Current Research in Environmental Sustainability 6 (2023) 100237

Contents lists available at ScienceDirect

Current Research in Environmental Sustainability

journal homepage: www.sciencedirect.com/journal/current-research-in-environmental-sustainability

# The role of landscape management practices to address natural resource degradation and human vulnerability in Awash River basin, Ethiopia

Wolde Mekuria [a,*], Mulugeta Tadesse [a], Wondye Admassu [b], Birhan Asmame [b], Assefa Tessema [b], Shawl Abebe [b], Eticha Shibiru [b], Mekonnen Yirga [b], Yemiamrew Jorgi [b], Fatuma Abdu [b], Befikadu Belay [b], Jemal Seid [b], Tsegaye Gobezie [b], Hailu Ayene [b], Gashaw Bekele [b], Mohamed Abdella [a], Abdulkarim Seid [a], Amare Haileslassie [a]

[a] *International Water Management Institute (IWMI), East Africa and Nile Basin Office, Addis Ababa, Ethiopia*
[b] *Wollo University, Dessie, Ethiopia*

ARTICLE INFO

*Keywords:*
Natural resources degradation
Vulnerability
Ecosystem services
Resilient community
Resilient environment

ABSTRACT

Landscape management practices (LMP) support addressing the vulnerability of small-scale producers (SSPs) through providing a means of sustaining and strengthening community livelihoods and building their resilience and the environment. However, addressing the vulnerability of SSPs through the implementation of LMP requires meaningful community engagement and assessing the benefits and costs from the perspective of local communities. This study was conducted in two watersheds, Maybar-Felana and Gelana, in the Awash River basin, Ethiopia. The study assessed the links between natural resource degradation and the vulnerability of SSPs, local communities' opinion on the benefits and costs of LMP and the implications of implementing LMP for addressing vulnerability. It gathered and analyzed data through key informant interviews (KII), focus group discussions (FGDs) and GIS and remote sensing techniques. Diverse LMP such as afforestation/reforestation, exclosures, terrace and bunds and crop- and soil-based soil amendments were adopted in the studied watersheds. These practices contributed to the improvement of natural resources such as forests and the services they provide. Over the last 21 years (2000–2021), forest cover increased by 11.5 and 42.5% in Maybar-Felana and Gelana watersheds, respectively, while shrublands increased by 41.1% in Maybar-Felana. In line with this, the SSPs identified multiple benefits of LMP including the restoration of degraded vegetation, reducing runoff and soil loss, improving access to water for multiple uses and increasing agricultural productivity. The adopted LMP contributed to reducing livelihood vulnerability through reducing incidents of weather extremes such as flood and drought, improving food and water security, enhancing resource availability, and building livelihood assets. The SSPs also identified multiple economic and social costs of LMP, suggesting that addressing the economic and social costs through balancing short-term economic losses with long-term environmental benefits of interventions is crucial to sustaining the LMP and the benefits they provide.

## 1. Introduction

Vulnerability is the human dimension of disasters and concerns in the wider environmental and social conditions that limit people and communities to cope with the impact of hazards (Jeong and Yoon, 2018; Babanawo et al., 2023). The vulnerability relates to several social (Dumenu and Takam Tiamgne, 2020; Lottering et al., 2021), economic (Sneessens et al., 2019; Sarkar et al., 2021) and environmental factors (Derbile et al., 2022; Dongdong et al., 2022). Worldwide, extreme weather and climate events such as floods, drought, unseasonal rainfall, increases in temperature and expansion of drylands have been occurring with more intensity and frequency as a result of climate change (Zhai et al., 2018).This has disproportionately affected the world's poorest population (Harrington et al., 2016), especially in Africa due to their marginalized location, low levels of technology, and reliance on natural resources and rainfed agriculture (Williams et al., 2018; Mashizha, 2019; Lottering et al., 2021).

Like other African countries, the agriculture sector and natural

* Corresponding author.
*E-mail address:* w.bori@cgiar.org (W. Mekuria).

https://doi.org/10.1016/j.crsust.2023.100237
Received 19 August 2023; Received in revised form 27 October 2023; Accepted 12 November 2023
Available online 17 November 2023

resource plays a key role in Ethiopian economy, and most farmers are small-scale producers (SSPs) who are highly exposed to climate change (Shukla et al., 2021). Studies (Kassie et al., 2014; Asfaw et al., 2021) suggested that Ethiopia suffers greatly from the risks associated with weather extremes such as floods and drought that have negatively influenced the agricultural sector in the past decades. The susceptibility of the Ethiopian agricultural system roots in the country's dependence on smallholder rainfed agriculture with limited use of modern farm management practices (Asfaw et al., 2021; Shukla et al., 2021). Moreover, Ethiopian's agropastoral and pastoralists, solely dependent on rainfed systems, are more exposed to climate change due to limited livelihood diversification mechanisms (Alobo Loison, 2015).

Like other parts of Ethiopia, the livelihood of the SSPs in the Awash River basin, the study area, heavily depend on rainfed agriculture, pastoral and agropastoral systems (Maru et al., 2023), and are exposed to the impacts of climate change (Mitiku et al., 2023). In recent years, the vulnerability of SSPs in the basin is mounting and that noticing simple indicators such as rainfall variability, flooding, low agricultural productivity, and poor water resource planning and management is a common phenomenon (Mekonen and Berlie, 2021). Despite an apparently abundant supply of water in aggregate terms, the basin routinely suffers from localized water shortages at specific points in space and time and is prone to destructive episodes of flood and drought and making the SSPs vulnerable to climate change (Mitiku et al., 2023).

Particularly, the vulnerability of SSPs in the Awash River basin, and the status and sustainability of natural ecosystems, are closely interlinked (Wassie, 2020). Because natural resources such as forests, woodlands, wetlands, exclosures, grasslands, and croplands yield resources that are used directly to generate income and subsistence for the SSPs in the basin (Fekadu et al., 2021). Landscape management practices (LMP) are envisaged to support the restoration of degraded natural resources and provide a means of sustaining and strengthening community livelihoods (Erbaugh and Oldekop, 2018) and builds their resilience and the environment (World Bank, 2021). In this study, LMP refers to household-, farm-, and watershed-level land and water management practices. These practices include afforestation/reforestation, establishment of exclosures, terraces, soil and stone bunds, water harvesting structures, and organic soil amendments such as compost and manure.

Investigating local communities' perspectives on the benefits and costs of landscape restoration is crucial for the sustainable planning, design, implementation and management of interventions and building livelihood resilience and the environment. Cost-benefit analysis (CBA) is a commonly applied tool in the economic analysis of landscape restoration (Wainaina et al., 2020), however, studies investigating the benefits and costs of LMP from the perspective of local communities are often lacking. Therefore, this study was conducted in the Awash River basin, Ethiopia to (a) characterize the distribution, status and availability of natural resources such forest, shrublands, grasslands, croplands and water resources, (b) assess the link between the degradation of these natural resource and livelihood vulnerability, and (c) investigate SSPs opinion on the contributions of LMP to reducing livelihood vulnerability or building resilience.

The study hypothesized that the nature of livelihoods (i.e., natural resource-dependent people), and their constraints and shortfalls, forces members of SSPs to degrade natural resources and aggravate their vulnerability to external shocks. It was also hypothesized that SSPs could have contrasting opinions on the benefits and costs of LMP and preferences. Investigating and understanding such diverse opinions and preferences supports sustaining the interventions and associated tangible economic benefits and ecosystem services and reducing the vulnerability of SSPs. Furthermore, the use of both quantitative (e.g., GIS and remote sensing) and qualitative methods (e.g., KII and FGDs) enables to gather comprehensive data and better assess the status, availability, and the spatial and temporal distributions of natural resources in the study area.

## 2. Linkage between natural resource degradation and livelihood vulnerability

The well-being of four-fifths of the world's poor people living in rural areas is linked to the status and availability of natural resources (e.g., forests, water, croplands, pasturelands, etc.) (IFAD (International Fund for Agricultural Development), 2015; World Bank, 2018). Cotula (2002) also argued that the livelihoods of rural people without access to natural resources are vulnerable because they have difficulty in obtaining food, accumulating other assets, and recuperating after external shocks. Thus, the sustainable use of these natural resource assets is increasingly recognized as a key factor in reducing livelihood vulnerability or building resilience (Robledo et al., 2012).

However, natural resources on which poor people depend are increasingly being degraded, posing significant risks to resource-dependent communities (World Bank, 2021). At local level, the case in the study area, the problem of natural resource degradation revolving around deterioration of grazing lands, declining soil fertility, deforestation, soil erosion, and pollution of freshwater ecosystems (Wassie, 2020), increasing susceptibility and exposure to climate shocks and further strains the adaptive capacity of resource-dependent communities (Lange et al., 2018).

In line with this, World Bank (2021) developed "The Natural Resource Degradation and Vulnerability (NRDV) nexus," analytical framework, which supports the analyses of the linkage between natural resource degradation and livelihood vulnerability (Fig. 1). This framework included a spectrum of natural resource degradation, vulnerability among resource-dependent people, and nexus indicated at the intersection between highly degraded resources and highly vulnerable resource-dependent people (Fig. 1). The present study adopted this analytical framework to analyze and summarize the status and availability of natural resources and analyze the linkages between natural resources degradation and livelihood vulnerability in the context of Awash River Basin, Ethiopia.

## 3. Methods

### 3.1. Study area description

We used multi-stage purposive sampling to select specific study watersheds in the Awash River basin. First, we identified climate variability hotspot areas using multiple indicators (Table 1). Using these criteria and grided data (Table 1), we run the spatial analyses in the entire basin. Based on this spatial analysis, areas with larger agricultural stress index (ASI) values (i.e., moisture stressed areas), displayed rainfall variability and historically impacted by El nino and high temperature were given a priority. We then identified the dominant livelihood zones on those priority catchments or climate hot spot areas. Following this, we identified catchments with diverse livelihood mechanisms, specifically, mixed crop-livestock agricultural system, agropastoral and pastoral systems. Accordingly, we selected two catchments, Borkena and Mille (Fig. 2), as these two catchments showed larger ASI values, rainfall variability and high temperature as well as possess both mixed crop-livestock agricultural and agropastoral systems.

In each of these catchments, we selected a learning watershed representing the dominant livelihood zones (i.e., mixed crop-livestock agricultural and agropastoral systems) and those that exhibit diverse household and farm characteristics. The selection of such watersheds helps to assess the benefits and costs of LMP as well as the contributions of interventions to restore degraded ecosystems and address the vulnerability of SSPs under different or contrasting conditions. Accordingly, this study was conducted in two learning watersheds: Maybar-Felana and Gelana (Fig. 2). The long-term mean annual rainfall in Maybar-Felana watershed was 1211 mm, whereas it was 1024 mm in Gelana. The mean minimum and maximum temperature in the Maybar-Felana watershed were 11.4 and 21.6 °C, respectively. In the Gelana

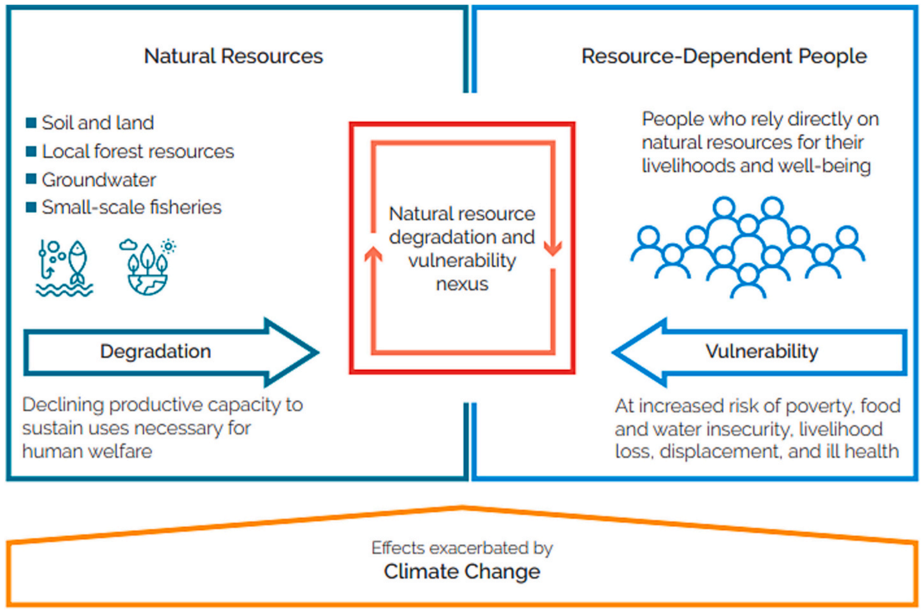


**Fig. 1.** Natural resource degradation and vulnerability Nexus (World Bank, 2021).

**Table 1**
Selected indicators used in the identification of climate hot spot areas.

| No | Indicators | Relevance | Method |
|---|---|---|---|
| 1 | Annual and seasonal spatial rainfall. | Used to characterize the spatial rainfall distribution in the basin in different seasons and at annual scale. | Grided rainfall analyses based on CHIRPS data (1981–2021). |
| 2 | Trend in total seasonal rainfall. | Used to detect the presence of long-term trend in the total amount of rainfall in the growing seasons of the basin. | Grided rainfall analyses based on CHIRPS data (1981–2021). |
| 3 | Trend in inter-quartile range of seasonal rainfall. | Used to assess the presence of long-term trend in the variability of rainfall in the growing seasons of the basin. | Grided rainfall analyses based on CHIRPS data (1981–2021). |
| 4 | Standard precipitation index (SPI). | Used to detect different meteorological drought conditions in the basin at monthly scale. | SPI at monthly time scale (McKee et al. (1993). |
| 5 | Dry spell frequency. | Used to assess the frequency of long dry spell conditions during the growing seasons of the basin. | Ten consecutive days below 1 mm/day rainfall. |
| 6 | Agricultural stress index (ASI). | Helps to identify the locations where large percentage of cropland and grassland suffered from severe drought conditions. | ASI analyses based on FAO data (FAO - Agricultural Stress Index System (ASIS), http://www.fao.org/giews/earthobservation/, [accessed in 2021]). |
| 7 | Seasonal maximum and minimum temperature. | Used to characterize the spatial temperature distribution in the basin in different seasons and at annual scale and their long-term trends. | Grided temperature analyses based on CHIRTS data (1981–2016). |

watershed, these temperature values were 10.6 and 21.5 °C, respectively. The mean livestock holdings expressed in terms of topical livestock unit was 3.25 in the Maybar-Felana watershed, whereas it was 2.75 in Gelana. In both sites, the mean household size was 4.77. Additional characteristics of the study watersheds are presented in Table 2.

### 3.2. Data collection

#### 3.2.1. Qualitative data collection

The study employed qualitative data collection methods such as key informant interviews (KII) and focus group discussions (FGDs) (Gill et al., 2008; Nchanji et al., 2017). KII were conducted to assess the perspective of local communities on the availability and distribution of natural resources, and key changes in the learning watersheds following the implementation of LMP. Criteria such as knowledge on historical changes in the learning watersheds (particularly relates to elderly people and religious leaders who lived for long time in the watersheds) and the direct and indirect involvement in natural resources management were used to select key informants. During the entire study, 30 key informants (15 from each learning watershed) were selected from local practitioners (8), knowledgeable farmers (10), irrigation water user associations (4), representative of youth (1), community watershed team (3), elders (2), and religious leaders (2). The practitioners included as key informants possess diverse expertise including environmental protection, livestock and fishery resources management, natural resource management, horticulture, forestry, and irrigation.

In addition, separate FGDs for men, women and youth in the two learning watersheds were conducted. This was translated to a total of 6 FGDs (3 per learning watershed). The size of each focus group was 9 individuals. The FGDs were used to assess the environmental, economic and social advantages (or benefits) and disadvantages (costs) of diverse farm and watershed-level LMP implemented in the learning watersheds (Table 3). These interventions were selected for further assessment after synthesizing data on adopted LMP identified during KII. During the FGDs, first, the farm and watershed level LMP were established (i.e., the practices were presented using understandable and local language and confirmed by the participants). Second, the advantages and disadvantages of each LMP were identified from the perspective of local communities. Third, the participants were asked to rate the importance of each identified advantage and disadvantage (i.e., giving 3 points for the most important, 2 for the intermediate and 1 for the less important one). Fourth, the participants assigned the overall rating for each practice or intervention (i.e., rating each practice or intervention as positive, negative, or neutral). Fifth, the participants were asked to identify the most advantageous and disadvantageous LMP (i.e., further ranking of the positively and negatively rated practices).

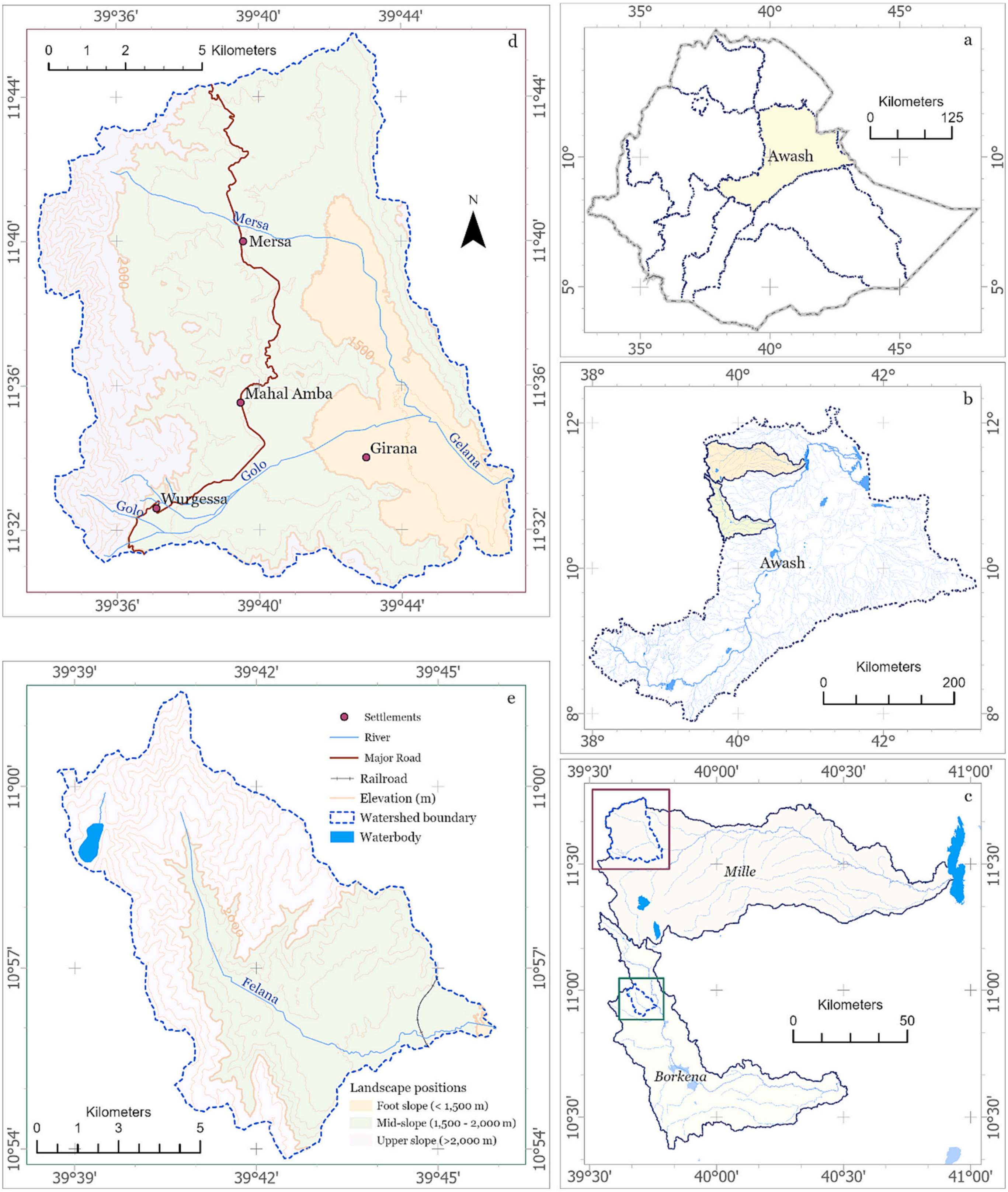


**Fig. 2.** Location map of the study area: (a) Awash River basin within Ethiopia, (b) Borkena and Mille catchments within Awash River basin, (c) Gelana learning watershed within Mille catchment and Maybar-Felana learning watershed within Borkena catchment, (d) Gelana learning watershed, and (e) Maybar-Felana learning watershed.

**Table 2**
Selected characteristics of the two learning watersheds.

| Variables | Maybar-Felana watershed | Gelana watershed | Remark |
|---|---|---|---|
| Elevation (meter) | Ranges from 1490 to 3001. | Ranges from 1345 to 3558. | |
| Area (ha) | 8215 | 45,428 | |
| Agroecological zones | Moist Kolla, Moist Weynadega and Moist Dega. | Moist Kolla, moist Weynadega and moist Dega. | Hurni et al. (2016); Egigu (2022) Miheretu and Yimer (2017) |
| Rainfall pattern | Bimodal, main rainy season occurs between June and September and the short rainy season between March and May | Unimodal, nearly 59% of the rainfall occurs between June and September | Miheretu and Yimer (2017) |
| Major soil types | Leptosols | Leptosols, Vertisols, and Cambisols | Miheretu and Yimer (2017) |
| Dominant agricultural system | Mixed crop-livestock, dominantly rainfed with limited small-scale irrigation practices (about 10% of farmers practice irrigation). | Mixed crop-livestock, dominantly rainfed with limited small-scale irrigation practices (about 24% of farmers practice irrigation). | |
| Cultivated crops | Sorghum, wheat, teff, maize, pulses and mung bean. Farmers also produce vegetable and perennial crops using irrigated agriculture. | Sorghum, wheat, teff, maize, and pulses. Farmers also produce onion, papaya, and mango, and sugar cane using irrigated agriculture. | |

**Table 3**
Assessed landscape management practices in the learning watersheds and their description as explained to local communities.

| Landscape management practices | Descriptions |
|---|---|
| Hillside terraces | Soil and water conservation measure implemented in mountains and steep slopes. |
| Afforestation/reforestation | Refers to raising, planting and managing trees. |
| Exclosures | Restoring degraded landscapes through restricting human and livestock interference. |
| In-situ water harvesting structures (Trenches, micro-basin, farm ponds) | Micro-catchment water harvesting technologies that are used to collect and use water. |
| Bunds | Soil and stone bunds that are constructed on farmlands. |
| Gully rehabilitation measures | Check dams made of small rocks or vegetation logs or gabions. |
| Soil fertility management | Application of cow dung or compost to the soil and using mulches as well as agronomic practices such as crop rotation and intercropping. |
| Irrigation water management | Refers to using both surface and groundwater resources for small-scale irrigation. |
| Spring development and shallow groundwater use | Developing springs and shallow groundwater resources for multiple use (e.g., domestic, irrigation, livestock). |

*Note:* Most of the participants of FGDs engaged in both rainfed and irrigated agriculture.

### 3.2.2. Land use and land cover analyses

To complement the perspective of local communities in the availability, status, and distribution of natural resources, we analyzed the long-term (2000–2021) dynamics of land use and land cover (LULC) changes. Accordingly, satellite images for the years 2000, 2010 and 2021 were acquired from analysis ready images repository of the Digital Earth Africa (DEA) (https://explorer.digitalearth.africa/products). The DEA provides annual and cloud free Landsat 5,7,8 and 9 imageries from its GeoMAD services, which is surface reflectance geo-median and triple Median Absolute Deviation data service. For the years 2000 and 2010, we used cloud free annual composite of Landsat 5 and 7, whereas cloud free annual composite of Landsat 8 and 9 were used for the year 2021. Detailed list of images products and image bands used in LULC classification are summarized in supplementary material 1. All the Landsat imageries had 30-m resolutions. These data were also used to analyze the dynamics of LULC from 2000 to 2010, 2010 to 2021, and 2000 to 2021. We used the definition of the European Space Agency (ESA) to classify the LULC of the two learning watersheds (Table 4).

The classification of the LULC classes of 2000, 2010 and 2021 were supported by ground control points (GCPs) collected using Google earth imagery, visual interpretation of Landsat images, and Environmental Systems Research Institute (ESRI) base maps images. To collect GCPs in both watersheds, first permanent features or reference points were identified and validated with the results of supervised classification. The identification of these permanent features or reference points was conducted due mainly to ensure a good spatial distribution of reference data over the entire studied watersheds. Accordingly, in the Maybar-Felana watershed, a total of 4200, 3900, and 4500 GCPs were collected for the years 2000, 2010 and 2021, respectively. In the Gelana watershed, a total of 15,500, 17,200, and 17,000 GCPs were collected for the years 2000, 2010 and 2021.

The study used random forest (RF) classifier to classify the LULC classes. We selected the RF classifier among eight commonly used machine learning algorithms employed in remote sensing image analysis (Maxwell et al., 2018; Supplementary material 2). We used multiple criteria such as accuracy, recall, area under the curve, precession, and time taken to run a model in seconds to assess the performance of the multiscale classifiers and select the most performing classifier (in this case RF) (supplementary material 2).

The classification of LULC classes was then done using Digital Earth Africa sandbox, which is a cloud-based platform. The performance of the supervised LULC classification was assessed via two steps. First, the performance was assessed using visual inspection based on the acquired

**Table 4**
Descriptions of LULC classes based on ESA (Van De Kerchove et al., 2022).

| LULC classes | Description |
|---|---|
| Forest or tree cover | Refers to areas of land covered by 10% or more of standing trees or forest cover. Includes natural forest, plantation, and orchard trees. |
| Shrubland | Areas covered with 10% or more of perennial vegetation without any defined main stem <5 m tall. Includes scattered trees <10% coverage, herbaceous and woody plants either evergreen or deciduous. |
| Grassland | Area of land covered with 10% or more of herbaceous plants. Includes scattered trees and shrubs <10% coverage, uncultivated/fallow lands, and grasses. |
| Cropland | This includes area of land covered by seasonal or annual crops developed as rainfed or irrigated agriculture. The croplands may include scattered trees or woody vegetation. |
| Waterbody | Area of land covered by water for >9 months a year, which includes lakes, reservoirs, rivers, manmade water harvesting ponds, aquaculture, etc. |
| Wetland | Areas of land covered for >10% of natural herbaceous vegetation that is permanently or regularly flooded by water. |
| River channel | This refers to rivers with wider channels and wadies (wide water ways in the lowland areas which transports ephemeral flood flows). |
| Bare land | Land with exposed soil, sand, or rocks and never has >10% vegetation cover during any time of the year. |
| Built-up | Areas of land covered by any type of buildings (residential or industrial), roads, railroads, greenhouses, and other manmade structures. |

knowledge from the field surveys. Second, a confusion matrix with appropriate accuracy assessment indices (user accuracy (UA), producer accuracy (PA) and overall accuracy (OA)) and nonparametric Kappa coefficient were used (Lillesand et al., 2004; Jensen, 2005; Congalton and Green, 2019). Post-classification technique was used to identify and quantify LULC dynamics over a period of 21 years (2000–2021). The transition matrix was mapped, and losses and gains for each LULC class determined for the 2000 to 2010, 2010 to 2021 and 2000 to 2021 periods. Of the collected GCPs, 70% were used for training and the remaining 30% was used for accuracy assessment.

### 3.3. Data analyses

The qualitative data analysis was processed through manual topic coding and building categories, which involves repeated reading of transcribed data. After repeated reading, the first themes were identified (e.g., type, distribution, status and availability of natural resources, management and allocation of natural resources, people interactions, biophysical impacts, etc.) and keywords and phrases representing each theme were categorized or summarized. Then, using deductive coding, each identified word or phrase was further coded (e.g., forest resources, water resources, uniform, or uneven spatial distribution, degraded or pristine state, impact on water availability, impact on agricultural productivity, environmental impact, economic impact, social impact, etc.). Finally, each response was tagged with all themes and sub-themes presented in the dataset and analyzed. Also, geospatial analysis (GIS and remote sensing techniques and related software) was used to analyze the long-term LULC changes.

## 4. Results and discussion

### 4.1. Accuracies of the LULC classification processes

The results of the accuracy assessment for the LULC classification (Fig. 3) can be considered substantial or very good (Girma et al., 2022), suggesting the classified maps can be used for further analyses (Dey et al., 2021). Specifically, the OA of the base year (i.e., 2000) in the Maybar-Felana watershed was 93%, 94% for 2010 and 95% for 2021. In the Gelana watershed, the OA figures were 96% for 2000, 94% for 2010, 97% for 2021. The Kappa coefficient in the Maybar-Felana watershed for 2000 was 0.87, 0.89 for 2010 and 0.92 for 2021. In the Gelana watershed it was 0.89 for 2000, 0.87 for 2010, and 0.91 for 2021. Fig. 3 summarized the PA and UA for each LULC class. The classification of grasslands displayed the lowest UA in both watersheds and big fluctuations between PA and UA across years were observed (Fig. 3). This could be attributed to the lower coverage of grasslands in the learning watersheds, which reduced training samples and resulted in class imbalance. This could also be related to the misclassification between croplands and grasslands.

### 4.2. Distribution and availability of natural resources

The LULC analyses indicated that forest cover was more dominant in the upper slope (having an elevation of >2000 m, Fig. 2) and mid-slope landscape positions (found between 1500 and 2000 m) in the Maybar-Felana watershed, while shrublands were relatively distributed in all landscape positions (Fig. 4). Croplands were mainly found in the upper and lower slope landscape positions (Fig. 4). Waterbodies (mainly the Maybar Lake, picture 1) found in the upper slope landscape position and wetlands found in the downstream areas near the Borkena River (Figs. 2 and 4). In the Gelana watershed, the mountainous and mid-slope (areas having >2000 m elevation, and areas found between 1500 and 2000 m, Figs. 2, 5) landscape positions were dominantly covered by forest and shrublands (Picture 2). Croplands were found in the entire watershed though it was dominantly found in the mid- and foot-slope landscape positions (Fig. 5). Wetlands were mainly found in the foot slope landscape positions (Fig. 5).

The key informants indicated that both watersheds possess diverse natural resources such as forests, grasslands, farmlands, surface and groundwater, aquatic resources such as fish and economically important aquatic plants (e.g., *Typha latifolia, Cyperus species)* and wildlife. The respondents further elaborated that the spatial distribution of these resources displayed big differences with landscape positions, which is also detected by the LULC analyses (Figs. 4, 5). Respondents indicated that the better vegetation cover in the upper landscape positions of the watersheds is mainly due to the restoration of degraded landscapes through establishing exclosures and afforestation and reforestation practices.

In addition, respondents indicated that the cultivation of crops and livestock production are influenced by landscape positions. For example, in the upper-slope positions, mainly cereals are cultivated while in both mid- and foot-slope positions, farmers cultivate both cereals and high-value crops such as vegetables and fruits. Compared to

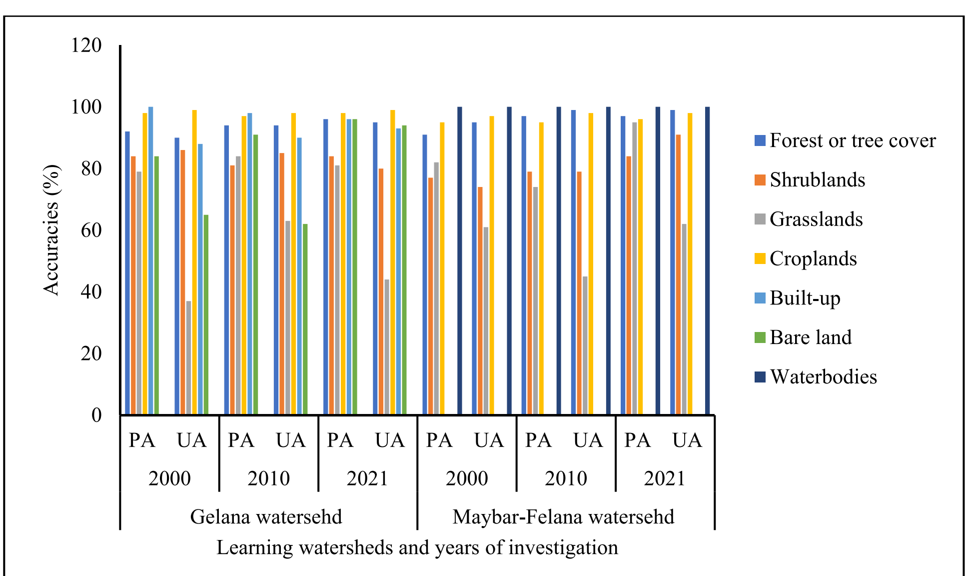


**Fig. 3.** Confusion matrix showing the accuracy of the classification of the land use and land cover classes. Wetlands and river channels were manually digitized and were not included in the accuracy assessment. PA and UA refer to producer and user accuracies, respectively.

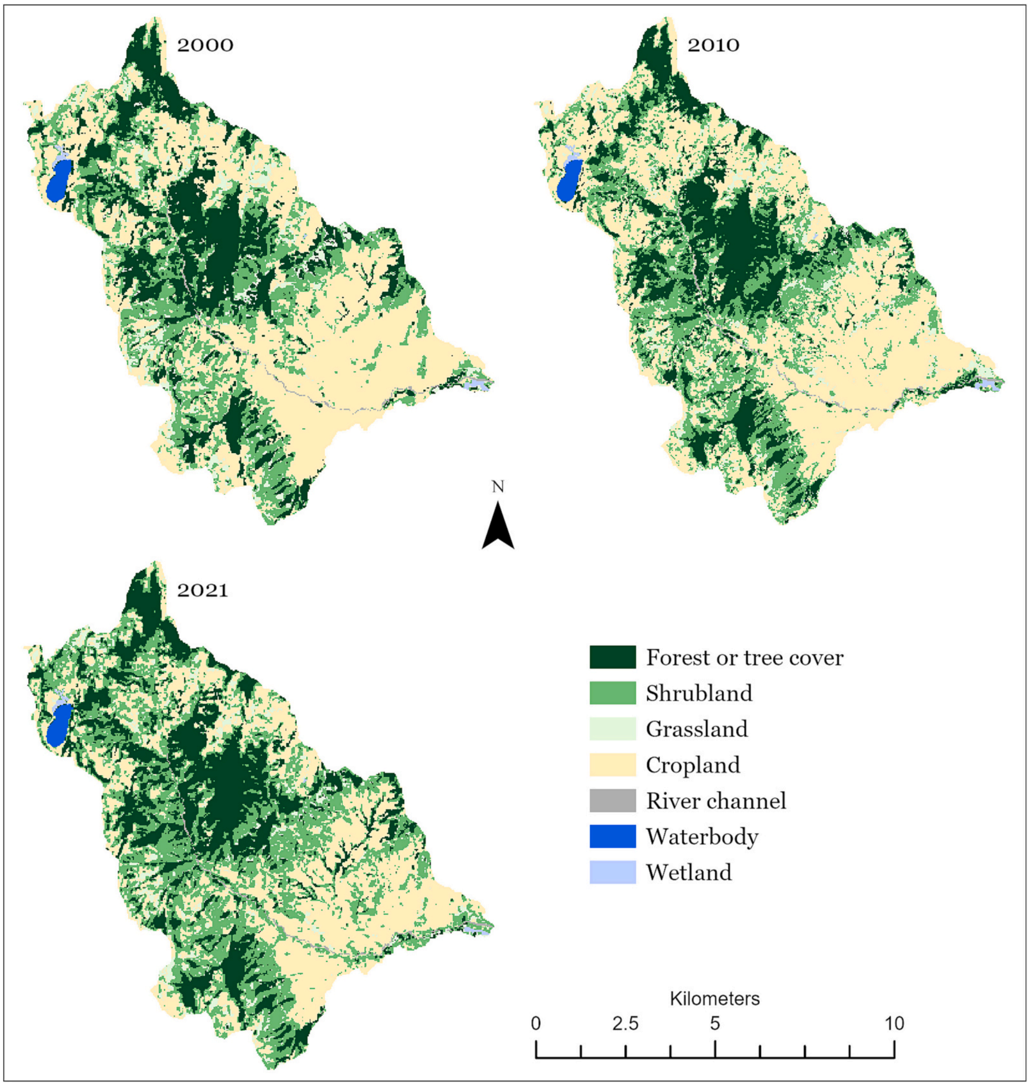


**Fig. 4.** LULC classes in Maybar-Felana watershed, Awash River basin, Ethiopia for the years 2000, 2010 and 2021.

**Picture 1.** Lake Maybar located in the upper landscape position of the Maybar-Felana watershed.

the upper slope landscape positions, both middle and foot slope landscape positions are characterized by fertile soils and better landholdings and livestock resources. The produces are used for both household consumption and market.

Furthermore, the key informants mentioned that the availability of resources varies with seasons. Natural resources such as water and forest are more available during the rainy season. However, wildlife resources are abundant during the dry season, which is attributed to the availability of food (i.e., harvesting season).

### 4.3. Status of natural resources and dynamics of LULC

The LULC analyses indicated that forest cover showed positive changes in both watersheds, while both forest and shrublands showed positive changes in Maybar-Felana watershed over a period of 21 years (Table 5). Unlike most of the results reported in other similar studies conducted in Ethiopia (e.g., Gashaw et al., 2018; Elias et al., 2019; Mesfin et al., 2020), croplands in both watersheds decreased, while forestlands increased over a period of 21 years (Table 5). Particularly, it was interesting that the positive changes in forest cover in both watersheds during 2010 and 2021 were higher than the changes during 2000–2010 and 2000–2021 (Table 5). This could be attributed to the effectiveness of multiple landscape restoration initiatives in the country including community-based watershed development activities, and sustainable landscape management and productivity safety net programs implemented since 1980s to restoring degraded landscapes. These activities and initiatives involved tree planting, restoration of degraded

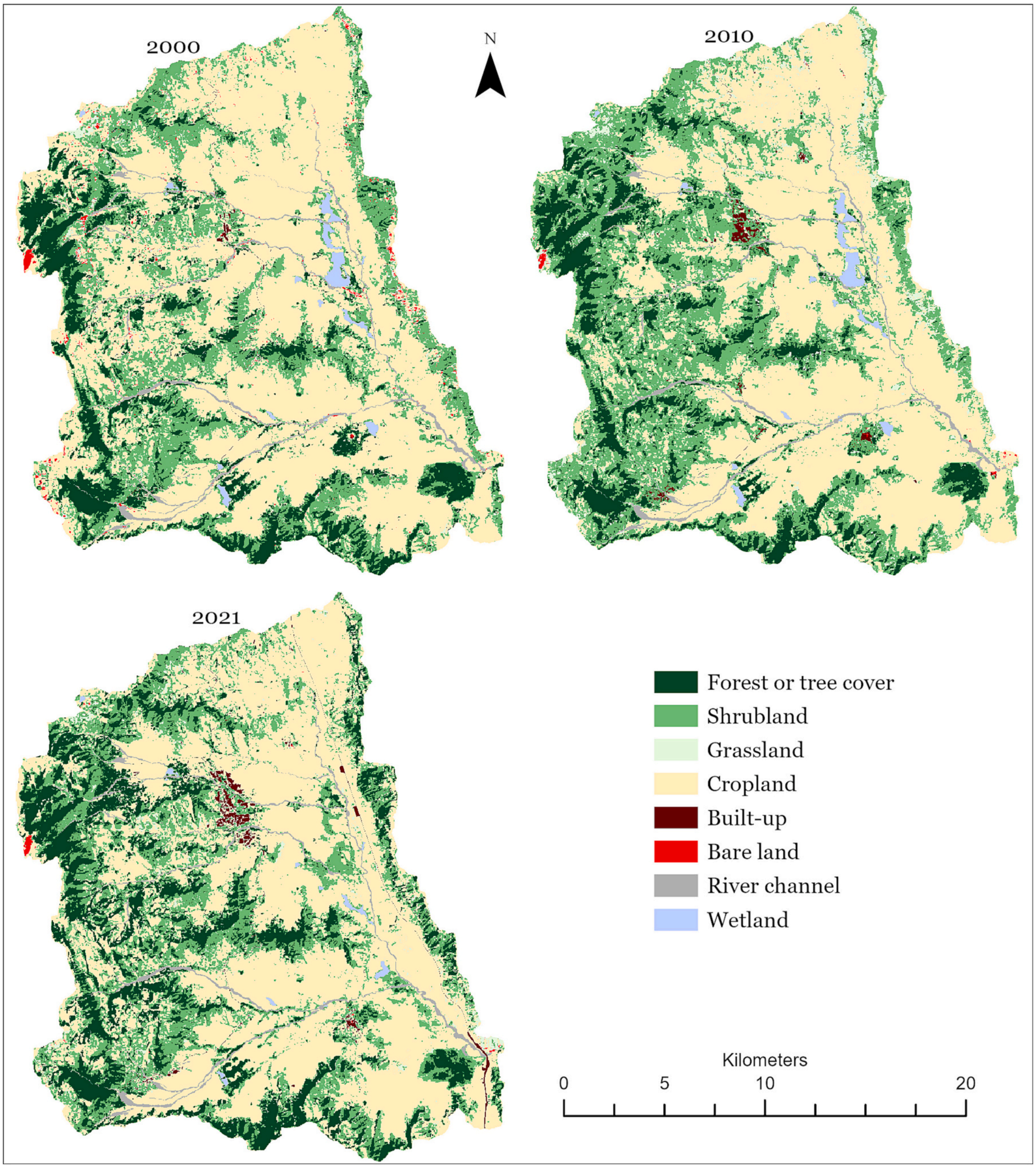


**Fig. 5.** LULC classes in Gelana watershed, Awash River basin, Ethiopia for the years 2000, 2010 and 2021.

landscapes through the establishment of exclosures and construction of diverse soil and water conservation measures that support the restoration of degraded landscapes.

The positive changes in forest and shrublands in the studied watersheds were also supported by key informants. One of the key informants in Gelana watershed elaborated this as:

> *"The establishment of exclosures in two sub-watersheds, Woficho and Fafum restored indigenous trees and shrubs and increased the vegetation cover in recent years. These two sub-watersheds are managed by the community watershed team, which is responsible for the use, management, and protection of the resources in the sub-watersheds. This arrangement supported the sustainable management of the protected areas".*

Both the local communities and the LULC analyses (Table 5) supported that grazing lands are diminishing, suggesting the need for expanding forage development in the watersheds to sustain the number and productivity of livestock. The key informants attributed the decrease in grazing lands to the government decision of allocating the grazing lands for investors involved in the production of onion, tomato, and mango.

We detected several trajectories of LULC changes in both watersheds (Table 6). The expansion of forestlands in the Maybar-Felana watershed over a period of 21 years, for example, has occurred at the expense of croplands (where 247 ha of croplands converted to forestlands), shrublands (242 ha) and grasslands (53.5 ha) (Table 6). The conversion of croplands to forestlands and shrublands could be related to abandoning the cultivation of steep slopes. This could also be attributed to the implementation of community-based watershed development activities in mountainous and steep slope areas involving afforestation/reforestation and establishment of exclosures. The conversion of shrublands to forestlands might be a sign of some of the restored areas

**Picture 2.** Landscape features of the learning watersheds: (a) upper slope landscape position of Maybar-Felana watershed, (b) Upper- and mid-slope landscape positions of Gelana watershed.

**Table 5**
Area extent and changes in major LULC classes in the study watersheds.

| LULC classes | Maybar – Felana learning watershed | | | | | | % Change in area cover | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2000 (Ha) | (%) | 2010 (Ha) | (%) | 2021 (Ha) | (%) | 2000–2010 | 2010–2021 | 2000–2021 |
| Forests | 1913 | 23.3 | 1801 | 21.9 | 2133 | 26.0 | −5.9 | 18.4 | 11.5 |
| Shrublands | 1913 | 23.3 | 2123 | 25.8 | 2699 | 32.9 | 11.0 | 27.1 | 41.1 |
| Grasslands | 476 | 5.8 | 373 | 4.5 | 359 | 4.4 | −21.6 | −3.8 | −24.6 |
| Croplands | 3803 | 46.3 | 3810 | 46.4 | 2916 | 35.5 | 0.2 | −23.5 | −23.3 |
| Waterbodies | 53 | 0.6 | 51 | 0.6 | 54 | 0.7 | −3.8 | 5.9 | 1.9 |
| River channel | 34 | 0.4 | 34 | 0.4 | 34 | 0.4 | 0.0 | 0.0 | 0.0 |
| Wetlands | 23 | 0.3 | 23 | 0.3 | 18 | 0.2 | 0.0 | −21.7 | −21.7 |
| Total | 8215 | 100 | 8215 | 100 | 8215 | 100 | | | |
| Gelana learning watershed | | | | | | | | | |
| Forests | 5715 | 12.6 | 5362 | 11.8 | 8143 | 17.9 | −6.2 | 51.9 | 42.5 |
| Shrublands | 10,289 | 22.6 | 13,409 | 29.5 | 10,066 | 22.2 | 30.3 | −24.9 | −2.2 |
| Grasslands | 570 | 1.3 | 1632 | 3.6 | 539 | 1.2 | 186.3 | −67.0 | −5.4 |
| Croplands | 27,270 | 60.0 | 23,588 | 51.9 | 25,422 | 56.0 | −13.5 | 7.8 | −6.8 |
| Built-up | 76 | 0.2 | 271 | 0.6 | 369 | 0.8 | 256.6 | 36.2 | 385.5 |
| Bare land | 382 | 0.8 | 38 | 0.1 | 43 | 0.1 | −90.1 | 13.2 | −88.7 |
| River channel | 712 | 1.6 | 712 | 1.6 | 712 | 1.6 | 0.0 | 0.0 | 0.0 |
| Wetlands | 416 | 0.9 | 416 | 0.9 | 134 | 0.3 | 0.0 | −67.8 | −67.8 |
| Total | 45,428 | 100.0 | 45,428 | 100.0 | 45,428 | 100.0 | | | |

Note: There were no waterbodies which were visible at the scale of classification in Gelana watershed. Instead, the river channels were digitized from Google earth image and masked during post classification analysis.

through the establishment of exclosures and enrichment plantations within exclosures reached to climax and being considered as forest. The expansion of shrublands in the Maybar-Felana watershed has occurred at the expense of croplands (850.5 ha), forestlands (277.5 ha) and grasslands (155.6 ha) (Table 6). The expansion of shrublands at the expense of forestlands suggests the degradation of natural forests and their conversion into secondary forests. This is consistent with the opinion of some of the key informants who indicated that there is still forest degradation in the studied watersheds.

The expansion of forestlands in the Gelana watershed has occurred at the expense of shrublands (2139 ha), croplands (1275 ha.) and grasslands (143 ha.) (Table 6). The expansion of forestlands at the expense of shrublands could be attributed to the effectiveness of community-based watershed development activities implemented in the last two decades. The expansion of built-up areas in Gelana watershed mainly occurred at the expense of croplands (227 ha), shrublands (52 ha) and forestlands (27 ha) (Table 6). The key informants also highlighted the expansion of built-up areas at the expense of their fertile and irrigable lands, which requires attention as it is taking productive lands. The results of the LULC analyses (Tables 6) and the qualitative study suggested that designing and implementing better forest and landscape restoration measures that consider both the human and environmental dimensions could help restore degraded landscapes and increase both the tangible economic benefits and ecosystem services.

### *4.4. The link between natural resources degradation and vulnerability of SSPs*

The results indicated that the respondents are aware of the link between natural resources degradation and vulnerability of SSPs as illustrated in the adopted world bank analytical framework (World Bank, 2021). In relation to the degradation of natural resources, the respondents described multiple indicators such as loss of soil fertility, increased gully formation, landslides, reduced forest cover, loss of biodiversity, and reduced multiple ecosystem services (Fig. 6). Furthermore, the respondents mentioned that their livelihood is vulnerable due to the degradation of natural resources. In line with this, the respondents elaborated multiple risks such as increased flood and drought incidents, scarcity of water, food insecurity, and increased internal displacement and conflicts over resource use (Fig. 6). Particularly, increased incidents of flooding in the watersheds (Fig. 6) were attributed to the degradation of wetlands, which had the potential to regulate floods. The LULC analyses also suggested the degradation of wetlands over the last 21 years (Table 5).

**Table 6**
Patterns of LULC change (i.e., “from–to” changes) in the studied watersheds.

Maybar-Felana learning watershed

| 2000–2021 | Forestlands | Shrublands | Grasslands | Croplands | Waterbodies | River channel | Wetlands | Loss 2021(ha) |
|---|---|---|---|---|---|---|---|---|
| Forestlands | | 277.5 | 16.1 | 27.8 | 1.1 | 0.0 | 0.3 | 322.7 |
| Shrublands | 241.9 | | 87.9 | 171.8 | 0.0 | 0.0 | 0.0 | 501.7 |
| Grasslands | 53.5 | 155.6 | | 122.8 | 0.0 | 0.0 | 0.8 | 332.6 |
| Croplands | 247.4 | 850.5 | 111.6 | | 0.8 | 0.0 | 0.0 | 1210.3 |
| Waterbodies | 0.1 | 0.3 | 0.0 | 0.1 | | 0.0 | 0.0 | 0.5 |
| River channel | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 | 0.0 |
| Wetlands | 0.0 | 4.1 | 0.1 | 1.1 | 0.0 | 0.0 | | 5.3 |
| Gain 2021(ha) | 542.9 | 1288.0 | 215.7 | 323.6 | 1.9 | 0.0 | 1.08 | |
| **Net changes** (ha) | **220.1** | **786.3** | **−116.91** | **−886.8** | **1.4** | **0.0** | **−4.2** | |

Gelana learning watershed

| 2000–2021 | Forestlands | Shrublands | Grasslands | Croplands | Built-up | Bare land | River channel | Wetlands | Loss 2021(ha) |
|---|---|---|---|---|---|---|---|---|---|
| Forestlands | | 807.5 | 3.9 | 352.0 | 26.7 | 0.1 | 0.0 | 0.0 | 1190.2 |
| Shrublands | 2139.0 | | 197.4 | 2290.3 | 52.1 | 0.7 | 0.0 | 0.0 | 4679.6 |
| Grasslands | 143.0 | 185.4 | | 147.0 | 2.9 | 0.7 | 0.0 | 0.0 | 479.0 |
| Croplands | 1274.9 | 3126.0 | 216.6 | | 226.9 | 9.9 | 0.0 | 0.0 | 4854.3 |
| Built-up | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 | 0.0 | 0.0 | 0.0 |
| Bare land | 22.6 | 121.5 | 26.1 | 176.2 | 3.8 | | 0.0 | 0.0 | 350.2 |
| River channel | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 0.0 | 0.0 |
| Wetlands | 47.9 | 223.5 | 2.5 | 40.0 | 0.0 | 0.0 | 0.0 | | 313.8 |
| Gain 2021(ha) | 3627.5 | 4463.8 | 446.5 | 3005.5 | 312.4 | 11.4 | 0.0 | 0.0 | |
| **Net changes** (ha) | **2437.3** | **−215.7** | **−32.5** | **−1848.9** | **312.4** | **−338.8** | **0.0** | **−313.8** | |

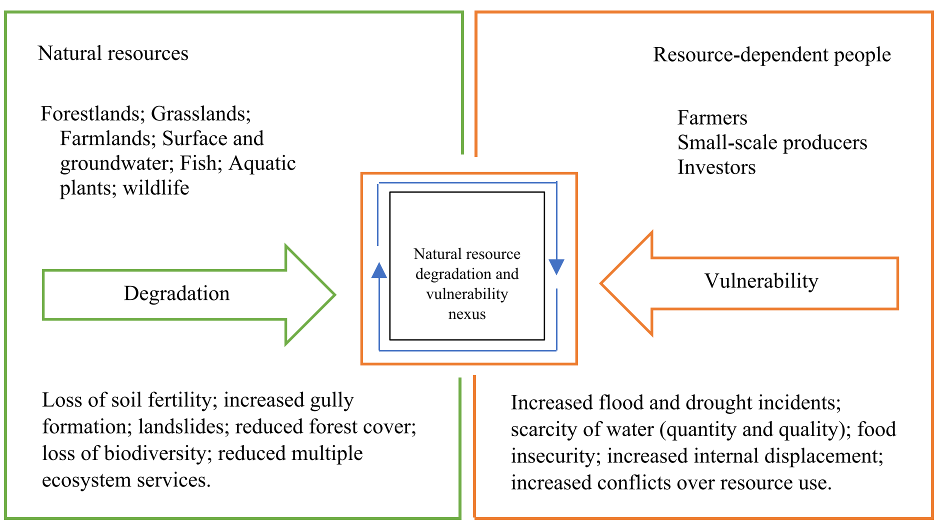


**Fig. 6.** The natural resource degradation and vulnerability nexus in the context of Awash River basin, Ethiopia.

Key informants suggested that multiple environmental, socio-economic, policy and rule enforcement and land use and management factors resulted in natural resource degradation and increased livelihood vulnerability (Table 7). For example, respondents mentioned that point (e.g., expansion of recession agriculture (Picture 3), use of unregulated agrochemicals) and non-point sources of pollution (e.g., runoff and sedimentation) deteriorated the quality of water resources and reduced water-related ecosystem services, leading to increased livelihood vulnerability. Respondents also mentioned that the clearing of trees and deforestation in the watersheds reduced benefits from forests and forest resources, increasing the vulnerability of poor rural communities. In line with this, studies (World Bank, 2021; Azimi et al., 2022) indicated that many of the world's poor people depend on natural resources for their well-being and that natural resources degradation is posing significant risks to resource-dependent communities.

The governance of natural resources in the watersheds is usually complex in that land degradation in the upstream areas of the watershed is also seen as an opportunity for some groups of the communities living in the downstream areas, which is related to the contrasting interests of the upstream and downstream communities (Table 7). This is mainly attributed to the increase in sand in downstream areas, creating fertile ground for sand mining. This, in turn, suggest that addressing such conflicting interests and power relations among the different groups of a community is crucial to reducing the degradation of natural resources and addressing the vulnerability of poor rural communities (Amanzi et al., 2021).

Furthermore, the management of natural resources for resilient communities and environment is constrained by the lack of commitment to enforcing rules and regulations by different levels of local administrative bodies. One of the key informants elaborated this as:

> *“When free riders are caught red-handed or in suspicion while cutting trees and encroaching into protected areas, the government authorities do not sanction as required. Instead, the authorities receive bribes and release the free riders. This has led to increased degradation of natural resources and vulnerability of SSPs”.*

**Table 7**
Drivers of natural resource degradation in the context of the study watersheds.

| Categories of drivers | | | |
|---|---|---|---|
| Environmental | Socio-economic | Policy and rule enforcement | Land use and land management |
| - Deforestation.<br>- Wetlands degradation.<br>- Overgrazing.<br>- Extractive farming practices.<br>- Soil acidity.<br>- Weather extremes. | - Inefficient irrigation practices.<br>- Increased demand for water.<br>- Reduction in grazing lands.<br>- Shortage of livestock feed.<br>- Population pressure.<br>- Poor livelihood diversification.<br>- Contrasting interests of the upstream and downstream communities.<br>- Preference of local communities to short-term economic benefits.<br>- Increased price of agricultural inputs.<br>- Expansion of recession agriculture. | - Lack of commitment to enforce rules.<br>- Poor collaboration.<br>- Illegal cutting of trees.<br>- Insecure land tenure. | - Land use conversions.<br>- Lack of buffer zone management.<br>- Inadequate plantation of indigenous tree.<br>- Urban expansion and illegal settlement. |

**Picture 3.** Recession agriculture close to Lake Maybar in the Maybar-Felana watershed.

### 4.5. Benefits and costs of LMP and implications to reducing vulnerability

Participants of FGDs representing men, women and mixed groups identified 62 benefits (or advantages) factors of nine LMP assessed in the two learning watersheds (Supplementary material 3). The multiple benefit factors identified by the participant of FGDs were diverse and covered both environmental (e.g., improves local microclimate, conserves soil moisture or water, improves/increases/sustain soil fertility, reduces runoff and soil erosion, restores vegetation), economic (e.g., increases wood product for multiple uses, increases income, increases the availability of livestock feed and crop production) and social (e.g., reduce the impact of drought, enables better movement of people and livestock, ensures food and nutrition security) categories (Fig. 7). All these benefits of LMP have positive implications to reducing the vulnerability of natural resource – dependent people (López et al., 2017).

It was detected that across all groups, the benefits of the assessed LMP were more related to the environmental and economic benefits (Fig. 7). This, in turn, suggests that the proper implementation of LMP in a landscape could improve ecosystems and associated ecosystem services, leading to resilient communities and environment (Bergamini et al., 2013). The respondents, however, also mentioned several environmental (e.g., causes water logging conditions, increases runoff and soil loss, increases soil salinity), economic (e.g., increases damage on crop and livestock by wildlife, reduces crop production, reduces farm or grazing lands, high labour and financial requirement), and social (e.g., causes conflicts among members of a community, causes waterborne diseases) costs of the assessed landscape management practices, suggesting improvements are needed to maximize benefits and built resilient communities and environment. Particularly, addressing the economic and social costs and sustaining LMP is key to address livelihood vulnerability.

Although the assessed LMP had some limitations, the results suggested that the benefits outweigh the costs for the assessed interventions, as the mean ratings of the importance values of benefits were higher than the values of costs (Fig. 8). Across all focus groups, the assessed LMP were evaluated as positive (Table 8). This, in turn, suggests that local communities had positive opinion on the contribution of LMP to restoring ecosystems and improving ecosystem services and thereby reducing livelihood vulnerability. Particularly, the respondents were keen to the role of LMP in reducing soil erosion, soil fertility degradation and vegetation restoration and in avoiding livelihood vulnerability through reducing flooding and impacts of drought, improving availability of resources and reducing the risk of food and water insecurities (Table 8).

The local communities considered both environmental and economic factors most compared to the social factors in their overall assessment of the LMP (Table 8). This suggests that generating short-term economic benefits is key to sustaining the LMP and associated tangible benefits and ecosystem services and reduce vulnerability of communities and environment. The participants of the FGDs further elaborated that hillside terrace is the most advantageous practice among the evaluated practices. The participants also mentioned that they consider soil and stone bunds as the most disadvantageous practice.

In both watersheds, key informants also indicated several positive impacts of landscape management practices, which have implications to reducing vulnerability. For example, 53% and 86% of the key informants in the Maybar-Felana and Gelana watersheds, respectively indicated that watershed-level management practices supported the restoration of indigenous tree and shrub species, reduced runoff and soil loss, and improved soil fertility and grazing land management. They attributed the improvement in soil fertility to both farm (e.g., use of compost and manure) and watershed (e.g., bunds) level landscape management practices. In relation to the improvement of grazing land management, local communities in both watersheds adopted cut and carry system and avoided free grazing in protected areas (e.g., exclosures) as well as adopted supplementary livestock feed like the use of crop residues and rearing few but productive livestock.

In addition, most (93%) of the key informants in both watersheds indicated that LMP contributed to extend dry season flow of surface water (e.g., rivers and streams) and enhanced the availability of water in the watershed. Also, access to shallow groundwater for homestead and livestock consumption increased over the last five years and local communities are accessing groundwater at shallow depth (e.g., not >3 m depth in Gelana). Further, the assessed LMP in the learning watersheds increased the number and discharge of springs. One of the key informants in Gelana watershed elaborated this as:

> *"The flow period of one spring in 06 kebele was extended throughout the year due to the implemented LMP".*

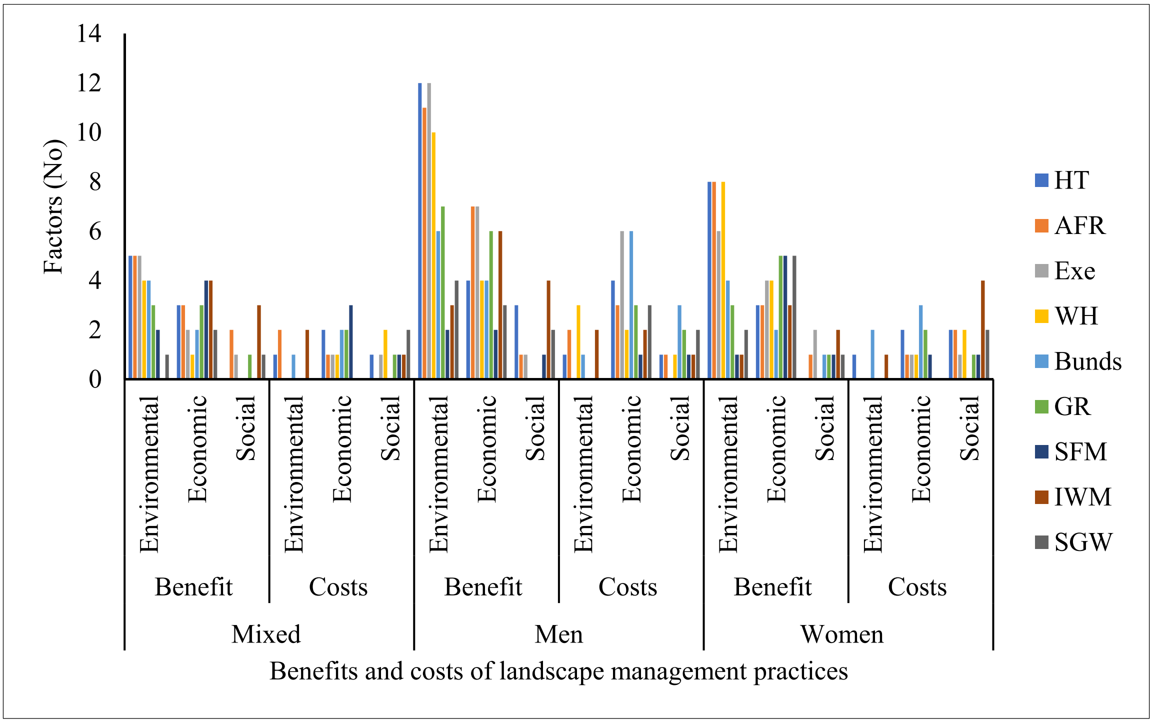


**Fig. 7.** The number of benefit and cost factors identified by the participants of FGDs. HT – refers to hillside terraces, AFR – afforestation/reforestation, Exe – exclosures, WH – water harvesting, GR – gully rehabilitation, SFM – soil fertility management, IWM – irrigation water management, SGW – shallow groundwater use and management.

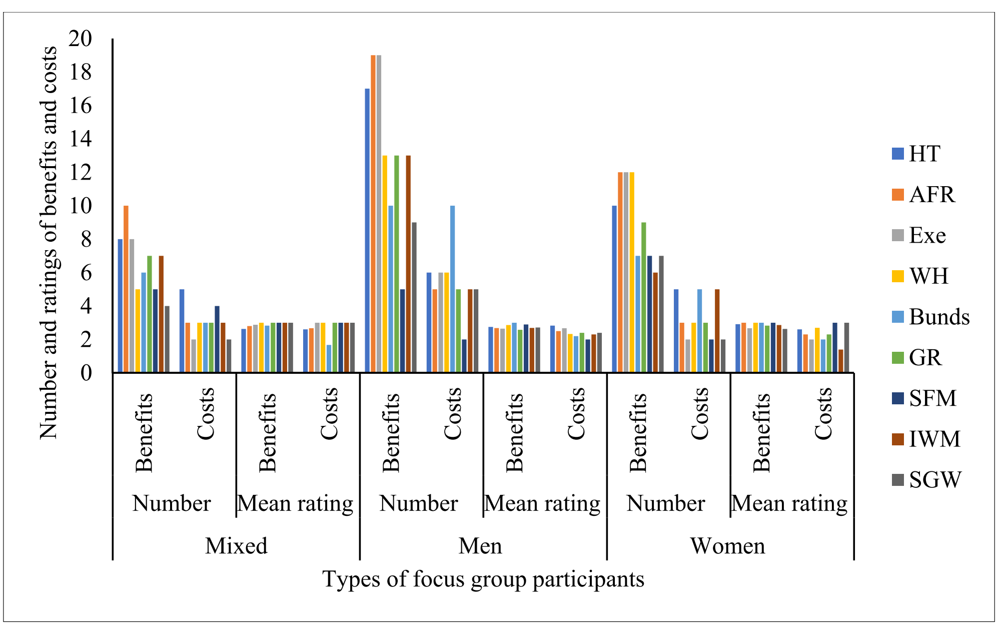


**Fig. 8.** The number and ratings of the importance of benefit and cost factors from the perspective of the local communities.

The key informants in Gelana watershed stressed that the contribution of LMP to reducing the degradation of land resources varied with landscape position, and that the practices are effective in middle slope areas compared to lower and upper catchment areas. This guides where to invest and implement diverse LMP to address the vulnerability of communities and environment. In general, the key informants pointed out that conflicts over natural resource use and weak law enforcement affecting the management practices and the associated ecosystem and economic benefits. Consistent with the opinion of key informant, Rüttinger et al. (2014) argued that natural resource management is closely linked to conflict management, prevention and resolution, and that conflict can undermine management institutions and lead to exploitation, environmental destruction and deteriorating livelihoods.

In contrast to most key informants, a few (20% in Maybar-Felana and 7% in Gelana) of the key informants indicated that the assessed LMP were not effective in reducing runoff and soil loss. These respondents argued that the planning, implementation and monitoring and evaluation of LMP in the learning watersheds were not carried out properly and

**Table 8**
Local communities' overall assessment of the assessed landscape management practices.

| Practices | Assessments | Contributions to improving natural resources | Contributions to reducing vulnerability |
|---|---|---|---|
| Mixed group | | | |
| HT | Positive | Improves in situ soil fertility and protecting natural and built resources in downstream areas. | Improve production; reduce food insecurity and loss of livelihood assets. |
| AFR | Positive | Reduces runoff, improves the local microclimate, increases wood products for multiple uses. | Reduce flood incidents; improve resource availability; moderate weather extremes. |
| Exclosures | Positive | Restores degraded vegetation; improves soil fertility and livestock feed. | Improves production, reduce food insecurity and resource availability. |
| WH | Positive | Mainly conserves water and increases availability in the dry season. | Improves resource availability. |
| Bunds | Positive | Mainly conserves water and increases the availability in the dry season. | Improves resource availability. |
| GR | Positive | Converts unproductive lands into productive lands. | Reduce food insecurity. |
| SFM | Positive | Helps to rehabilitate soils and increase production. | Reduce food insecurity and improves resource availability. |
| IWM | Positive | Helps to diversify livelihood, increase the frequency of production in a year, and increase income. | Builds assets, improves food security. |
| SGW | Positive | Increase the availability of water for multiple uses (homestead, livestock, agriculture, etc.). | Improves resource availability. |
| Men group | | | |
| HT | Positive | Conserves soil, reduces runoff, and enhances vegetation restoration. | Reduce incidents of flooding, improves resource availability. |
| AFR | Positive | Regulating microclimate, restores degraded landscapes and increase access to wood for multiple uses. | Moderate weather extremes, improves resource availability. |
| Exclosures | Positive | Restores degraded lands, reduces runoff, and creates job opportunities. | Improves food security, reduce flooding, builds livelihood assets. |
| WH | Positive | Conserves water reduces sedimentation and increases crop production. | Improves resource availability, reduce loss of assets, improves food security. |
| Bunds | Positive | Reduces soil erosion, improves soil fertility. | Reduce incidents of flooding, improves food security. |
| GR | Positive | Converts unproductive land into productive land, creates opportunities to develop livestock feed and high value crops. | Improves food security and resource availability. |
| SFM | Positive | Improves soil fertility, increases crop production. | Improves food security. |
| IWM | Positive | Increases income, support producing high values crops. | Build livelihood assets. |
| SGW | Positive | Increases the availability of water for multiple uses (homestead consumption, livestock, irrigation, etc.) | Improves resource availability. |
| Women group | | | |
| HT | Positive | Reduces runoff and conserves water. | Reduce flood incidents and improves resource availability. |
| AFR | Positive | Restores degraded lands and improves microclimate. | Improves resource availability and moderate weather extremes. |
| Exclosures | Positive | Restores native vegetation, conserves water and improves soil fertility. | Improves resource availability and food security. |
| WH | Positive | Conserves water and increases water availability in the dry season. | Improves resource availability. |
| Bunds | Positive | Helps to decrease soil erosion, improves soil fertility, and increase productivity. | Reduce flood incidents, improves food security. |
| GR | Positive | Reclaims gullies and decrease runoff. | Reduce flood incidents, improves resource availability. |
| SFM | Positive | Improves soil fertility, increase crop production, reduce the costs for inorganic fertilizers. | Improves food security, builds livelihood assets. |
| IWM | Positive | Diversify livelihood, increase crop production. | Builds assets, improves food security. |
| SGW | Positive | Improves the availability of water for multiple uses (homestead, livestock, agriculture, etc.). | Improves resource availability. |

that the implemented practices were not effective due to the practice of free grazing. This suggests that proper planning, implementation and monitoring and evaluation of interventions and avoiding free grazing are key to ensuring the effectiveness of interventions to improving tangible economic benefits and ecosystem services and thereby to sustainably reduce vulnerability.

In addition, few (26% in Maybar-Felana and 7% in Gelana) of the respondents indicated that the improvement in soil fertility due to the implementation of LMP is very low due to limited farm level interventions and loss of inorganic fertilizer by water erosion. Further, few (7%) respondents argue that the improvement in water availability such as improved dry season flow and the number and discharge of springs is more related to the increased availability of rainfall than the implemented LMP. These respondents substantiate their argument by explaining the reductions in river flows, particularly between April and June with time. In relation to the increase in rainfall, 93% of the key informants in the Maybar-Felana watershed mentioned that they are observing an improvement in the onset and cession of rainfall and that the area is receiving better rainfall for the last five to ten years. Few (7%) of the respondents in Maybar-Felana and all respondents in the Gelana watershed indicated that they observed climate variability affecting the onset and cession of both the summer and short rainy seasons negatively.

Like participants of FGDs, most (96%) of the key informants mentioned that LMP supported to improving crop yield. In addition, they elaborated that the yield of major crops increased up to 40–50% in recent years. Furthermore, the local communities can diversify agricultural crops and are producing staple food, fruits and vegetables. Consistent with the participants of FGDs, the key informants mentioned that the irrigation practices also supported to produce two to three times a year, resulting in increased income. Such changes could partly be attributed to the implemented LMP, and particularly associated with the improvement in water use efficiency (e.g., use of lined canals) and improved farmers' capacity in purchasing agricultural inputs such as inorganic fertilizers. Also, the productivity of livestock was enhanced due to the adoption of productive livestock breeds and increased availability of feed from exclosures and biomass from irrigated agriculture.

## 5. Conclusions

This study was conducted to assess the links between natural resource degradation and the vulnerability of resource-dependent people and investigate local communities opinion on the benefits and costs of landscape restoration measures and implications to address livelihood vulnerability. The study gathered and analyzed data through KII, FGDs and GIS and remote sensing techniques. The results suggested that the proper implementation of LMP in a landscape could improve natural resources and associated ecosystem services and could contribute to reducing livelihood vulnerability through reducing incidents of weather extremes such as flood and drought, improving food and water security, enhancing resource availability, and building livelihood assets. To maximize and sustain the contributions of LMP to reducing the vulnerability of SSPs, we suggested that (a) LMP should be diverse and include forest and landscape restoration measures, livestock feed development, and crop-based and soil-based amendments, (b) the planning and implementation of LMP should consider balancing the short-term economic benefits of LMP with the long-term environmental benefits, and (c) using multiple methods including GIS and remote sensing techniques supports to better assess the status, availability and spatial distribution of natural resources.

## Authors contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgement

This research study was undertaken as part of the prioritization of climate-smart water management practices project, funded by Bill & Melinda Gates Foundation, investment ID - INV-029027.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2023.100237.

## References


Alobo Loison, S., 2015. Rural livelihood diversification in sub-Saharan Africa: a literature review. J. Dev. Stud. 51 (9), 1125–1138.

Amanzi, N.S., Mbeyale, G.E., Lusambo, L.P., 2021. Power relations between upstream and downstream common Pool resource users: winners and losers in the Uluguru Mountains, Morogoro Tanzania. Tanzania J. For. Nat. Conserv. 90 (3), 156–166.

Asfaw, A., Bantider, A., Simane, B., Hassen, A., 2021. Smallholder farmers' livelihood vulnerability to climate change-induced hazards: agroecology-based comparative analysis in northcentral Ethiopia (Woleka Sub-basin). Helion 7, 4.

Azimi, M., Sharifian, A., Riazinia, V., Arzani, H., Abbaspour, K.C., 2022. Pastoral community's vulnerability under extreme floodings accelerated by rangeland degradation among Turkmen transhumant, Northern Iran. J. Flood Risk Manag. 15 (4), e12842.

Babanawo, D., Mattah, P.A.D., Agblorti, S.K., Aheto, D.W., 2023. Perspectives on factors that influence local communities' vulnerability to coastal floods in Ketu south municipality of Ghana. Int. J. Disast. Risk Reduct. 90, 103646.

Bergamini, N., Blasiak, R., Eyzaguirre, P.B., Ichikawa, K., Mijatovic, D., Nakao, F., Subramanian, S.M., 2013. Indicators of Resilience in Socio-Ecological Production Landscapes (SEPLs). United Nations University Institute of Advanced Studies (UNU-IAS).

Congalton, R.G., Green, K., 2019. Assessing the Accuracy of Remotely Sensed Data: Principles and Practices. CRC Press.

Cotula, L., 2002. Improving Access to Natural Resources for the Rural Poor: The Experience of FAO and of Other Key Organizations from a Sustainable Livelihoods Perspective. FAO, LSP WP, p. 2.

Derbile, E.K., Chirawurah, D., Naab, F.X., 2022. Vulnerability of smallholder agriculture to environmental change in North-Western Ghana and implications for development planning. Clim. Dev. 14 (1), 39–51.

Dey, N.N., Al Rakib, A., Kafy, A.A., Raikwar, V., 2021. Geospatial modelling of changes in land use/land cover dynamics using multi-layer perceptron Markov chain model in Rajshahi City, Bangladesh. Environ. Challeng. 4, 100148.

Dongdong, Y., Xi, Y., Weihong, S., 2022. How do ecological vulnerability and disaster shocks affect livelihood resilience building of farmers and herdsmen: an empirical study based on CNMASS data. Front. Environ. Sci. 10, 998527.

Dumenu, W.K., Takam Tiamgne, X., 2020. Social vulnerability of smallholder farmers to climate change in Zambia: the applicability of social vulnerability index. SN Appl. Sci. 2, 1–16.

Egigu, M.B., 2022. Hydro-Sediment Responses to Management Options under Current and Future Climate Change Scenarios in Maybar Sub-Watershed. South Wollo Zone.

Elias, E., Seifu, W., Tesfaye, B., Girmay, W., 2019. Impact of land use/cover changes on lake ecosystem of Ethiopia central rift valley. Cogent Food Agric. 5 (1), 1595876.

Erbaugh, J.T., Oldekop, J.A., 2018. Forest landscape restoration for livelihoods and well-being. Curr. Opin. Environ. Sustain. 32, 76–83.

Fekadu, A., Soromessa, T., Warkineh Dullo, B., 2021. Role of forest provisioning services to local livelihoods: based on relative forest income (RFI) approach in Southwest Ethiopia coffee forest. Environ. Syst. Res. 10, 1–15.

Gashaw, T., Tulu, T., Argaw, M., Worqlul, A.W., Tolessa, T., Kindu, M., 2018. Estimating the impacts of land use/land cover changes on ecosystem service values: the case of the Andassa watershed in the upper Blue Nile basin of Ethiopia. Ecosyst. Serv. 31, 219–228.

Gill, P., Stewart, K., Treasure, E., Chadwick, B., 2008. Methods of data collection in qualitative research: interviews and focus groups. Br. Dent. J. 204 (6), 291–295.

Girma, R., Fürst, C., Moges, A., 2022. Land use land cover change modeling by integrating artificial neural network with cellular automata-Markov chain model in Gidabo river basin, main Ethiopian rift. Environ. Challeng. 6, 100419.

Harrington, L.J., Frame, D.J., Fischer, E.M., Hawkins, E., Joshi, M., Jones, C.D., 2016. Poorest countries experience earlier anthropogenic emergence of daily temperature extremes. Environ. Res. Lett. 11 (5), 055007.

Hurni, H., Berhe, W.A., Chadhokar, P., Daniel, D., Gete, Z., Grunder, M., Kassaye, G., 2016. Soil and Water Conservation in Ethiopia: Guidelines for Development Agents. Second revised edition. Centre for Development and Environment (CDE), University of Bern, with Bern Open Publishing (BOP), Bern, Switzerland, p. 134.

IFAD (International Fund for Agricultural Development), 2015. IFAD Annual Report 2015. IFAD, Rome. https://www.ifad.org/en/web/knowledge/publication/asset/392180.

Jensen, J., 2005. Thematic Map Accuracy Assessment in Introductory Digital Image Processing– A Remote Sensing Perspective, 3rd ed. Prentice Hall, USA, pp. 495–515.

Jeong, S., Yoon, D.K., 2018. Examining vulnerability factors to natural disasters with a spatial autoregressive model: the case of South Korea. Sustainability 10 (5), 1651.

Kassie, B.T., Rötter, R.P., Hengsdijk, H., Asseng, S., van Ittersum, M.K., Kahiluoto, H., van Keulen, H., 2014. Climate variability and change in the central Rift Valley of Ethiopia: challenges for rainfed crop production. J. Agric. Sci. 152 (1), 58–74.

Lange, G.M., Wodon, Q., Carey, K. (Eds.), 2018. The Changing Wealth of Nations 2018: Building a Sustainable Future. World Bank Publications.

Lillesand, T.M., Kiefer, R.W., Chipman, J.W., 2004. Remote Sensing and Image Interpretation. (I. John Wiley & Sons, Ed.) (Fifth, Vol. 53). UG I GGS Information Services, United States of America.

López, D.R., Cavallero, L., Easdale, M.H., Carranza, C.H., Ledesma, M., Peri, P.L., 2017. Resilience management at the landscape level: An approach to tackling social-ecological vulnerability of agroforestry systems. In: Integrating Landscapes: Agroforestry for Biodiversity Conservation and Food Sovereignty, pp. 127–148.

Lottering, S.J., Mafongoya, P., Lottering, R.T., 2021. Assessing the social vulnerability of small-scale farmer's to drought in uMsinga, KwaZulu-Natal. Int. J. Disast. Risk Reduct. 65, 102568.

Maru, H., Haileslassie, A., Zeleke, T., 2023. Impacts of small-scale irrigation on farmers' livelihood: evidence from the drought prone areas of upper awash sub-basin, Ethiopia. Heliyon 9 (5).

Mashizha, T.M., 2019. Building adaptive capacity: reducing the climate vulnerability of smallholder farmers in Zimbabwe. Business Strategy Developm. 2 (3), 166–172.

Maxwell, A.E., Warner, T.A., Fang, F., 2018. Implementation of machine-learning classification in remote sensing: an applied review. Int. J. Remote Sens. 39 (9), 2784–2817.

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. In proceedings of the. In: 8th Conference on Applied Climatology, 17, 22, pp. 179–183.

Mekonen, A.A., Berlie, A.B., 2021. Rural households' livelihood vulnerability to climate variability and extremes: a livelihood zone-based approach in the northeastern highlands of Ethiopia. Ecol. Process. 10, 1–23.
Mesfin, D., Simane, B., Belay, A., Recha, J.W., Taddese, H., 2020. Woodland cover change in the central Rift Valley of Ethiopia. Forests 11 (9), 916.
Miheretu, B.A., Yimer, A.A., 2017. Land use/land cover changes and their environmental implications in the Gelana sub-watershed of Northern highlands of Ethiopia. Environ. Syst. Res. 6, 7. https://doi.org/10.1186/s40068-017-0084-7.
Mitiku, A.B., Meresa, G.A., Mulu, T., Woldemichael, A.T., 2023. Examining the impacts of climate variabilities and land use change on hydrological responses of Awash River basin, Ethiopia. HydroResearch 6, 16–28.
Nchanji, Y.K., Levang, P., Jalonen, R., 2017. Learning to select and apply qualitative and participatory methods in natural resource management research: self-critical assessment of research in Cameroon. For. Trees Livelihoods 26 (1), 47–64.
Robledo, C., Clot, N., Hammill, A., Riché, B., 2012. The role of forest ecosystems in community-based coping strategies to climate hazards: three examples from rural areas in Africa. Forest Policy Econ. 24, 20–28.
Rüttinger, L., Janßen, A., Knupp, C., Griestop, L., 2014. From Conflict to Collaboration in Natural Resource Management: A Handbook and Toolkit for Practitioners Working in Aquatic Resource Systems. Manual. Collaborating for Resilience.
Sarkar, S., Padaria, R.N., Bhowmik, A., 2021. Understanding the socio-economic vulnerability of farmers towards climate change in the himalayan ecosystem of India. Indian J. Extens. Educ. 57 (2), 15–27.
Shukla, R., Gleixner, S., Yalew, A.W., Schauberger, B., Sietz, D., Gornott, C., 2021. Dynamic vulnerability of smallholder agricultural systems in the face of climate change for Ethiopia. Environ. Res. Lett. 16 (4), 044007.
Sneessens, I., Sauvée, L., Randrianasolo-Rakotobe, H., Ingrand, S., 2019. A framework to assess the economic vulnerability of farming systems: application to mixed crop-livestock systems. Agric. Syst. 176, 102658.
Van De Kerchove, R., Zanaga, D., Xu, P., Tsendbazar, N., Lesiv, M., 2022. Product User Manual V 2.0.
Wainaina, P., Minang, P.A., Gituku, E., Duguma, L., 2020. Cost-benefit analysis of landscape restoration: a stocktake. Land 9 (11), 465.
Wassie, S.B., 2020. Natural resource degradation tendencies in Ethiopia: a review. Environ. Syst. Res. 9 (1), 1–29.
Williams, P.A., Crespo, O., Abu, M., Simpson, N.P., 2018. A systematic review of how vulnerability of smallholder agricultural systems to changing climate is assessed in Africa. Environ. Res. Lett. 13 (10), 103004.
World Bank, 2018. Poverty and Shared Prosperity 2018: Piecing Together the Poverty Puzzle. World Bank, Washington, DC.
World Bank, 2021. The Natural Resource Degradation and Vulnerability Nexus: An Evaluation of the World Bank's Support for Sustainable and Inclusive Natural Resource Management (2009–19). Independent Evaluation Group. World Bank, Washington, DC.
Zhai, P., Zhou, B., Chen, Y., 2018. A review of climate change attribution studies. J. Meteorol. Res. 32 (5), 671–692.