discussions (FGDs). These qualitative methods were used to collect data on access to resources, societal challenges, local communities' perception of land degradation and restoration efforts, as well as long-term LULC changes and LDN trends (Fig. 2, Supplementary Material 1). We complemented local community knowledge by assessing the long-term (1994–2024) LULC changes and LDN trends using GIS and remote sensing, as well as conducting ecosystem service valuation using the global ecosystem service valuation database (Fig. 2).

Local knowledge and scientific data were collected concurrently using two complementary methods. Integration was undertaken during the analytical phase through systematic comparison of findings from both data sources to identify convergences and divergences across specific contexts. This integrative analysis enabled a more comprehensive assessment of the challenges, responses, and associated benefits and disbenefits of SLM practices, thereby enhancing analytical robustness while maintaining contextual relevance.

2.3.2 Selection of participants for the qualitative study

In collaboration with various levels of agricultural offices, we selected 22 key informants from eight study Kebeles. These informants include experts from the zonal agricultural

Table 1 A multi-stage approach for selecting study kebeles

Stage and focus	Key activities	Criteria used	Output
Stage 1 – district selection	Desk review and consultation with the zonal agricultural office	Accessibility, landscape diversity, and preference of the agricultural office	Two out of three districts selected
Stage 2 – initial kebele screening	Selection of candidate Kebeles	Interest of district agricultural offices	16 kebeles (8 per district) selected
Stage 3 – Kebele prioritization	Stakeholder consultation, field observations	Institutional support, degradation status, restoration potential, and accessibility.	8 kebeles (4 per district) selected.

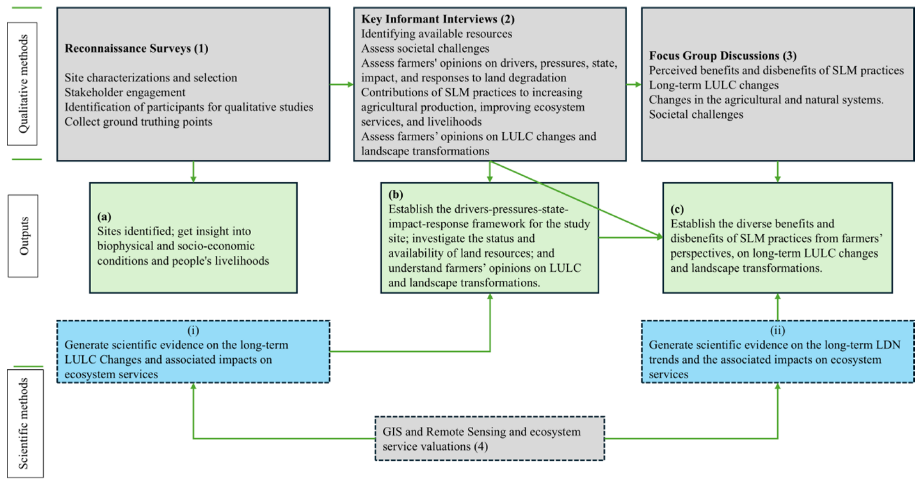

Fig. 2 Data collection framework used in the study. The numbers 1, 2, 3, and 4 indicate the procedures or steps used to collect data. Letters a, b, and c indicate the outputs obtained from local knowledge sources. The Roman numbers refer to the outputs generated through scientific knowledge. Different colors are used to identify the data collection methods (the gray-colored boxes), and outputs (green for outputs obtained from local knowledge, and blue from scientific knowledge)

office (2), woreda agricultural offices (2), and kebele agricultural offices (8). Additionally, local community representatives such as elders, model farmers, and members of administrative bodies (3), members of community-based organizations like community watershed teams and cooperatives (3), and representatives from non-governmental organizations (4) were included. The selection criteria for key informants focused on their knowledge of the area, involvement in landscape restoration activities, farming experience, and the number of years they had lived in the study Kebeles. To ensure a broader community perspective and complement the information gathered from key informants, we also conducted 10 focus group discussions (FGDs) with each focus group consisting of 8 to 12 individuals. Participant selection was carried out in close collaboration with local administrative bodies and agricultural offices, who supported the identification of individuals with diverse socio-economic backgrounds, livelihood strategies, and geographic locations within each Kebele.

Eight of the FGDs involved local community members from the selected Kebeles, one included experts from the district and zonal levels agricultural offices, and one brought together development agents working in the eight Kebeles. For community-based FGDs, explicit attention was given to balanced representation: each group included an equal number of men, women, and youth, as well as participants from both upstream and downstream communities. To reduce the risk of underrepresentation of marginalized groups, local administrators and development agents were requested to nominate participants from different wealth categories and social groups, including households with limited land or resources. While the purposive selection approach may not fully eliminate all forms of exclusion, these measures helped safeguard inclusive participation and minimize gender- and wealth-based bias in the discussions.

We acknowledge guidance to separate participant groups when topics are sensitive or power dynamics may suppress voices [28, 83]. However, in our study, the key discussion point, the benefits and trade-offs of SLM practices, was non-sensitive and centered on collective action. We therefore used mixed FGDs (men, women, youth) to intentionally elicit group interaction, shared norms, and negotiated differences that characterize community environmental decision-making. We also employed inclusive facilitation (balanced turn-taking, directed probes) to safeguard equitable participation and mitigate dominance. This design is consistent with established qualitative methods recommending mixed composition when the goal is to understand how views are formed, debated, and reconciled in non-sensitive topics [13, 46, 65].

2.3.3 Consent for participation and data saturation

Data collection procedures followed the International Water Management Institute (IWMI) Research Ethics Policy and the CGIAR Research Ethics Code. All key informant interviews and focus group discussions were conducted only after obtaining verbal informed consent from participants. Before beginning each session, the research team clearly explained the purpose of the study, the types of questions to be asked, the expected duration, and the voluntary nature of participation. Participants were informed that they had the right to decline to answer any question or withdraw at any time without consequence. Confidentiality was assured, no personally identifiable information was collected unless necessary, and all responses were treated as anonymous. Key informant interviews and focus group discussions were concluded once data saturation was reached, with no new themes emerging. These procedures are consistent with the COREQ guidelines for qualitative methods, which are outlined by [89].

2.3.4 Qualitative data collection

We used checklists to gather data through KIIs and FGDs (Supplementary Material 1). Figure 2 summarizes the key data collected using KIIs and FGDs. To gather the perceived benefits and disbenefits of the adopted 11 SLM practices using FGDs, the SLM practices (Table 6) were categorized into four groups: gully rehabilitation measures, bunds and water harvesting structures, biological conservation measures, and soil fertility management practices.

Participants of FGDs first reviewed SLM practices identified through KIIs to confirm their knowledge and adoption. Participants then discussed and identified the benefits and disbenefits of each practice and ranked their relative importance using a standardized scoring system (i.e., for benefits, giving a value of 3 for the most important, 2 for intermediate, and 1 for less important; for disbenefits, giving a value of −3 for the most important, −2 for intermediate, and −1 for less important). Based on these rankings, participants provided an overall assessment of management options (positive, negative, or neutral) and explained the key reasons for their assessment.

We used a simple numerical scoring method to capture how community members perceive the benefits and disbenefits of SLM practices based on their lived experience. This approach was chosen for its clarity, inclusivity across diverse groups, and ability to help participants express their judgments clearly during discussion. The simplified scale also facilitated consistent comparisons and consensus-building within the focus groups. By grounding the assessment in locally informed, easily interpretable scores, the method ensured that the results accurately reflect community perspectives without introducing unnecessary complexity [61].

2.3.5 Spatial data collection

Alongside engaging local communities and gathering local knowledge on land degradation and restoration, we gathered spatial data, including normalized difference vegetation index (NDVI), Landsat imagery for LULC analysis, and soil data. NDVI data from 1994 to 2004 were sourced from the Advanced Very High-Resolution Radiometer (AVHRR) through Global Inventory Modeling and Mapping Studies (GIMMS), while data for 2004–2014 and 2014–2024 were obtained from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1) Version 6. Landsat images (30-meter resolution, Path = 168 and 169, Raw 55) for 1994, 2004, 2014, and 2024 were retrieved from the System for Earth Observation Data Access, Processing, and Analysis for Land Monitoring (SEPAL) portal (https://sepal.io). Spatial soil data were obtained from the SoilGrids raster layer at 250-meter spatial resolution developed by the International Soil Reference Information Center (ISRIC) (https://soilgrids.org/). In the following, the use of this data is referred to as "scientific knowledge."

2.4 Data analysis

2.4.1 Qualitative data analysis

The Drivers-Pressures-State-Impact-Responses (DPSIR) framework [68], which is widely used as an effective tool for adaptive environmental management [35], facilitating system thinking [53], and supporting structured decision-making [42], was applied to capture farmers' perspectives on land degradation and restoration. The DPSIR framework was selected for this study with the underlying assumption that it effectively captures and analyzes the interactions between local communities and their environment, providing insights into whether livelihood activities contribute to the degradation or restoration of key ecosystems.

Before analysis, a coding scheme was developed based on key thematic areas, including drivers of land degradation, pressures on natural resources, environmental and socio-economic changes, impacts, and responses. Qualitative data from KIIs were then analyzed using a structured manual deductive coding approach grounded in the DPSIR framework, with predefined categories covering severity of degradation (Supplementary material 2), drivers and pressures, environmental and social impacts, and types of implemented SLM practices. To assess the relative importance of variables within each DPSIR component, the relative frequency of coded variables was calculated. In parallel, FGD data on perceived benefits and disbenefits of SLM practices were coded through repeated readings of transcripts, with themes categorized into environmental, social, and economic dimensions. Benefits were rated on an ordinal scale from + 1 to + 3 and disbenefits from − 1 to − 3, and average ratings were calculated for each SLM practice to enable comparison across management options.

2.4.2 Spatial analysis

The spatial analysis involved examining changes in LULC and LDN trends. We conducted image pre-processing and enhancement before LULC classification to refine the quality of the images. Image classification accuracy was assessed using three standard accuracy assessment criteria, overall accuracy (OA), user accuracy (UA), and producer accuracy (PA), together with the kappa coefficient (Kappa). The accuracy assessment was conducted in ERDAS Imagine, and the results are summarized in Supplementary material 3 The Kappa statistic was used to evaluate the level of agreement beyond chance, where values < 0 indicate no agreement, 0–0.20 indicate slight agreement, 0.21–0.40 poor agreement, 0.41–0.60 moderate agreement, 0.61–0.80 substantial agreement, and 0.81–1.00 perfect agreement [95]. The resulting OA, UA, and PA values indicate a generally robust classification performance across land use and land-cover classes. Moreover, the Kappa values fall within the substantial and perfect agreement range, suggesting that the generated spatial maps are reliable and suitable for further spatial analyses and interpretation.

A hybrid classification approach combining unsupervised and supervised methods was employed to analyze larger areas with diverse biophysical settings [39, 50]. LULC changes were quantified for three time periods: [1994–2004], [2004–2014], and [2014–2024]. The change in area for each LULC class was determined by subtracting the initial year's area from that of the subsequent year. The annual rate of change was then computed by dividing the total area change by the number of years between the two years [39]. Then, a transition matrix was generated and analyzed using ArcGIS (Zhang et al. 2017) to assess LULC dynamics.

LDN was assessed using the Good Practice Guidance (GPG) [82], integrating GIS and remote sensing techniques to quantify the three sub-indicators: land productivity (LP), land cover (LC), and soil organic carbon (SOC). To determine the change in (LP) sub-indicator (kg ha^{-1} year^{-1}), a time series of preprocessed annual NDVI datasets derived from AVHRR (GIMMS) for 1994–2004 and MODIS (MOD13Q1 Version 6) for 2004–2014 and 2014–2024 datasets was analyzed using Trends. Earth QGIS 3.12 plugin [75]. The analysis was conducted separately for each period using consistent NDVI datasets to avoid direct cross-sensor merging. The Trends. Earth computes LP using three complementary components (trajectory, state, and performance) to classify LP into increasing, stable, or declining categories. Details of adjusting the spatial and temporal effects of water availability on the rate of change in LP within an ecosystem, as well as methods of tracking change in water use efficiency over time, are described in [60].

To assess the (LC) sub-indicator, custom LULC data (1994, 2004, 2014, 2024) were used and reclassified into seven categories: forestlands, grasslands, croplands, wetlands, artificial areas, bare land, and waterbodies following the classification set by the (UNCCD) reporting and the Intergovernmental Panel on Climate Change (IPCC 2019). Then, the land cover transition matrix was generated for three periods (1994–2004, 2004–2014, and 2014–2024) to identify those pixels that remained in the same land cover class and those that changed [82]. As outlined by [60], a degradation typology was developed using expert knowledge to classify land as degraded, improved, or stable. Finally, Trend Earth combined the information from the LULC maps and the degradation typologies [60] by LC transition to compute the status of land degradation based on the LC sub-indicator for each period.

The (SOC) sub-indicator was assessed by analyzing relative changes in SOC (t ha^{-1}) using a combined LULC/SOC method in Trends. Earth. SOC changes were determined using land use conversion coefficients (Supplementary material 4) recommended by the IPCC and UNCCD [82]. The reference SOC stock value (t ha^{-1}) for the first 30 cm of the soil profile was obtained from the ISRIC SoilGrids database. SOC change was classified based on UNCCD-recommended thresholds: areas experiencing > 10% SOC loss were classified as potentially degraded, while those with > 10% gains were considered potentially improved [82]. Detailed SOC estimation methods and coefficient values are provided in the Trends. Earth user guide and the good practice guidelines [82].

Finally, the three sub-indicators were integrated using the "One-Out, All-Out" (1OAO) principle to classify land as degraded, improved, and stable. According to this approach, if any of the three indicators, LP, LC, or SOC, show degradation, the land is categorized as degraded, irrespective of positive trends in other indicators [75, 82].

2.4.3 Ecosystem service valuation

To assess changes in ESVs, the study used classified LULC conditions and a global synthesis of economic values for ecosystem services collected and organized in the Ecosystem Services Valuation Database (ESVD) [20]. ESVD contains over 1300 studies, yielding over 9,400 value estimates in monetary units [20]. To enable the comparison and synthesis of values, estimates in the ESVD are standardized to a common set of units (Int$/ha/year at 2020 price levels). This data provides a basis for value transfers to inform decision-making in current policy contexts. Accordingly, we used the value transfer method to estimate ESV changes in response to LULC changes in the studied site. Due to the lack of specific ESV data for Ethiopia, representative biomes from the ESVD were used as proxies for each LULC class (Table 2). The mean standardized values for each ecosystem service were extracted from the database summarized by[20] and contextualized to the study sites. For example, we assigned a value of 0 for built-up and settlement areas, as this LULC class does not provide a considerable contribution to any of the ecosystem services. We also assigned a value of 0 for some of the regulating ecosystem services related to forestlands and grasslands because most of the forestlands are eucalyptus plantations, and grasslands are mostly degraded.

In addition to contextualizing the global values to the study sites, a sensitivity analysis was conducted to evaluate the robustness of ecosystem service value (ESV) estimates to uncertainties in two key parameters: ecosystem service coefficients and the magnitude of LULC changes. A baseline scenario was first established using the original coefficients and observed LULC changes for 1994, 2004, 2014, and 2024. Subsequently, ecosystem service coefficients were decreased and increased by 25% and 50%, while keeping LULC constant. In a parallel set of scenarios, the magnitude of LULC changes was similarly adjusted (−50%, −25%, +25%, +50%) while maintaining the original coefficients. The resulting ESVs were compared against the baseline to assess the relative sensitivity of the estimates to each parameter.

Table 2 Land use and land cover classes, the corresponding biomes, and mean standardized values per ecosystem service biome based on the updated values [20]. The values are given in Int$/Hectare/Year (2020 Price Levels)

LULC class	Equivalent biome	Mean ESVs
Waterbodies	Rivers and lakes	31,235
Forestlands	Tropical and sub-tropical forest	8152
Farmlands	Intensive land uses	11,341
Bare land	Desert	0.0
Built-up areas	Urban and industrial areas	0.0
Grasslands	Rangeland, natural grasslands and savannas	3258
Shrublands	Shrubland and shrubby woodland	596

The total ESVs and percentage changes in ESVs from 1994 to 2024 were estimated using established equations [63]. At this point, it is worth mentioning that the results of the assessment reflect potential values derived by linking LULC classes with ESVD valuation coefficients [20], with only minor adjustments for local conditions, and do not incorporate biophysical constraints such as soil erosion, water shortages, or productivity declines. This suggests that increases in land area in some LULC classes, such as farmland, may not always translate into proportional increases in ecosystem service values. Consequently, the ESV estimates presented in this study reflect LULC-based potential values rather than realized ecosystem service flows.

3 Results

3.1 Societal challenges and impacts on people and the environment

Table 3 summarizes the results of the KIIs and FGDs on societal challenges, contributing factors, and the diverse ways of affecting people's livelihoods. A considerable proportion of the key informants (68%) identified the decline in soil fertility and water shortages as the major societal challenges, though they perceive that the ongoing watershed development activities are helping to address land degradation. Most key informants (64%) suggested that land degradation is severe or very severe in forest ecosystems compared to agricultural and grazing lands (Supplemental material 2). Consistent with key information, the participants of FGDs indicated that up to 65% of the land area is affected by land degradation.

Table 3 Societal challenges as perceived by local communities. The sum of % of mentions is greater than 100%, as a key informant can mention multiple challenges

Societal challenge	Contributing factors	Potential impact on people and the environment	Importance or % of mention
Decline in soil fertility	Extractive farming system, runoff, and soil erosion	Reduce agricultural productivity and income, degradation of ecosystems, and reduce ecosystem services	15 out of the 22 (68%)
Water shortages/drought	Erratic rainfall patterns, limited water infrastructures, the absence of freshwater ecosystems like rivers, and climate variability	Consumes the productive time of women and children, lowering agricultural production	15 out of the 22 (68%)
A decrease in livestock numbers	Fodder shortages and disease	Reduce the community's income and resilience to natural shocks	6 out of the 22 (27%)
Gully expansion	Poor land management and high flooding	Restricts human and livestock movement or reduces interactions among communities	5 out of the 22 (23%)
Shortage of fuelwood	Deforestation	Consumes the productive time of women and children in search of fuelwood	5 out of the 22 (23%)
The reduction in beekeeping activities	Deforestation, habitat loss	Loss of biodiversity and income	2 out of the 22 (9%)

3.2 Availability and spatial distribution of land resources

The results of KIIs and FGDs suggest that the study area has diverse land resources, including water, grazing lands, forests, agricultural land, and exclosures. Most (86%) of the key informants and FGD participants identified agricultural land as the most crucial land resource for people's livelihood, emphasizing its role in both sustenance and economic stability. Data gathered using scientific knowledge supports this, identifying seven major LULC classes (Fig. 3), with farmland as a dominant type.

Key informants and FGD participants are aware of the spatial variability in the availability of land resources. For instance, they noted that forests are primarily located in upper slope areas, whereas farmlands and grazing lands are spread across study sites. This observation is also supported by scientific knowledge (Fig. 4), which shows patches of forests in the upper catchment area, while farmlands and grasslands are scattered throughout the study sites. Key informants highlighted that spatial differences in land resource distribution affect equity in access, noting that households near community ponds have easier water access, while those in upstream areas have better access to forest resources than downstream households.

The scientific knowledge depicted temporal variabilities in resource availability. Specifically, the LULC analysis indicated a reduction in bare land and an increase in forestlands, waterbodies, grazing lands, and shrublands between 2014 and 2024, a reversal of the declining trend between 1994 and 2014 (Fig. 3). These findings were reinforced by insights from KIIs and FGDs, which consistently emphasized the pivotal role of SLM practices in restoring degraded ecosystems.

In summary, the results indicate that both local knowledge and scientific analyses consistently indicate that agricultural land is the dominant and most critical resource for livelihoods, and that land resources exhibit clear spatial variability, with forests concentrated in upper catchments and farmlands and grazing lands more widely distributed. Additionally, recent positive land-cover changes identified through LULC analysis align with local perceptions that SLM practices have contributed to ecosystem restoration.

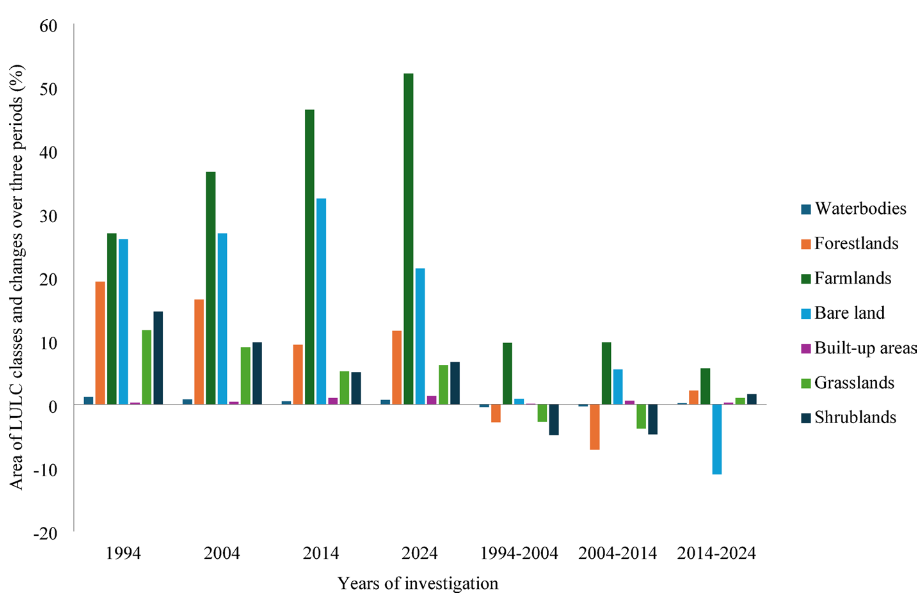

Fig. 3 Area (%) of major land use and land cover types and changes over three periods. The areas of each land use and land cover class were calculated directly from the spatial maps presented in Fig. 4

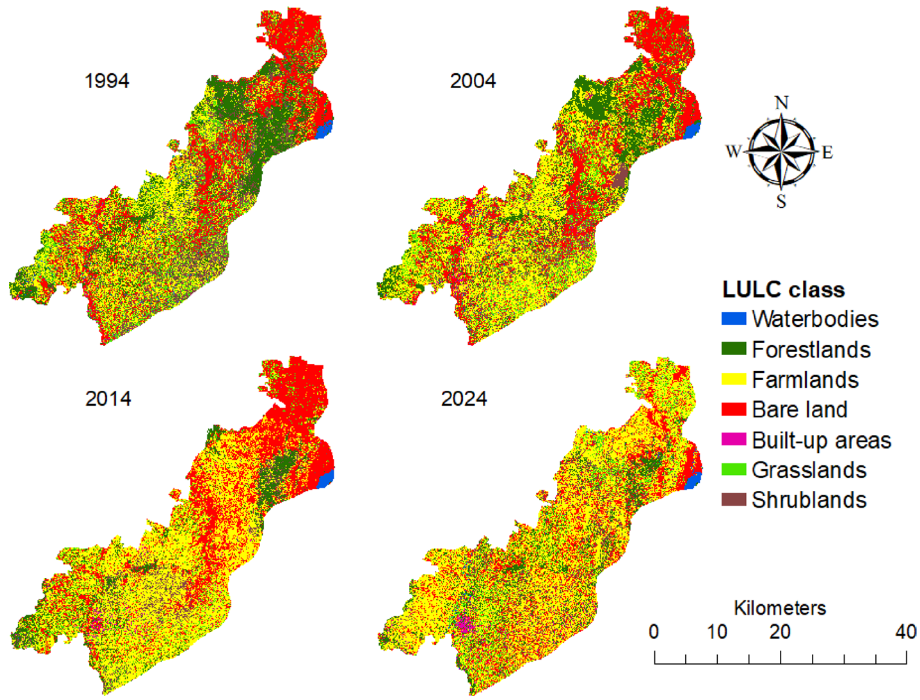

Fig. 4 Land Use Land Cover types for the years 1994, 2004, 2014, and 2024. *Source*: Author's creation using SEPAL portal (https://sepal.io) and ArcGIS 10.8.

Table 4 Seasonal variations in the availability of land resources

Land resources	Sufficiently available	Responses (%)	Key reasons	Insufficient	Responses (%)	Key reasons
Water	May to September	74	Rainfall, availability, and harvested water in community ponds	November–March	77	Drying up of community ponds, drought, and lack of freshwater ecosystems like rivers
	April to October	26		September–March	23	
Livestock feed	May to January	90	Good grass and vegetation growth due to rainfall and the availability of crop residues	February–April	63	Vegetation degradation and prolonged drought
	May to September	10		October–April	37	
Fuelwood	November to February	91		March–October	86	Forest degradation, lack of alternative energy sources
	November to April	9		May-October	14	

3.3 Seasonal variations in land resource availability

Table 4 summarizes the seasonal variability in the availability of land resources and key reasons. We detected slight differences among respondents in their perceived duration of resource availability. Key informants reported that unregulated upstream irrigation has reduced downstream flows, causing the Bilate River to dry for extended periods with adverse effects on livelihoods and ecosystems. The results suggest that the communities face significant water and livestock feed shortages during the long dry seasons.

3.4 Seasonal variation of communities' demand for land resources

Respondents perceive that forest resources are equally needed in dry and wet seasons. The demand for agricultural lands, resources in exclosures, and grazing lands is perceived as higher in the rainy season than in the dry season, while community ponds are mainly needed in the dry season. Dependency on specific land resources also varied across different community groups (Supplementary Material 5). Interestingly, men mainly depend on agricultural lands, while women depend on all land resources. A comparison between wealthier and poorer households reveals that the demand for agricultural and grazing land was significantly higher among wealthier households (supplementary material 5). Conversely, the poor households exhibited higher dependency on forests, exclosures, and community ponds. In summary, dependence on land resources varies seasonally and across social groups, with distinct differences by gender and wealth status.

3.5 The driver-pressures-state-impact-response (DPSIR) framework for land degradation and restoration

The results of KIIs and FGDs suggest a concerning trajectory of landscape degradation, where initial minor impacts have escalated into significant pressures due to the contributions of human activities, natural events, and climate change. Respondents identified various forms of land degradation occurring across most LULC classes (supplementary material 6), all of which negatively impact local livelihoods.

Multiple drivers cause land degradation in the study area (Fig. 5). Drivers are linked to land management (e.g., free grazing and insufficient SWC practices), terrain, and soil (e.g., topography, soil type/erodibility), people (e.g., population), and governance. These drivers influence human behavior in using and managing natural resources, consequently exerting pressure on land resources in many ways (Fig. 5). Consistent with the local knowledge, the analysis of LDN indicates a decline in stable land and an increase in degradation across the three-time ranges: 1994 to 2004, 2004 to 2014, and 2014 to 2024 (Fig. 6), suggesting overexploitation or increased pressure on natural ecosystems.

The resulting pressures on land resources due to changes in human behavior led to changes in the state of the environment and people (Fig. 5). The observed changes in the state of the environment impact the environment and people's livelihoods by increasing

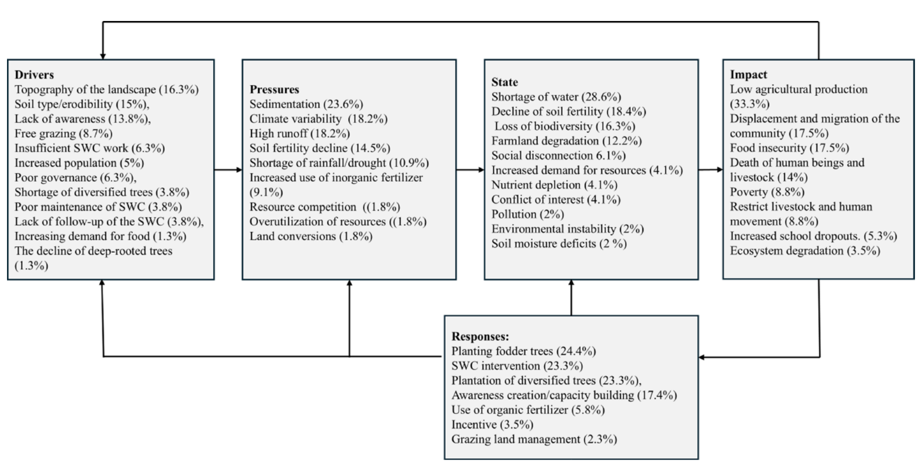

Fig. 5 The drivers-pressures-state-impact-response framework for land degradation and restoration in Halaba, Ethiopia. Numbers in the brackets indicate the relative frequency of each identified variable

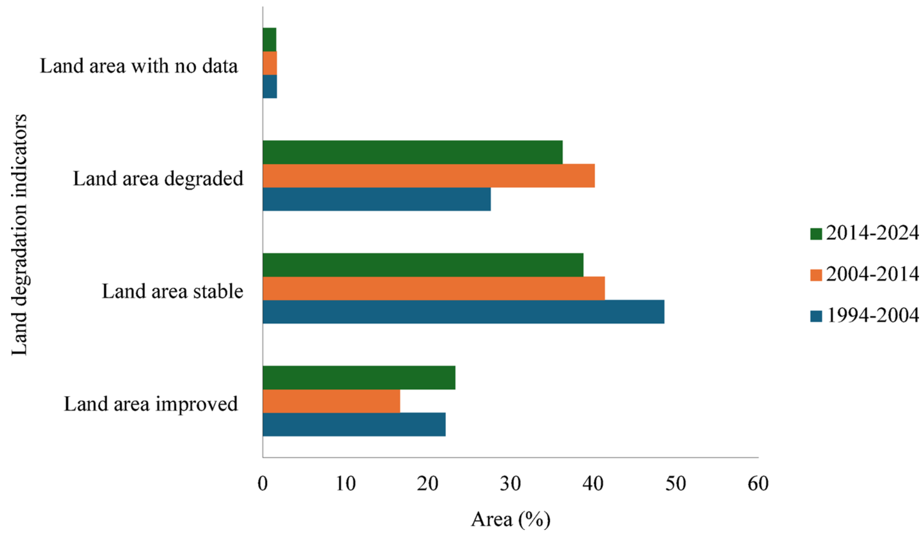

Fig. 6 Summary of land degradation status using the three sub-indicators

ecosystem degradation, food insecurity, rural migration, school dropouts, human mortality, livestock mortality, and poverty (Fig. 5).

The key informants identified various responses to address land degradation and associated impacts (Fig. 5). The two most important responses identified by the key informants were planting fodder trees and constructing various SWC measures (Fig. 5). The key informants discussed and encouraged capacity-building activities that involve tailored training on agricultural practices, climate adaptation strategies, the use and management of improved seeds, as well as material support. Such tailored training has been provided for diverse groups: agricultural experts working at different levels, communities, and community-based organizations.

Overall, the results indicate that both local and scientific evidence indicate escalating land degradation driven by multiple interacting pressures, with SLM practices identified as key responses to mitigate impacts on ecosystems and livelihoods.

3.6 Benefits and disbenefits of land management practices

FGD participants identified 51 benefits (Supplementary material 7) and 36 cost factors (Supplementary material 8) of the adopted SLM practices. The benefits are more related to environmental factors, while costs are linked to social and economic factors (Fig. 7). FGD participants from community groups value biological conservation measures, experts value bunds and water harvesting structures, and development agents favor gully rehabilitation measures (Fig. 7). Across groups, gully rehabilitation entails the highest economic costs, while bunds and water harvesting structures involve the highest social costs.

FGD participants mainly associate environmental benefits with regulating ecosystem services (Fig. 8). Consistently, scientific evidence shows that SLM practices implemented during 2014 and 2024 contributed to the restoration of degraded forests and increased ESVs (Fig. 9).

The results of the sensitivity analysis on the changes in ESVs show that ESVs were more sensitive to changes in ecosystem service coefficients than to variations in the magnitude of LULC change (Fig. 10a, b). Adjusting the coefficients led to substantial

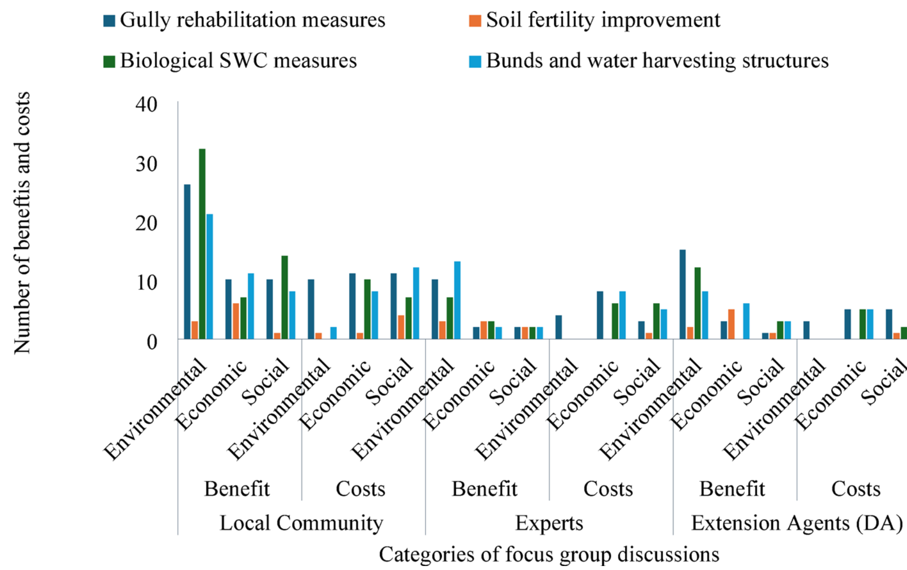

Fig. 7 The number of benefit and cost factors from the perspective of the local communities and practitioners. Gully rehabilitation measures include stone, vegetation, sandbags, and gabion check dams; Biological SWC conservation measures include afforestation or reforestation, planting fodder trees on the banks of SWC measures and exclosures; Soil fertility management measures include the use of compost and/or manure; as well as bunds and water harvesting structures include soil and stone bunds and community ponds

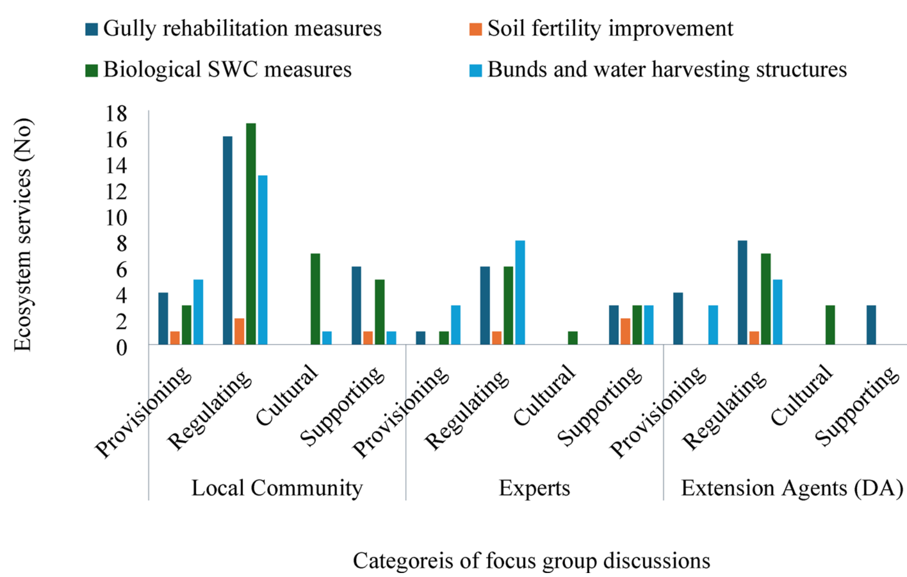

Fig. 8 Ecosystem services provided by adopted sustainable land management practices

proportional changes in ESVs across all land use categories and time periods, indicating that valuation assumptions strongly influence total ESVs. In contrast, modifying the magnitude of LULC changes resulted in relatively small variations in ESVs, with overall impacts remaining limited even under ±50% adjustment scenarios. The comparatively low sensitivity to LULC magnitude likely reflects the compensatory effects of opposing land use trajectories, where increases in some land cover types offset declines in others. Overall, the findings highlight that uncertainty in ecosystem service coefficients is the dominant source of variability in ESV estimates, underscoring the importance of careful coefficient selection and transparent reporting in ecosystem service valuation studies.

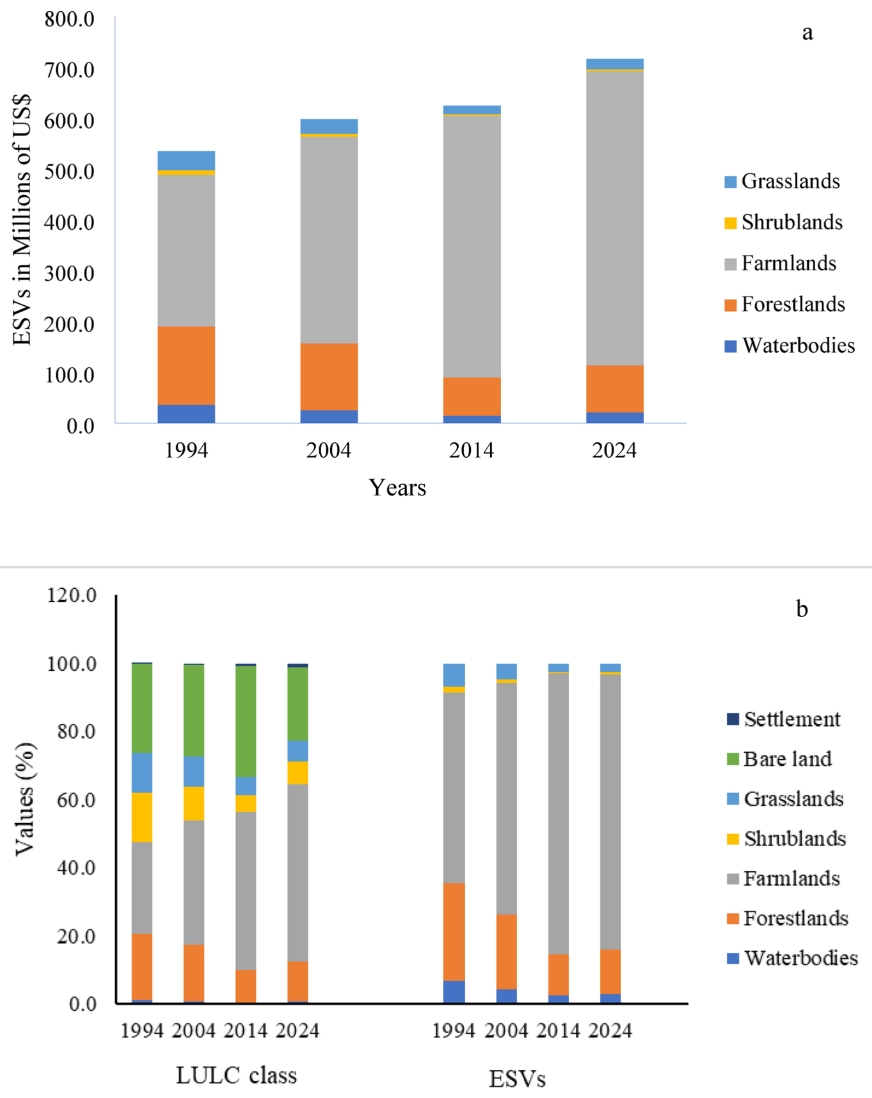

Fig. 9 Total ecosystem service values (**a**) for 1994, 2004, 2014, and 2024; and (**b**) percent change in ecosystem service values due to change in LULC

Table 5 summarizes the commonly mentioned benefits and costs of adopted responses and the benefits and costs that were specifically identified by a particular group

3.7 Overall ranking of land management practices

Overall, benefits outweighed costs for most interventions (Fig. 7). Across FGD groups, mean benefit ratings were consistently higher than mean cost ratings (maximum score = 3 for both benefits and costs): community groups reported mean values of 2.8 for benefits and 2.2 for costs, experts 2.8 and 2.6, and development agents 2.7 and 2.1, respectively. Table 6 summarizes the overall assessments of 11 SLM practices grouped into four categories. All practices were evaluated positively except gabion check-dams, which were rated negatively due to high costs and limited feasibility for implementation by local communities.

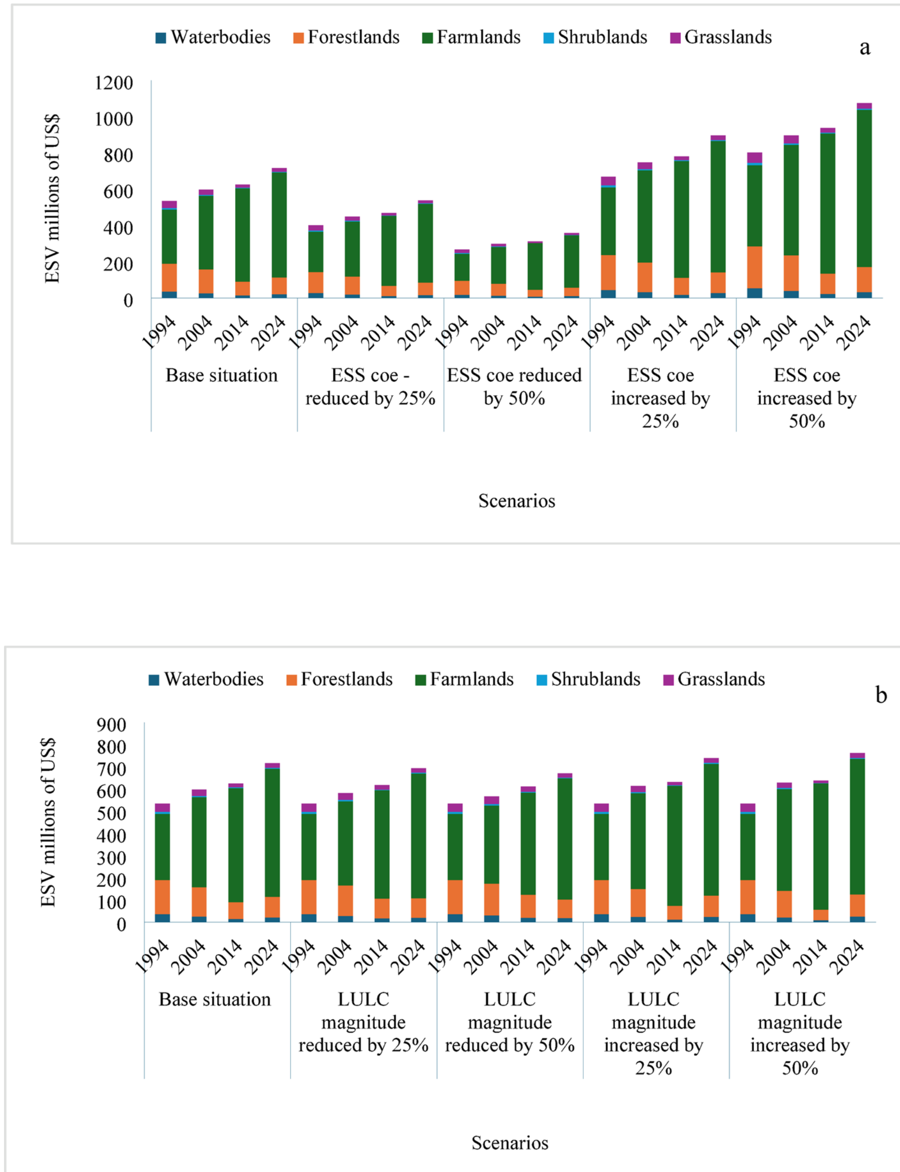

Fig. 10 The changes in the ecosystem service values due to changes in the coefficients of ecosystem services (**a**) and the magnitude of changes in land use and land cover (**b**)

3.8 Stakeholders' participation

Key informant interviews and FGDs indicate that a wide range of stakeholders, including government and non-governmental organizations, communities, community-based organizations, and local administrative bodies, are involved in the planning, designing, and implementation of SLM practices (Table 7). Most key informants (55%) rated stakeholder participation as strong, while 27% assessed it as medium. Smallholder participation is constrained by limited awareness, distance to intervention sites, poor access due to gully erosion, labor shortages, and economic constraints. Participation is further affected by perceived inequities in benefit distribution, where households closer to intervention areas experience greater benefits, and by competing livelihood demands, particularly during the dry season when farmers prioritize fodder collection and water access.

Table 5 Frequently mentioned benefits and cost factors

Commonly mentioned benefit factors	Categories	Benefits specific to		
		Community groups	Expert group	Development agent group
Water conservation	Environmental	Reduce drought impacts; stabilize embankments, support animal fattening, support crop diversification, provide a source of seeds, facilitate livestock movement, expand the area of usable farmland, restore medicinal plants, provide shade for humans, increase wild food, provide sources of wild food, increase construction materials	Reduce pollution	Enhance the quality of agricultural products
Improved tree regeneration	Environmental			
Increased soil moisture	Environmental			
Improving microclimate	Environmental			
Reducing flooding	Environmental			
Reduce soil erosion	Environmental			
Rehabilitate gullies	Environmental			
Increase biodiversity	Environmental			
Improve agricultural productivity	Economic			
Increase income	Economic			
Lowers agricultural input costs	Economic			
Livelihood diversification	Economic			
Increase fuelwood availability	Social			
Increase water access	Social			
Commonly mentioned benefit factors	**Categories**	**Costs specific to**		
		Community groups	**Expert group**	**Development agent group**
Aggravate soil erosion	Environmental	Increased erosion, ineffectiveness in water retention, waterlogging, lack of locally available construction materials, increased risks of accidents around water harvesting structures, and a higher likelihood of water-borne diseases.	Decline in soil fertility due to the use of a sandbag check dam	Disrupt the natural spatial distribution of water due to the use of water harvesting structures.
Disturb local ecosystems	Environmental			
Environmental pollution	Environmental			
Risk of deforestation	Environmental			
Fees for guards	Economic			
High labor demand	Economic			
Reduce farm size	Economic			

Table 5 (continued)

Commonly mentioned benefit factors	Categories	Costs specific to		
		Community groups	Expert group	Development agent group
Requires locally unavailable construction materials	Economic			
Increased risk of human disease	Social			
Increase conflicts over resource use	Social			
Restricts human and livestock movement	Social			
Increase wildlife attacks	Social			

Table 6 The overall assessment of adopted sustainable land management practices

No	Land management practices	Assessment	Reasons
Category one: Gully rehabilitation measures			
1	Stone check dam	Positive	Controls soil erosion, improves land quality, increases soil moisture, and enhances agricultural productivity
2	Vegetation or log check dam	Positive	Restores gullies and is constructed using local materials.
3	Gabion check dam	Negative	High construction costs and the need for skilled labor
4	Sandbag check dam	Positive	Cost-effective solution for erosion control, and uses local materials
Category two: biological conservation measures			
5	Afforestation/reforestation	Positive	It offers long-term benefits like improved soil health, reduced erosion, and increased availability of resources for communities.
6	Exclosures	Positive	Restores degraded lands and diversifies livelihoods
7	Planting grasses and fodder trees, fruit trees	Positive	Stabilize conservation measures, increase livestock feed, and support food security
Category three: soil fertility management			
8	Compost/manure	Positive	It enhances soil health and boosts crop yields
Category four: bunds and water harvesting structures			
9	Hillside terraces	Positive	Enhance land productivity by reducing runoff and soil erosion, leading to better water retention.
10	Soil/stone bund	Positive	Conserves soil and increases agricultural productivity
11	Water harvesting structures	Positive	Increase access and availability of water for multiple uses

Table 7 Key stakeholders involved in the planning, design, and implementation of SLM practices

Stakeholders	Key roles	How they work
Agricultural offices	Planning and designing watershed development activities; providing technical, material, and financial support; and capacity building	The agricultural offices work closely with communities and community-based organizations to coordinate the implementation of SLM practices
NGOs	Provide technical, financial, and material support as well as contribute to providing capacity-building training for farmers, extension agents, and woreda-level experts	NGOs also collaborate with other partners, government offices, and farmers who work for the watershed development activities
Health offices	Providing support for individuals who may sustain injuries during soil and water conservation activities	The health and agricultural extension services and safety considerations are integrated
The Kebele, District and Zonal administrations	Mobilizing resources, coordinating efforts among stakeholders, and overseeing monitoring and evaluation processes	The administrative offices coordinate with farmers and solve the community issues in collaboration with other community-based organizations
Youth groups, informal institutions (Idir), and farmers' committees	Provide unpaid labor and contribute materials	These groups are involved during problem identification and technology implementations
Schools (elementary and high schools)	Provide unpaid labor	All the students and teachers participate during the SLM implementation periods
Political party offices	Create a comprehensive network that enhances the sustainability and effectiveness of watershed development initiatives	Participate during the community mobilization period, especially once per year for a month

4 Discussion

4.1 Value of integrating knowledge systems

Integrating local and scientific knowledge when evaluating the effectiveness of SLM practices in restoring degraded ecosystems and improving livelihoods offers a powerful, complementary approach to understanding complex environmental and socio-economic challenges in planning, designing, and implementing interventions, as well as for designing better future practices [72]. While scientific knowledge employed in this study provides systematic data on landscape alterations and changes in ecosystem services, local knowledge provides generations of lived experience, contextual understanding, and adaptive practices developed in response to local conditions. Our study in Halaba, Ethiopia, demonstrates that neither source of knowledge alone can fully capture the nuanced dynamics of land degradation, resource use, and livelihood dependency. By combining these two perspectives, we can generate a more holistic and accurate picture not just of the drivers and consequences of land degradation, but also the effectiveness of respective SLM interventions.

A key insight from integrating scientific and local knowledge is the differentiated land use needs and resource access across gender, wealth groups, and seasons. While scientific analyses identify spatial and ecological patterns, local knowledge reveals how these translate to social equity, food security, and household resilience. For example, women's reliance on diverse land resources and poorer households' dependence on forests and communal ponds – features often poorly captured by remote sensing [93], underscore the limits of biophysical data alone. Aligning scientific evidence with locally articulated priorities is therefore essential for more inclusive, targeted, and socially legitimate SLM interventions, and for strengthening community ownership and long-term effectiveness [61]. In addition, integrating local and scientific knowledge supports the scaling and long-term sustainability of SLM initiatives by identifying drivers and barriers to adoption [30] and by facilitating the development of robust, adaptable, and socially equitable strategies [69].

Going forward, institutionalizing this integrative approach in SLM planning and implementation processes can enhance the effectiveness and scalability of land restoration efforts. This requires creating platforms for meaningful dialogue between researchers, policymakers, and local communities; ensuring inclusive participation; and embedding local knowledge in policy frameworks. By doing so, future land management practices can not only restore degraded ecosystems but also strengthen community resilience, reduce poverty, and support sustainable development goals in regions like Halaba and beyond.

4.2 Societal challenges, socio-economic inequalities and land resource access

The societal challenges associated with land degradation identified by local communities (Table 3) highlight the need for integrated and adaptive SLM strategies that move beyond biophysical restoration alone. Consistent with evidence from Ethiopia showing links between land degradation, declining productivity, and loss of ecosystem services [98], these challenges underscore the importance of SLM approaches that simultaneously address soil restoration, water conservation, and biodiversity enhancement [15]. Effective responses, therefore, require agroecological practices, improved water-use efficiency, erosion control, and diversified livelihood options such as sustainable beekeeping. Moreover, reducing the disproportionate time burdens on women and children linked to limited resource access calls for gender-sensitive policies and community empowerment [10]. Integrating climate resilience, ecosystem rehabilitation, and inclusive economic opportunities within SLM frameworks can thus enhance productivity, restore ecosystems, and improve livelihoods while supporting long-term sustainability [99].

Given the central role of agriculture in Halaba and comparable mixed crop–livestock systems in Ethiopia [61, 63], recognizing spatial differences in resource availability is critical to avoiding localized scarcity, competition, and social tensions [91]. In addition, the findings underscore that understanding seasonal variability in land resources, together with inequalities among community groups in access to land resources, is critical for designing effective interventions. Community groups in Halaba perceive seasonal variability in key land resources, particularly water and livestock feed, differently, reflecting disparities in household and farm characteristics, including landholding size, livestock ownership, and access to natural resources [55]. Resource scarcity is most pronounced during the prolonged dry season, indicating the need for targeted and differentiated interventions, including improved water storage, drought-resilient forage crops, and more equitable resource distribution mechanisms. Tailoring solutions to the varying capacities and constraints of different households and farm types is essential for enhancing resilience and reducing vulnerability during periods of scarcity [85]. The sustained demand for forest resources across both dry and wet seasons further indicates the central role of biomass energy in meeting year-round household needs, reinforcing the importance of sustainable forest management as a key coping strategy [64]. Seasonal pressures also shape land-use dynamics, with higher demand for agricultural land, exclosures, and grazing areas during the rainy season, partly due to cropland occupation. During this period, communities increasingly depend on fuelwood and fodder from exclosures and private grazing lands, intensifying pressure on these resources. In contrast, community ponds become particularly critical in the dry season, when water shortages are most acute.

The variation in dependency on specific land resources among different community groups points to socio-economic and gender-based drivers that must be considered in sustainable land management planning [5]. Men's focus on agricultural land reflects their greater engagement in crop production, while women's reliance on a wider range of land resources suggests their multifaceted roles in securing household needs, including water, fuel, and fodder, alongside their engagement in agriculture [97]. Similarly, wealthier households' higher demand for agricultural and grazing lands aligns with their greater asset ownership, particularly livestock, whereas poorer households rely more on communal and forest resources due to their heavy dependence on forest resources for income by selling fuelwood and for meeting their household energy needs [9]. These patterns highlight the need for inclusive and differentiated land management strategies that address members' unique needs and pressures, ensuring equity and sustainability in resource use [16].

4.3 Effectiveness of land management practices

The observed land-cover dynamics suggest a broader shift toward ecological recovery following the introduction of community-based watershed development initiatives. Since around 2010, the trend indicates a transition away from landscape degradation toward restoration, with improvements linked to the widespread adoption of SLM practices across communal and agricultural lands (Fig. 3). The reversal is best understood as the outcome of sustained national and local restoration efforts, including community-based watershed development, sustainable landscape management, and productivity safety-net programs aimed at rehabilitating degraded landscapes [63]. Key mechanisms underlying this trend include the establishment of exclosures and the promotion of physical soil and water conservation measures, which have been systematically supported by local institutions and embraced by communities. Consequently, improvements in forest and shrubland cover and reductions in bare land reflect active restoration processes, enhanced natural regeneration, and strengthened local land-management practices, rather than a reduction in grazing or livelihood pressures.

It is worth mentioning that the observed increases in forest cover and ecosystem service values between 2014 and 2024 reflect a combination of native vegetation regeneration and shifts toward plantation-based land uses. Forest recovery reflects both native regenerations enabled by exclosures, which reduced grazing pressure, and increased tree cover from targeted plantations. While both pathways raise ecosystem service values, native regeneration is more supportive of biodiversity and long-term resilience, whereas plantation-driven gains mainly enhance short- to medium-term provisioning services. Distinguishing these trajectories is therefore essential for interpreting LULC/ESV trends and assessing the sustainability of SLM outcomes.

In addition, addressing the social and economic costs associated with SLM practices (Fig. 7) and balancing technical effectiveness with community acceptance is crucial to ensure long-term adoption [51, 76]. Most importantly, addressing these cost concerns through inclusive planning, cost-sharing mechanisms, and labor support could enhance SLM initiatives' sustainability and local ownership [25].

The emphasis on regulating ecosystem services as key environmental benefits of SLM practices, highlighted by FGD participants (Fig. 8) and supported by scientific knowledge (Fig. 9), underscores the critical role of ecosystem restoration in enhancing ecological stability [79]. Restoring degraded ecosystems improves functions such as water regulation, soil fertility, and climate moderation, which are essential for sustaining agricultural productivity and, by extension, local livelihoods [52]. These findings point to the potential of ecosystem-based approaches to reverse land degradation and increase ecosystem service delivery, thereby supporting more resilient and sustainable rural communities [79].

Although national assessments estimate that Ethiopia has lost approximately 85 billion USD due to land degradation caused by LULC changes [18], our findings from Halaba reveal a contrasting local trajectory. Spatial analyses and community-based assessments show that targeted restoration efforts, including sustained SLM practices, have reduced bare land and supported observable ecosystem recovery between 2014 and 2024 (Fig. 3), improving ecosystem service provision (Fig. 9). Discrepancy arises because national figures aggregate widespread degradation across diverse agroecological zones, often masking localized successes driven by strong community engagement and context-specific interventions. This underscores that land degradation and restoration outcomes are highly sensitive to local actions and conditions [27], and that locally led restoration can meaningfully enhance ecosystem services despite broader national-scale losses [21, 74].

The overall positive assessment of most SLM practices suggests strong community support and clear potential for scaling up interventions, provided that cost-related barriers are addressed [29]. The finding that benefits generally outweigh costs reinforces the value of investing in these practices for long-term environmental and livelihood gains. However, the negative evaluation of gabion check-dams highlights a critical need for future planning to align technical solutions with local capacities [61]. This underscores the importance of selecting context-appropriate, cost-effective practices and ensuring that future land management initiatives are designed with both ecological impact and community feasibility in mind [47].

4.4 The participation of stakeholders in land management practices

The involvement of diverse stakeholders in planning, designing, and implementing SLM practices reflects a promising foundation for inclusive and collaborative land governance [16]. This engagement reflects the presence of multi-level institutional arrangements in which government agencies and development actors provide technical guidance and resources, local administrative bodies facilitate coordination and enforcement, and community-based organizations support on-the-ground implementation. However, the variation in perceived levels of participation, where 27% of key informants rated it as only medium, points to a gap in how these governance structures function in practice. In particular, political and administrative actors at local levels influence participation through decisions related to resource allocation, beneficiary selection for safety-net programs, and the prioritization of intervention sites, where these processes lack transparency or inclusiveness, stakeholder engagement tends to weaken.

Barriers to smallholder participation are rooted in intersecting socio-economic and logistical constraints, including limited awareness, physical inaccessibility of intervention sites, labor shortages, and economic hardship. These constraints not only limit engagement but also affect the performance and sustainability of SLM interventions, as reduced participation undermines local ownership, maintenance, and long-term adoption. In addition, uneven distribution of benefits and partial safety-net coverage reinforce perceptions of inequality, reducing motivation to participate and increasing dependency. Strengthening participation is therefore directly linked to improving SLM outcomes and requires governance arrangements that ensure access to materials and support [16], promote fair and transparent benefit distribution [36], and align intervention activities with farmers' seasonal workloads and livelihood demands [31]. Enhanced awareness campaigns and community-based support systems can further empower smallholders to engage meaningfully in land management. Overall, more consistent, equitable, and accountable involvement of all actors, particularly political and administrative institutions at the grassroots level, is essential to ensure that SLM initiatives are locally relevant, widely supported, and sustainable over time [8, 24].

5 Conclusions

The study, using Halaba, Ethiopia, as a case study, evaluates the benefits and disbenefits of sustainable land management practices by using both local and scientific knowledge. The results reveal significant variation in resource access and land use needs among different groups, influenced by socio-economic status and seasonal patterns. Households with greater resources tend to prioritize agricultural and grazing lands, whereas those with fewer resources rely more on diverse and communal assets, such as forests and community ponds. These findings underscore the importance of inclusive interventions that address varying needs across social and economic contexts. The joint understanding of degradation drivers and resource variability from both knowledge systems supports more context-sensitive community-driven land management strategies. Insights from local and scientific knowledge also highlight significant environmental, economic, and social benefits of adopted or implemented SLM interventions. Using local and scientific knowledge to deduce the benefits and disbenefits of SLM practices helps to understand the varying preferences of the diverse groups. While communities favor biologically focused conservation measures, experts tend to support more structural interventions that may carry higher social and financial costs.

6 Recommendations

To improve future planning and implementation of SLM practices, we suggest: (i) use local and scientific knowledge in SLM planning to ensure context-specific, holistic solutions that reflect both ecological data and community realities; (ii) design inclusive and equitable interventions by addressing the diverse needs of community groups based on gender, wealth, and seasonal resource use patterns; (iii) promote low-cost, locally adapted practices to maximize effectiveness and long-term stability; (iv) remove participation barriers by offering labor support, cost sharing, and aligning activities with seasonal workloads to enable broader smallholder involvement; (v) ensure continuous follow-up, maintenance, and community incentives to sustain engagement and impact; and (vi) emphasize ecosystem-based and adaptive approaches by restoring ecosystem services and using hybrid monitoring (scientific and local input) for continuous improvement.

Supplementary Information

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Supplementary Material 1

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Author contributions

Desalegn Tegegne: Conceptualization; Methodology; Data curation; Formal analysis; Visualization; and Writing original draft. Stefan Sieber: Writing review and editing, validation of results, and overall supervision. Goetz Uckert: Writing review and editing, and supervision. Rediet Girma: Formal analysis; Methodology, Writing review and editing. Awdenegest Moges: Writing review and editing. Wolde Mekuria: Conceptualization; Methodology; Formal analysis; Writing review and editing, and overall supervision.

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Data availability

The paper presents two primary datasets: (i) data for system understanding, including information on drivers, pressures, states, impacts, and responses related to land degradation and restoration, and (ii) the benefits and costs of adopting sustainable land management practices. These data were primarily gathered through key informant interviews and focus group discussions. Following the IWMI Research Ethics Policy, CGIAR Research Ethics Code and Responsible Data Guidelines, we ensured that respondents would remain anonymous. Furthermore, the information provided, which reflects the opinions of organizations or institutions, will be treated as confidential and will not be publicly disclosed. However, certain data may be made available upon request. For data availability inquiries, the contact person is Desalegn Tegegne with his email address [d.tegegne@cgiar.org](mailto: d.tegegne@cgiar.org) .

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval

The method of data collection was reviewed by the International Water Management Institute (IWMI) Institutional Review Board (IRB) (with an approval number of 2024_23) and was approved based on IWMI's Research Ethics Policy and the CGIAR Research Ethics Code and Responsible Data Guidelines.

Consent to participate

Verbally informed consent was obtained from all participants before conducting interviews, after explaining the objectives and purpose of the study. Verbal consent was used because many of the participants, particularly farmers, were unable to read and write. Anonymity and confidentiality of the participants were strictly ensured in the course of the entire research process.

Consent for publication

Not applicable.

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