frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 27 June 2024
DOI 10.3389/fenvs.2024.1386026

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OPEN ACCESS

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RECEIVED 14 February 2024
ACCEPTED 30 April 2024
PUBLISHED 27 June 2024

CITATION
Haileslassie A, Taye MT, Diyessa M and Mekuria W (2024), Land use and land cover changes and their effect on ecosystem service values in the Bale Ecoregion, southeastern Ethiopia.
Front. Environ. Sci. 12:1386026.
doi: 10.3389/fenvs.2024.1386026

Land use and land cover changes and their effect on ecosystem service values in the Bale Ecoregion, southeastern Ethiopia

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The Bale Ecoregion (BER) is known for its global importance in biodiversity and as a water tower for East African drylands. Land use and land covers (LULC) have been changing for decades, affecting forest ecosystem service values (ESVs), but available information is limited. The present study addresses these gaps by using contrasting watersheds representing the highland, midland, and lowland agroecologies in the BER. LULC classifications were performed using GIS and remote sensing tools. Multisite imagery data (using Landsat image resolution 30 m × 30 m) were generated for four observation periods: 1992, 2002, 2012, and 2022. A recently updated global ESV coefficient and the value transfer valuation method were applied to estimate the changes in ESVs related to LULC changes. The result demonstrates that between 1992 and 2022, forest land has decreased by 3%, 63%, and 22% in the highland, midland, and lowland areas, respectively. Different degrees of loss of ESVs were observed across the study periods and LULC. Of the 21 specific ESVs investigated, the highest annual losses were recorded for water ecosystem services both in the midland and lowland landscape positions. Increased ESVs for cultivated land could not offset losses in food ESVs at the scale of agroecology. Significant impacts of LULC changes on specific ecosystem services, such as water, and changes in natural connectivity between the highland and lowland areas were observed. The result suggests that stakeholders need to co-plan and manage the BER. This evidence provides a scientific underpinning for understanding the connection between LULC change and ESVs and supports informed policy decisions.

KEYWORDS

landscape, water resources, deforestation, East Africa, Africa

1 Introduction

Land use and land cover (LULC) change across scales is gaining increasing attention (Spruce et al., 2020). Land use refers to the main functional role (cropland, coffee agroforestry, and grazing land for livestock production) of land. Land cover denotes its natural/manmade physical attributes (e.g., forest and grassland) (Nanda et al., 2014). Change refers to the conversion/alteration of its uses/attributes due to human intervention (Gashaw et al., 2018a; Abdul Athick and Hankar, 2019). The major conversion observed within Sub-Saharan countries is from forests, shrubs and grasslands, and alpine vegetation to cropland (Nanda et al., 2014; Regasa, et al., 2021). For instance, Foley et al. (2011) also noted that approximately 40% of the earth's land surface is in agricultural use. Godfray et al.

(2010) reported that to meet the soaring global food demand, agricultural production must increase by 70%–100% by 2050. This means that, with the current trend, associated LULC changes will place substantial pressure on ecosystem service values (ESVs) (Foley et al., 2011).

Land use and land cover form one of the important structures of a landscape ecosystem (Tolessa et al., 2017). Landscape structure and functions are highly interconnected. The landscape structure shapes several ecosystem functions (Debie and Awoke, 2023), including provisioning (such as the production of food and water), regulating (control of climate and disease), supporting (nutrient cycles and oxygen production), and cultural (spiritual and recreational benefits) (Tolessa et al., 2017; Haileslassie et al., 2020; Mekuria et al., 2021; Mengist et al., 2022). The degree of soil degradation, runoff, carbon emissions, and decreasing productivity (examples of ESVs) depends on LULC. In this regard, Haileslassie et al. (2020) suggested that land use and land cover (e.g., cultivated, forest lands, soil and water conservation, and water harvesting) are secondary landscape structures.

Hailemariam et al. (2016), Haileslassie et al. (2020), and Regasa et al. (2021) reported that there are substantial LULC changes in Ethiopia. However, the magnitude with which these changes impact the state of the ecosystem and its services in Sub-Saharan Africa (SSA) is not documented sufficiently or limited to a few ESVs (Debie, and Awoke, 2023).

The deforestation rate in Africa is three times greater than the global figure (ADB, 2011). Growing population pressure coupled with reduced agricultural land productivity exacerbates the land cover conversion rate (Bilsborrow, 1992). Unsustainable agricultural practices are one of the chief causes of severe land degradation, leading to a vicious circle of poverty through the reduced availability of natural goods and services of ecosystems (Olsson et al., 2005; UNEP, 2012; Gashaw et al., 2018b). Consequently, poor farmers are abandoning their existing degraded cropland and are extending cultivation to other land use types, and, in turn, their livelihoods are highly vulnerable to environmental and climate change shocks (Scherr, 2000; UNEP, 2012).

Ethiopia's forest land cover, as indicated in EFAP (1994), has plummeted from 35%–40% to 2.7% from the outset of the 19th century to the early 1990s. Recent estimates by the Global Forest Watch indicated that in 2010, Ethiopia had 12.4 million ha of tree cover, extending over 11% of its land area. In 2022, it lost 19.9 kha of tree cover, equivalent to 17.7 Mt of CO_2 emissions. Despite changing forest cover, major types of natural vegetation still widely persist in Ethiopia, ranging from thorny bushes to tropical forests and mountain vegetation (Othow et al., 2017). Currently, there are efforts in Ethiopia, such as the Reduction of Emission from Deforestation and Degradation (REDD+), the country's voluntary commitment to the Bonn Challenge, and the "green legacy"— the project to plant four billion trees to restore forest land (Melnikova et al., 2007; Kibret et al., 2020).

In the mountainous part of the Bale Ecoregion (BER), as reported by Hailemariam et al. (2016), forest cover reduced by 3.28% during 1985–2015, whereas farmlands expanded by 7.76%. This rate of deforestation, which aggregates the different agroecologies (highland, midland, and lowland), is much lower than the deforestation rate reported by many studies conducted in Ethiopia. For example, since the 1950s, in the Lake Tana sub-basin watersheds, farmlands and settlements expanded by 57.7%; shrubs, forests, and grasslands decreased by 18.6, 83.8, and 53.5%, respectively (Hassen and Assen, 2018). In the Gog district of the Gambella regional state of Ethiopia, the annual deforestation rate since 2002 was recorded to be 1.45% per annum (Othow et al., 2017). In the Bilate Alaba sub-watershed of southern Ethiopia, cultivated land has expanded by 67.38% over the past 45 years (Godebo et al., 2018). In the Chirokella micro-watershed of southeastern Ethiopia, the dense forest cover decreased by over 80% (Assen and Nigussie, 2009). The doubt remains as to the magnitude of losses of the ESVs under such LULC changes and the variation of changes among different agroecologies and policy implications.

While many studies conducted in Ethiopia have often focused on a particular aspect of deforestation, they lack illustrating ESV changes in the context of the driver–pressure–state–impact–response (DPSIR) framework (Kewessa et al., 2019) to provide policy recommendations. Moreover, there are very few comprehensive studies on ESVs across ecoregions under different historical time series, and existing literature often does not account for the connectivity of sub-regions (highland, midland, and lowland) through ecosystem service flows (Tolessa et al., 2017). In this regard, Luedeling et al. (2011) reported that, regionally, there are gaps in the evidence on ESV estimation in the highly heterogeneous landscapes of the East African highland.

The Bale Ecoregion is well-known for its global importance in biodiversity and its numerous ecosystem services—it serves as the water tower for approximately 12 million people in the drier part of East Africa, as over 40 streams drain to the southern drainage system of Oromia and Somali regional states of Ethiopia, the Republic of Somalia, and North Kenya (FZS, 2007). Negative pressures impacting natural resources are a consequence of the increasing demand for food and biomass-based household energy in the BER (Bilsborrow, 1992; FARM Africa, 2008; Green et al., 2022). The sharp upsurge in demand for food can be met either by extensification or intensification. Of these, extensification offers inadequate options in the BER due to limited land and legal restrictions on deforestation. Under such circumstances, as suggested by Abate (2011), detecting LULC change and its implication on ESVs in the context of the driver–pressure–state–impact–response framework is important for understanding the context and planning sustainable intensification pathways to attain the food security SDG in SSA (Haileslassie et al., 2022; Kremen, 2015; Phalan et al., 2011). Thus, the objectives of this study were i) to provide empirical evidence on the LULC conversion magnitude, rate, and pattern of change across time and space for the three study watersheds in the BER and ii) to estimate the LULC conversion effect on ESVs and synthesize its implications for sustainable management.

2 Methodology

2.1 Study area description

The BER is found in the Oromia region[1], Bale, and West Arsi zones in Ethiopia and consists of 16 woredas. It covers a total land area of approximately 38,036 km^2 (Table 1). It spans across an

1 Region, zone, and Woreda are first-, second-· and third-level administrative units in Ethiopia, respectively.

TABLE 1 Agroecological classification of land areas in the Bale Ecoregion based on the classes of Hurni (1998).

		Elevation (masl)	Area (m^2)	Percent	
Highland	*Wurch*	>3,200	211,749.37	5.56%	Main crop: barley Vegetation: degraded Erica Soil: mainly black, poorly drained
	Dega	2,300–3,200	800,995.25	21.05%	Main crops: barley, wheat, and pulses Vegetation: *Juniperus*, *Hagenia*, coffee, and *Podocarpus* Soil: mainly brown clay
Midland	*Weyna Dega*	1,500–2,300	837,431.79	22.01%	Main crops: wheat, teff, rarely maize, niger seed, and coffee depending on the level of moisture Vegetation: *Cordia* and *Acacia major* Soil: mainly well drained, deeply weathered red brown
Lowland	*Kola*	500–1,500	1,921,571.17	50.49%	Main crops: sorghum, teff, and millet Vegetation: *Cordia*, *Ficus*, *and Acacia*. Soil: sandy soil
	Bereha	<500	33,740.76	0.89%	Vegetation: *Acacia* bushes Soil: yellow sandy soil
		Total	3,805,488.34	100	

altitude of 272 m above sea level (masl) in the south to 4,377 masl in the north, which influences the diversity of climate in the BER. Based on the agroecological (traditional altitude belt) system classification offered by Hurni (1998), Ethiopia's altitude range and rainfall are used as proxy indicators to define agroecological zones, i.e., *Wurch* and *Dega* (highland), *Woyna-Dega* (midland), *Kolla* (lowland), and *Bereha* (dry lowland)

The BER is the source of about 40 springs and discharges to two international river basins—Genale and Wabi Shebelle rivers—flowing to Somalia and Kenya. As a result, the BER is known as a water tower in the dry lowlands (see Table 1).

There are five agroecological zones in the BER. *Kola* is the drier and has the largest agroecology (covering 50.49% of the BER), followed by -*Wona Dega*, *Dega*, *Wurch*, *and Bereha* in that order of area extent (Table 1). In the BER, in *Wona-Dega* and *Dega* agroecology, a mixed crop–livestock system is practiced, while in *Kola*, pastoral and agropastoral systems dominate. *Bereha and Wurch* have temperature and moisture limitations and, thus, are of limited use for agriculture (Hurni, 1998).

This study focuses on three watersheds: *Bekaye*, *Hawao*, *and Hora Soba*, representing the lowland, midland, and highland agroecological zones, respectively (Figure 1). The sizes of the *Bekaye*, *Hawao*, *and Hora Soba* watersheds are 502, 293, and 1,048 ha, respectively. These watersheds were selected as model watersheds for longer-term landscape management intervention, and sediment and water discharge measurements are ongoing following soil and water conservation interventions by a project called "Supporting the Horn of Africa's Resilience" (SHARE BER).

2.2 Analytical framework

Figure 2 depicts the overall analytical framework applied in this study. It is designed to facilitate the demonstration of technical data generation of LULC linked to ESV changes by embedding the DPSIR framework (Lalande et al., 2014).

DPSIR (driver, pressure, state, impact, and response model of intervention) is a causal framework used to describe the interactions between society and the environment. DPSIR can be applied to diverse circumstances, depending on the outcome targeted (Lalande et al., 2014). Since this study focuses on quantifying LULC changes and their processes and how these changes impact ecosystem service values, we applied DPSIR. The application of DPSIR structures the conceptual understanding of the local community on land use and land cover and ESV change processes (Bell, 2012; Rebecca et al., 2016; Maxim et al., 2009). DPSIR can be constructed before focus group discussion (FGD) and key informant interview (KII) based on the literature and can be used to guide FGD and KII, or it can be constructed post-KII and FGD and empirical findings to better demonstrate and discuss the result and communicate it to policymakers.

Correspondingly, the framework involves data sourcing, elaborating driver–pressure–state–impact, and synthesizing responses (Figure 2). For data sourcing, satellite imagery (Landsat 30 × 30 m), desk study, and field observation on the cause and effects of deforestation were major ingredients (Figure 2). The middle section of the framework presents a discussion on LULC and ESV changes in the context of DPSIR, as shown in Figure 6. Land use and land cover change and ESVs were sequentially studied here (Spruce et al., 2020). The last part is where current national and local responses were illustrated and knowledge for future alternative land use was synthesized. Details are provided in the next section.

2.3 Data type and sources

Following the methods described by Huang et al. (2008), two types of remote sensing images, namely, Landsat and SPOT 5 imageries, were used for LULC change analyses. Georeferenced and radiometrically corrected SPOT 5 imageries were obtained from the Ethiopian Geospatial Institute (EGI) for

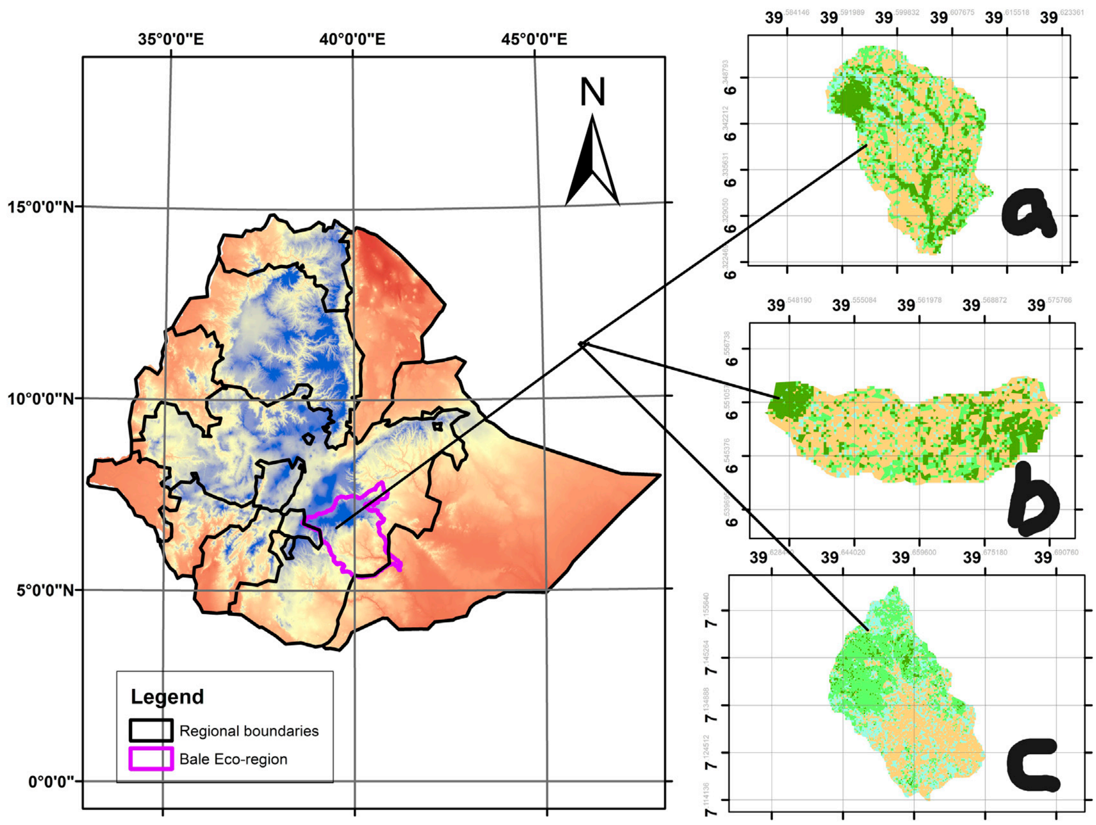

FIGURE 1
Location of Bale Eco-Region (BER) in Ethiopia and study watersheds in the highland (**(A)**-*Hora Soba*), midland (**(B)**- *Hawo*), and lowland agroecology **(C)**-*Bekaye*) watershed.

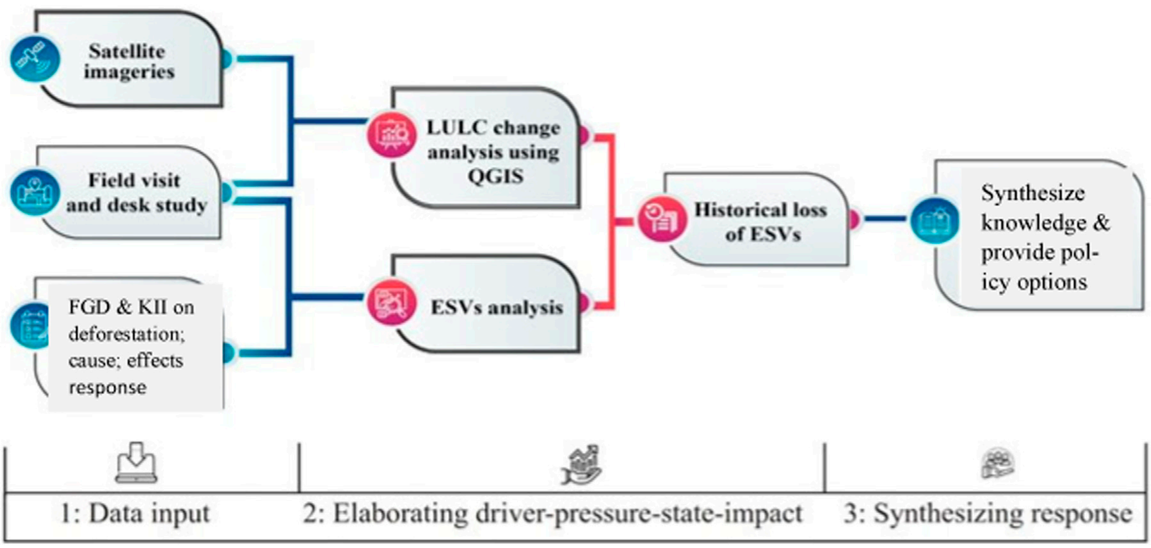

FIGURE 2
Analytical framework used to study land use land cover changes and its effect on ESVs in the Bale Ecoregion.

accuracy assessment, whereas Landsat imageries were accessed from the United States Geological Survey (USGS) website [http://www.usgs.gov (Table 2)]. Landsat images were of medium resolution (30 m). For 1991 and 2006, the images were derived from Thematic Mapper™; for 2016 and 2022, we used Landsat Enhanced Thematic Mapper (ETM) and Landsat 8, respectively.

TABLE 2 Details of raster and vector data used and their sources.

Type of spacecraft	Format	Resolution	Year	Source
Landsat 4	Raster	30 m	1992	USGS/TM
Landsat 7	Raster	30 m	2002	USGS/TM
Landsat 8	Raster	30 m	2012 and 2022	USGS/ETM+
BER and watersheds	Shapefile	-		+QSWAT and WRC
DEM	Raster	20 m	--	SRTM
Google Earth imagery	JPEG	-	2022	Google Earth

The acquisition dates of the satellite images slightly differ within and between years, although the acquisition was carried out within the dry-season months (January to February). Multispectral satellite images were used (WRS_PATH/RAW = 168/55, 167/56, 168/56, and 167/55; Reference Datum = "WGS84," Reference Ellipsoid = "WGS84," Map Projection = "UTM," and Projection = "UTM"). The selected images are free of clouds, allowing for interpreting diverse types of land use. Digital elevation model (DEM from SRTM) and outlet global positioning system (GPS) coordinates were used for delineating the watershed boundaries of the sample study sites using QSWAT version 3.10.3 (SWATplus plugged-in to QGIS) (Neitsch et al., 2011).

2.4 Image classification and accuracy assessment methods

2.4.1 Defining the spatiotemporal boundaries of the study

The land use and land cover of each studied watershed were analyzed and compared. Consultation with the local communities and Alemayehu et al. (2017) demonstrated that land use change has been severely increasing since 2008, particularly in the lowlands and midlands. To account for the same, breaking into shorter time intervals is critical to validating these local arguments. Thus, LULC changes of 1992–2002, 2002–2012, and 2012–2022 time intervals were considered. Different historical periods and 10-year intervals enable the detection of significant LULC changes.

2.4.2 Image pre-processing

Typical pre-processing operations used include band combination, image clipping, and image enhancement checking for geometric correction. The major image processing steps undertaken here encompass image layer stacking, resampling, and image enhancement of the image dataset. We used ENVI 4.7 for both preprocessing and image processing. Image enhancement allows for a raw image to be readily interpretable for a particular application. The enhancements were operationalized using the same methods as those used by Hailemariam et al. (2016). After these were checked by the image histogram, enhancement was performed using the stretch and stretch to MinMax methods. From the mosaicked image, the portion that fell within the study area was extracted to limit the size of the mosaicked image to that of the study watersheds—*Hora Soba*, *Hawo*, and *Bekaye* (Figure 1).

2.4.3 Image classification

Land use and land cover classification was carried out using both unsupervised and supervised classification methods. First, we categorized all pixels of an image automatically into major land cover classes. In this study, the iterative self-organizing data analysis (ISODATA) technique of image clustering—described by Kantakumar and Neelamsetti (2015) and ERDAS (1999)—was applied to obtain unsupervised image classification. Second, the images representing all the studied dates were supervised and classified using the maximum likelihood classifier algorithm. A classification scheme was subsequently used to nominate major land cover classes, and finally, the classification accuracy was calculated. Following layer stacks and signature editing, image classifications were completed using earth resource data analysis QGIS software, version 3.10.3 (www.qgis.org/en/site/).

The supervised classification approach necessitates a clear idea of the number of land cover types existing in the study area. In the present study, classification algorithms were used to separate the feature space according to the selected training samples designated by the region of interest (ROI). The training sets were identified for each land cover class based on previous field knowledge and using the Google Earth tool. Accordingly, four major land cover classes were designated (Table 3) and chosen for the digital classification of the study watershed images.

2.4.4 Accuracy assessment

The quality of the image classification was checked and quantified against the ground truth. For each study site, 160 training points were generated for the land cover classifications, and 30% of the total training points (48 GCP and 12 GCP for each land cover type) were also collected from the field using Garmin GPS as ground truth points to assess the accuracy of the classified images. We followed multi-step accuracy and performance assessment techniques, as elaborated by Mekuria et al. (2021). We followed visual inspection during field visits and a confusion matrix using user, producer, and overall accuracy indexes and a nonparametric Kappa coefficient (Jensen, J., 2005; Kantakumar and Neelamsetti, 2015; ERDAS, 1999).

2.5 Estimation of losses of ESVs

2.5.1 Estimation of ESVs

One of the key impacts of LULC change is on ecosystem services and their values. However, coupling LULC with ESVs and

TABLE 3 Description of the identified LULC classes in the study areas.

Land use/land cover classes	Description
Forest land (FL)	Land covered by dense natural forest
Bush/shrub land (BS)	Vegetation dominated by shrubs, often also including grasses and herbs
Grazing land (GL)	Land covered mixed up with both small shrubs and grasses commonly used for livestock grazing
Cultivated land (CL)	Areas covered by annual crops including cereals and leguminous crops

estimating values per ecosystem service, which is the basis for ESV estimation, is data-intensive (Tolessa et al., 2017; Mekuria et al., 2021; Mengist et al., 2022). Globally, ecosystem service value coefficients have been modified several times since they were first established in 1997 (Costanza et al., 2014; de Groot et al., 2020). For the present study, we used the Ecosystem Services Valuation Database (ESVD), a follow-up to The Economics of Ecosystems and Biodiversity (TEEB) database. The Economics of Ecosystems and Biodiversity, as explained by de Groot et al. (2020), comprised over 1,300 data points from 267 case studies on the monetary values of ecosystem services across all biomes (de Groot et al., 2020). The new updated version of the ESVD contains 4,042 value records based on 693 studies across the world.

The ESVD was utilized to assess ESVs for 1991 (the base year) and 2022 (the study watershed). Although the ecosystem service value coefficients are not specific to the different agroecologies considered in this study, they show the degree of impact of LULC and have important policy implications. Therefore, they help in better understanding the impacts of LULC change, the trends of ecosystem service flow (in the context of the bigger river basins) between the highland, midland, and lowland areas, and its future management implications. Similar approaches have been used by Gashaw et al. (2018b), Mekuria et al. (2021), Richardson et al. (2015), and Tolessa et al. (2017) to estimate ESVs for different agroecologies in complex settings of population and environmental interactions. De Groot et al. (2020) indicated that the number of value records for Africa is about 309, while Asia and Europe have a total of 4,042 value records globally.

Given the complexity of the landscape of the Bale Ecoregion, the estimation of ESVs in this study was based on filtering and matching international values for similar biomes (USD ha yr $^{-1}$ at 2020 price levels). The process involves two scales: i) four land use and land covers (forest, grazing land, cultivated, and bush/shrub lands) and ii) 21 specific ESVs (water, food, raw materials, genetic resources, medicinal resources, climate regulation, moderation of extreme events, regulation of water flows, erosion prevention, opportunities for recreation and tourism, etc.). We presented the result for all specific ecosystem services, while our discussion emphasizes only prominent ESVs.

The total value of ecosystem services in the LULC for the study period was obtained following the methodology (Eq. 1) suggested by Mekuria et al. (2021), Tolessa et al. (2017), and Mengist et al. (2022).

$$ESV = \sum (A_K \, X \, VC_K), \quad (1)$$

where ESV is the estimated ecosystem service value, A_k is the area (ha), and VC_k is the ESV (USD ha yr $^{-1}$) as per 2020 price levels for LULC category k. The change in the ecosystem service value for different LULCs was estimated as the difference between the reference year (1991) and 2022. Additionally, we estimated the impacts of LULC changes on 21 specific ecosystem services in the study area; the values of the specific ecosystem services were estimated using Eq. 2 and the value coefficient obtained by de Groot et al. (2020).

$$ESV_f = \sum \left(A_k \, X \, VC_{fk}\right), \quad (2)$$

where ESV_f is the estimated ecosystem service value of function f, A_k is the area (ha), and VC_{fk} is the value coefficient of function f (USD ha yr $^{-1}$ at 2020 price levels) for LULC category k. The value coefficients can be obtained from the study by de Groot et al. (2020), and Table 4 depicts specific ecosystem service values (Int$/ha/yr) by ecosystem service categories.

2.6 Additional data on livelihood and agricultural practices

Madda Walabu University, in collaboration with the International Water Management Institute as part of the SHARE I Bale Ecoregion studies (unpublished data), generated qualitative data from 30 key informants across households in lowland, midland, and highland areas. Fifteen FGDs (four with men, three with women, three with youths, and five with Woreda experts) were conducted. Moreover, 30 key informants were involved in an in-depth interview using checklists prepared on economic activities, utilization of natural resources, constraints on using existing natural resources, temporal variation in natural resources, and other related issues. The study followed a multi-stage sampling procedure to select Woreda, Kebele, and individual participants in the different discussions. While the selection of Woreda and Kebele was systemic, the selection of individual participants was guided by extension agents. At the same time, personal observation was employed to identify economic activities, usages of natural resources, constraints on using existing natural resources, and the current situation of natural resources in the study area. We used this information and literature values to discuss the whole spectrum of LULC and the ESV change in the context of the DPSIR framework.

3 Results

3.1 Accuracy assessment

The overall accuracies of 2022, 2012, 2002, and 1992 varied by the years, LULC types, and study areas. The overall accuracy assessment values (Annex 2) ranged between 96% and 83%. These figures are within the acceptable range of accuracy levels (Hailemariam et al., 2016; Hassen and Assen, 2018).

3.2 Magnitude and rate of LULC changes across the study watersheds

Figures 3–5 depict LULC changes during the observation period for the study watersheds representing highland, midland, and

TABLE 4 LULC and specific ecosystem service values (Int$/ha/yr) by ecosystem service categories.

Ecosystem service category	Specific ecosystem services	Land use and land cover type			
		Forest land (Int$/ha/yr)	Woodland (Int$/ha/yr)	Grazing land (Int$/ha/yr)	Cultivated land (Int$/ha/yr)
Provision service	FD	602	8		510
	RM	47,869		313	604
	GR	11,739	1	637	6
	MR	16			
	MGD	3	1		
Regulating service	Wa	309	7	8	10
	AQR	658	89	73	10
	CR	108			993
	MEE	442	71	43	17
	RWF	12			40
	WT	604			173
	WP	42			34
	BC	877			1,498
Cultural services	P	14			621
	AI	19			
	ORT	7			
	ICAD		38		395
	ICD	52,789	124	92	3,101
	EBV	5	214	284	16
Supporting service	MLCMS		214	147	
	MSF	2,960	2		

FD, food; Wa, water; RM, raw material; GR, genetic resource; MR, medicinal resource; AQR, air quality regulation; CR, climate regulation; MEE, moderation of extreme event; RWF, regulation of water flow; WT, waste treatment; WP, erosion prevention; MSF, maintenance of soil fertility; P, pollination; BC, biological control; MLCM, maintenance of life cycles of migratory species; MGD, maintenance of genetic diversity; AI, aesthetic information; ORT, opportunities for recreation and tourism; ICAD, inspiration for culture, art, and design; ICD, information for cognitive development; EBV, existence and bequest values.

[a]Stands for gain, and - stands for losses of ESVs.

lowland agroecologies in the BER. Apparently, there were differences in the magnitude of gains and losses of areas under different land use types in the three watersheds (Tables 5, 6).

Table 6 illustrates that in the highlands, grazing land continuously shrank at an increasing rate (3%, 7%, and 87% losses) for 1992–2002, 202–2012, and 2012–2022, respectively. Similarly, in the midland and lowland watersheds, grazing land was observed to decrease at an increasing rate during the observation period (Tables 5, 6).

Very sharp LULC changes in the study watersheds were noted, with a sizeable increase in the cultivated land. The observed changes were stronger for the midland and lowland study areas. Consequently, during the entire observation period (1992–2022), the cultivated land in the lowland expanded from 43% to 66%, from 10% to 69% in the midland, and from 16% to 32% in the highland, indicating steeper changes in lowland and midland areas (Tables 5, 6).

Notably, a strong increase in cultivated land across all study watersheds was observed to be at the expense of forest land. A substantial decrease in the forest land area was observed, with different magnitudes among the study watersheds. For instance, in the highlands, forest land decreased from about 3% to 0.64% between 1992 and 2002 (Tables 4, 5). In the midland, forest land steadily decreased from about 89% to 26.6% between 1992 and 2022. In the lowland watershed, forest lands decreased from about 45.51% to 24.45% during 1992–2022. The trend in losses in the forest area seemingly corresponds well to the gain in cultivated land (Annex 1).

The annual rate of forest land degradation in the lowland was −4.65, −0.78, and −5.64 for three consecutive decades of observation. In the midland, the rate of change was of comparable magnitude, while the highland rate of change was smaller than that of the two study sites (Table 6).

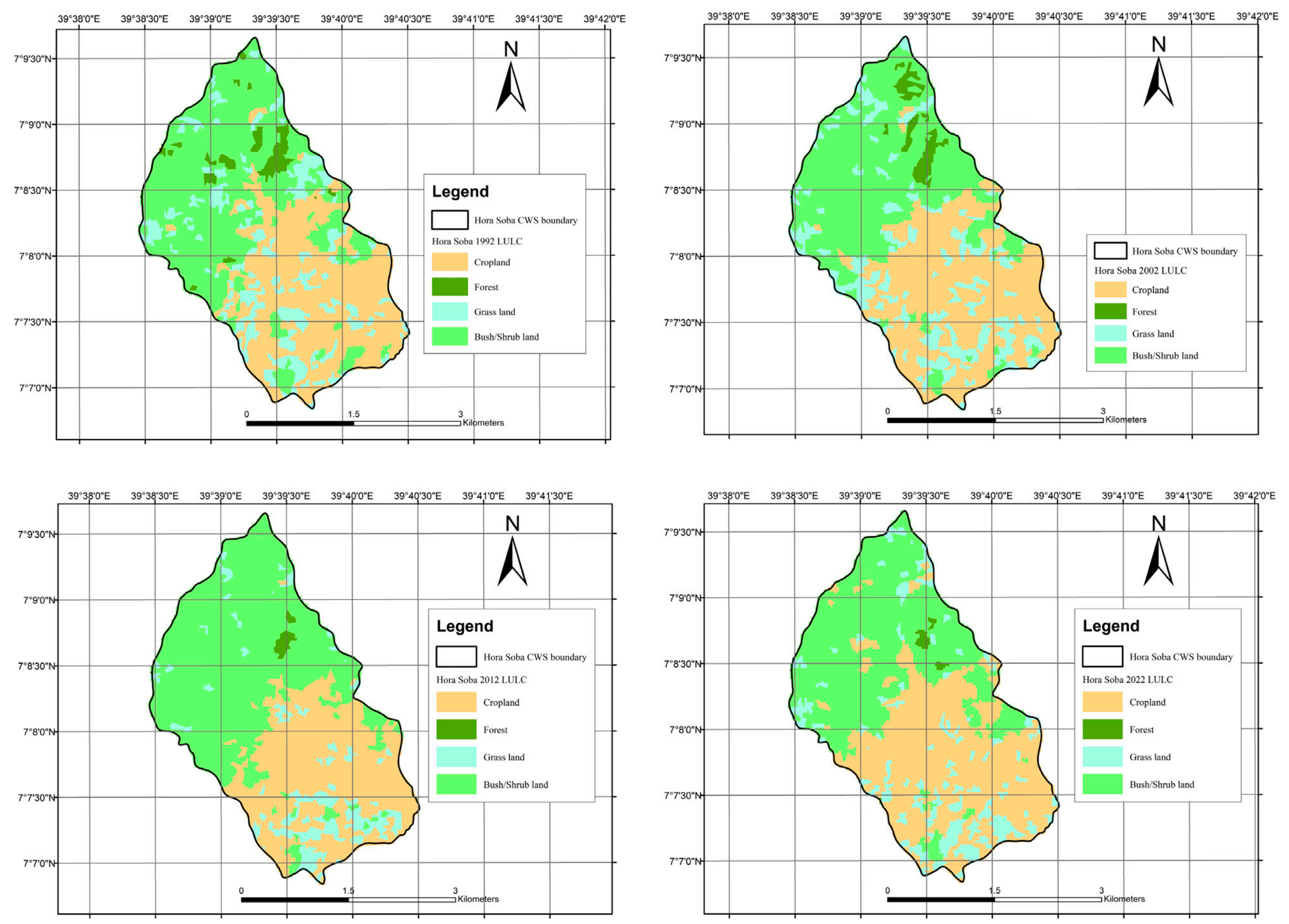

FIGURE 3
LULC changes in the highland (*Hora Soba*) watershed of the BER during 1992 -2022 (CWS is for catchment watershed).

3.3 Ecosystem service value changes in relation to LULC in the study watersheds (BER)

The estimation of the overall ESVs for the base year (1992) was 68 million USD, while for 2022, the figure was only 33 million USD (Table 7). This indicates that the total ESV loss over the last 30 years was estimated at >108% from the base year (1992) and at a rate of >1 million USD ha^{-1} yr^{-1}. Losses from the forest were the highest and estimated at an annual rate of 0.1, 0.7, and 0.4 million USD ha^{-1} for the highland, midland, and lowland study areas, respectively (Table 7).

In all the study areas, the ESV increase for cultivated land for the study period was substantial, ranging between 85% (at the midland), 35% (lowland), and 28% (highland) (Table 7). The question, however, of whether this change will maintain or improve the baseline year-specific ESVs for food provision remains.

In terms of various specific ESVs depicted in Tables 8–10, substantial losses were recorded. Of the 21 specific ESVs investigated, only 33% showed a value increase for the highland and midland, while for the lowland, the figure was less strong (Tables 8–10). These increasing specific ESV trends include pollination, biological control, and waste treatment in all the study areas (Table 11).

The highest magnitude of losses was recorded for water (from a change in forest land) and recreation and tourism-related ESVs, with the magnitude of losses differing across the three study sites (Table 11). A loss in water flow regulation values, which links the highland, midland, and lowland areas of the BER, was also observed. Despite the increase in cultivated land, specific ESVs for food have significantly diminished, except for some increase in the highland areas (Table 11).

The sum of the values of overall ESV changes suggests 71% of losses of ESVs in the lowland, 187% in the midland, and 42% in the highland compared to the base year [1992 (Tables 7–9)].

4 Discussion

4.1 Variability of land use and land cover changes across the study agroecologies of the BER

The results revealed that the magnitude of LULC changes in the study areas for the observation periods was divergent. Overall, there was a pressure of a steady increase in cultivated land and a contrasting decrease in forest lands. Information from the FGD indicated that the LULC changes were mainly related to the expansion of agricultural land as a result of the increasing population and the associated demand for

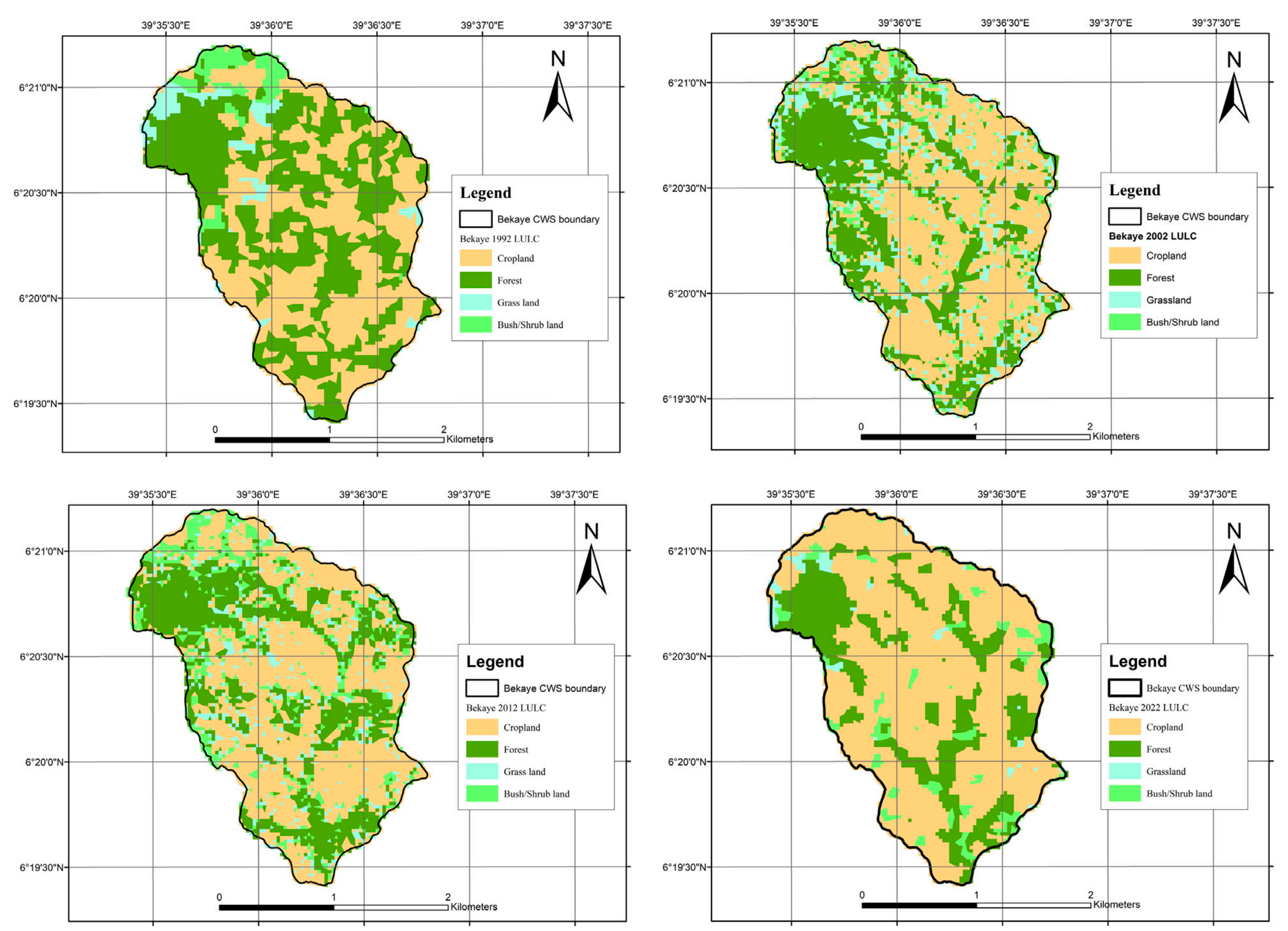

FIGURE 4
LULC changes in the midland (Hawo) watershed of the BER during 1992 -2022 (CWS is for catchment watershed).

food. This substantiates the work of Deribew and Dalacho (2019), who attributed forest LULC change to an expansion of cultivated land in Ethiopia. The drivers, as demonstrated by Hailemariam et al. (2016), are population growth, climate change, and regional policies [see Figure 6 (Bilsborrow, 1992)].

A closer look at the magnitude and trends of LULC changes in each of the study areas reveals new insights. For instance, in the highland study areas, forest cover decreased from 3.12% in 1992 to >1% in 2022. This is in contrast to the trend in the midland and lowland watersheds, where a stronger and sharper decrease in forest land was observed. The slow rate of deforestation in the highlands could be explained by the ongoing reforestation and land restoration programs, including the practices of participatory forest management (PFM) in Ethiopia, and could be considered one of the responses. We also argue that the remnant forest in the highland areas is mainly on marginal land, which is less suitable for alternative land uses and, thus, does not attract the attention of illegal settlers. PFM is mainly focused on the highland and midland areas, as indicated by Alemneh et al. (2019), Lemenih and Kassa (2014), and Badesso et al. (2020). Discussants from the FGD underlined the critical role of the ongoing PFM approach regarding the rehabilitation and protection of forest land in the highland areas of the BER. Programs such as REDD+ in the BER are highly focused on the PFM approach. Lemenih et al. (2015) reported that the first PFM approach was introduced in Ethiopia in the mid-1990s by Farm Africa, SOS Sahel, GTZ, and JICA. It has been gradually recognized by the government of Ethiopia (policy-influenced) as a mechanism to reverse deforestation and improve the management of state-owned natural forests in the country (Lemenih et al., 2015). Recent findings from the Central Rift Valley by Girma et al. (2023) indicate that PFM improves the livelihood assets of farmers and, in turn, reduces encroachment into forest areas through agroforestry development, soil and water conservation, and the use of non-wood forest products. Despite this emerging evidence, deforestation has remained a challenge in different parts of the country, such as the remote lowland areas in the BER.

The lowland forest area decreased from 47% in 1992 to 25% in 2022. The deforestation rate in the lowland area was stronger than that in the highland areas; on average, it was more than two-fold higher than in the highland, according to the various LULC reports in different parts of the country, such as in the Bilate Alaba catchment (Godebo et al., 2018) and the Goga district of Gambela (Othow et al., 2017). This can be accounted for by the increasing transformation of pastoral communities into agropastoral and sedentary farmers. For example, Hailemariam

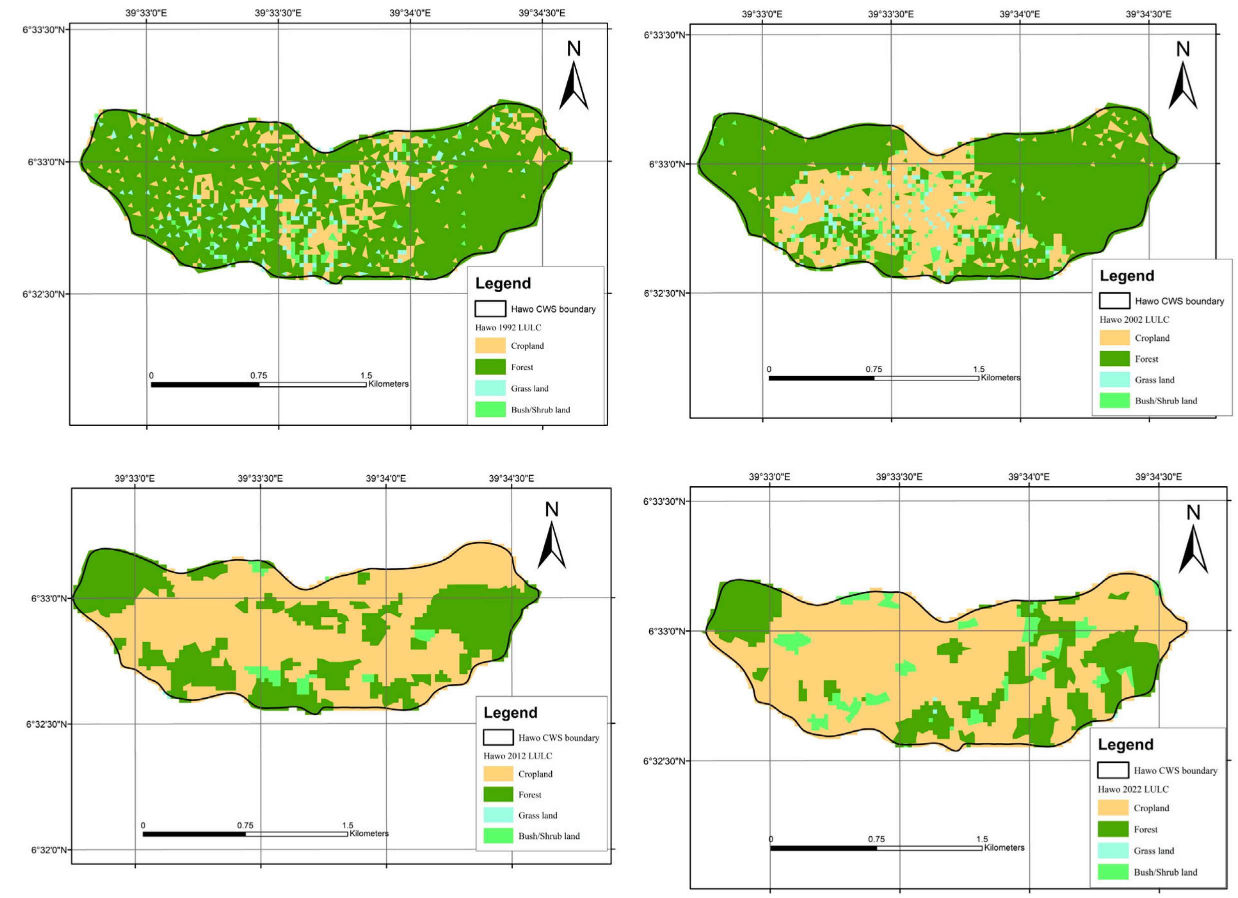

FIGURE 5
LULC changes in the lowland (Bekaye) of the BER during 1992 -2022 (CWS is for catchment watershed).

et al. (2016) argued that drought forces many local people to migrate (pressure created by climate change) from drought-stricken areas to forest regions in the lowland; the latter allows for better space for agriculture, water, foraging opportunities, and irrigation. FGD and KII participants suggested that pastoralists were forced to settle down through the "villagization" program in the lowland ecoregion; thus, regional policy plays a role in accelerating LULC changes (ibid). Rates of deforestation in the three study areas were above the net annual rate of East and West Africa and the national average of 1.28% (FAO, 2015). The average rate of cultivated land increase was slightly different among the highland, midland, and lowland studies, ranging between 4 and 6 ha yr^{-1}. Similarly, Gibbs et al. (2010) estimated that newly cultivated land increased annually by more than 4% in the tropics during the 1980s and 1990s at the cost of forest land (see also Tolessa et al., 2017; Mekuria et al., 2021).

In addition to the spatial variability in the magnitude and rate of deforestation, this study revealed variability in the pattern of LULC changes—how they evolved from one type to another. A closer inspection of the pattern of LULC change epochs illustrates that the general pathway of LULC changes follows forest land–bush/shrub–grassland/grazing land–cultivated land, with some variants and feedback loops across the study agroecology (Annex 1a–c). For example, for all study areas during most observation periods, LULC changed mainly from forest land to cultivated land (Annex 1a–c). However, a unique pattern observed was a change of grassland to bush/shrub in the *Hora soba* highland during 2012–2022. Arguably, this could be due to recent interventions by government and non-governmental organizations to rehabilitate ecosystems through different interventions, including area exclosure and PFM. Overall, despite the similarity in the overall trends of the LULC change pathway, there are differences in patterns among the study areas. Possibly, this shows a disparity in the management necessary for the conservation of forests and to sustainably restore the ecosystem.

DPSIR is a causal framework for describing the interactions between society and the environment to support evidence-based decision-making. It is significant in this context to understand the key driver and pressure, as shown in Figure 6. Alemayehu et al. (2017 unpublished) reported that population growth is a chief factor driving the increased demand for food and household energy in the BER.

The high population growth rate is a compound effect of the inherent growth and influx of migrants within the BER and from other parts of the country (Rudel, 1991; Bilsborrow, 1992; Hailemariam et al., 2016; Mezgebu and Workineh, 2017). The growth rate is estimated at 3.81% for the entire BER. The population density decreases along the altitude gradient (from highland to lowland), implying population growth as a driving factor that plays different roles in the three watersheds.

TABLE 5 Area coverage of major LULC types in the study watersheds (BER).

Study agroecology	LULC type	1992		2002		2012		2022	
		Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Bekaye (lowland, 501.46 ha)	Cultivated land	217.71	43.42	287.13	57.26	298.33	59.49	334.11	66.63
	Forest	233.23	46.51	186.72	37.24	178.96	35.69	122.59	24.45
	Grazing land	24.75	4.94	20.92	4.17	4.67	0.93	10.61	2.12
	Bush/shrub land	25.77	5.14	6.69	1.33	19.5	3.89	34.15	6.81
Hawo (midland, 292.66 ha)	Cultivated land	29.69	10.14	102.57	35.05	182.35	62.31	203.92	69.68
	Forest	261.92	89.50	187.48	64.06	103.86	35.49	77.99	26.65
	Grazing land	0.17	0.06	0.35	0.12	0.17	0.06	0.26	0.09
	Bush/shrub land	0.88	0.30	2.26	0.77	6.28	2.15	10.49	3.58
Hora soba (highland, 1,048.22 ha)	Cultivated land	343.6	32.78	414.7	39.56	456.32	43.53	478.87	45.68
	Forest	32.66	3.12	31.8	3.03	8.05	0.77	6.75	0.64
	Grazing land	184.82	17.63	179.27	17.10	168.39	16.06	90.03	8.59
	Bush/shrub land	487.14	46.47	422.45	40.30	415.46	39.63	472.57	45.08

TABLE 6 Major LULC (%) and decadal rate of change in the study watersheds (BER).

Study agroecology	Major LULC type	LULC change (%)			Rate of LULC change		
		1992–2002	2002–2012	2012–2022	1992–2002	2002–2012	2012–2022
Bekaye (lowland)	Cultivated land	24.18	3.75	10.71	6.94	1.12	3.58
	Forest	−24.91	−4.34	−45.98	−4.65	−0.78	−5.64
	Grazing land	−18.31	−347.97	55.98	−0.38	−1.63	0.59
	Bush/shrub land	−285.20	65.69	42.90	−1.91	1.28	1.47
Hawo (midland)	Cultivated land	71.05	43.75	10.58	7.29	7.98	2.16
	Forest	−39.71	−80.51	−33.17	−7.44	−8.36	−2.59
	Grazing land	51.43	−105.88	34.62	0.02	−0.02	0.01
	Bush/shrub land	61.06	64.01	40.13	0.14	0.40	0.42
Hora soba (highland)	Cultivated land	17.14	9.12	4.71	7.11	4.16	2.26
	Forest	−2.70	−295.03	−19.26	−0.09	−2.38	−0.13
	Grazing land	−3.10	−6.46	−87.04	−0.55	−1.09	−7.84
	Bush/shrub land	−15.31	−1.68	12.08	−6.47	−0.70	5.71

Discussants during the FGDs confirmed that the strategies for meeting the growing food demand in all the study areas focus on higher production through an expansion of cropland and an increase in livestock population (Rudel, 1991). This is a mechanism by which the driver contributes to change in the state, involving deforestation, change in livelihood strategy, overgrazing, and expansion of cultivated land, as depicted in Figure 6 (Tolessa et al., 2017).

Population growth not only increases pressure through increasing demand for food but also exacerbates the demand for household energy. In this regard, Alemayehu et al. (2017 unpublished) indicated that about 98% of household energy consumption in the BER is sourced from biomass. Third, population growth and the subsequent increase in the area of land for cultivation also warrant the demand for more livestock traction power (Rudel, 1991). In this regard, a positive and strong correlation between human and livestock population growth in the BER has been reported (Hailemariam et al., 2016). However, such an increase in livestock population contrasts with the substantial conversion of grazing land to cultivated land across all study areas. FGDs confirm the shortage of animal feed—as a result, increased overgrazing and increased use of crop residues for animal feed led to more nutrient mining, particularly in the condition where manure is not returned to farmland.

TABLE 7 LULC classes, the corresponding biomes, and mean standardized values per ecosystem service biome based on the updated values (de Groot et al., 2020) and estimated change in ESVs between 1991 and 2022 for the BER.

Study watershed (agroecology)	LULC class	Equivalent biome	Mean standardized value per ecosystem service biome (Int$/hectare/year; 2020 price levels)	Area (ha) in the base year (1992)	Area (ha) in 2022	ESVs in the base year (1992)	ESV 2022 (USD)	Overall ESV change (%)	Rate of change over three decades (USD yr^{-1})[a]
Hora soba (highland)	Forest	Tropical forest	119,075.00	32.66	6.75	3,888,989.50	803,756.25	−384	−102,841.11
	Grazing land	Grassland	1,597.00	184.82	90.03	295,157.54	143,777.91	−105	−5,045.99
	Cultivated land	Cultivated areas	8,028.00	343.6	478.87	2,758,420.80	3,844,368.36	28	+36,198.25
	Shrub land	Wood and shrub land	769.00	487.14	472.57	374,610.66	363,406.33	−3	−373.48
Hawo (midland)	Forest	Tropical forest	119,075.00	261.92	77.99	31,188,124.00	9,286,659.25	−236	−730,048.83
	Grazing land	Grassland	1,597.00	0.17	0.26	271.49	415.22	35	+4.79
	Cultivated land	Cultivated areas	8,028.00	29.69	203.92	238,351.32	1,637,069.76	85	+46,623.95
	Shrub land	Wood and shrub land	769.00	0.88	10.49	676.72	8,066.81	92	+246.34
Bakaye (lowland)	Forest	Tropical forest	119,075.00	233.23	122.59	27,771,862.25	14,597,404.25	−90	−439,148.60
	Grazing land	Grassland	1,597.00	24.75	10.61	39,525.75	16,944.17	−133	−752.72
	Cultivated land	Cultivated areas	8,028.00	217.71	334.11	1,747,775.88	2,682,235.08	35	+31,148.64
	Shrub land	Wood and shrub land	769.00	25.77	34.15	19,817.13	26,261.35	25	+214.81
Total						68,323,583.04	33,410,364.74	−108	−1,163,773.94

[a]+ stands for ESV gain, and − stands for losses.

Historically, the lowland of the BER has mainly been pastoral and agropastoral (Elias, 2008). However, FGDs reveal recent changes in the livelihood strategy of the rural community, particularly in the lowland areas. The farming system has shifted from pastoral to agropastoral and a mixed-crop livestock system, causing a sharp decrease in areas of forest land during 1992–2022; this is notable because, about five decades ago, almost all households in the lowland areas of the BER primarily practiced livestock production. A discussion with the Bale Zone Pastoral Office suggested that within the Dallo Manna, Harena Buluk, and Madda Walabu lowland districts, the number of households engaged in pastoralism decreased from 50% to 11.67%. Contrastingly, household dependence on agropastoral and mixed-farming systems increased by 47.67% and 38.83%, respectively. There are several drivers of such changes, which the FGD and scholars such as Hailemariam et al. (2016) and Mezgebu and Workineh (2017) attribute to government policy in response to the negative impacts of climate change in lowland areas.

This shift in livelihood activities in the lowland areas might have been one of the main pressures on the system, according to information obtained from the local administration. Significant considerations include how government policy and climate change drivers intensify the level of pressure on the ecosystem. In this regard, Wynants et al. (2019) argued that these drivers were interdependent. The authors, for instance, attribute this livelihood activity change to a combination of administrative boundary enforcement, settlement policy, and significant population growth (Rudel, 1991; Hailemariam et al., 2016; Mezgebu and Workineh, 2017). Unlike in the past, the lowland communities have now gradually shifted toward cultivating more land for mosaics of crop production. Our observation suggests that only a few of the pastoralists move with their livestock toward unoccupied areas of the BER highland and midland during the dry season (off-cropping) and return to the lowlands during the wet season when the availability of enough pasture and water is secure.

The overall situation of multiple intertwining drivers with a multitude of pressure drives accelerated the change in the state of the ecosystem and the resultant impacts. This complicates the management process and entails the need for an integrated and context-specific approach.

TABLE 8 Values (Int$/hectare/year; 2020 price levels) of ESVs for four LULC classes in the *Hora soba* highland.

Ecosystem service	Forest land			Woodland			Grassland			Cultivated land			ESV sum	
	Int$/ ha/yr	ESV 1992	ESV 2022	Int$/ ha/yr	ESV 1992	ESV 2022	Int$/ ha/yr	ESV 1992	ESV 2022	Int$/ ha/yr	ESV 1992	ESV 2022	ESV 1992	ESV 2022
FD	602	19,661	4,064	8	3,897	3,780	0	0	0	510	175,236	244,224	198,794	252,067
Wa	47,869	1,563,402	323,116		0	0	313	57,849	28,179	604	207,534	289,237	1,828,785	640,533
RM	11,739	383,396	79,238	1	487	473	637	117,730	57,349	6	2,062	2,873	503,675	139,933
GR	16	523	108		0	0		0	0		0	0	523	108
MR	3	98	20	1	487	473		0	0		0	0	585	493
AQR	309	10,092	2,086	7	3,410	3,308	8	1,479	720	10	3,436	4,789	18,416	10,902
CR	658	21,490	4,442	89	43,355	42,054	73	13,492	6,572	10	3,436	4,789	81,774	57,857
MEE	108	3,527	729		0	0		0	0	993	341,195	475,518	344,722	476,247
RWF	442	14,436	2,984	71	34,587	33,549	43	7,947	3,871	17	5,841	8,141	62,811	48,545
WT	12	392	81		0	0		0	0	40	13,744	19,155	14,136	19,236
WP	604	19,727	4,077		0	0		0	0	173	59,443	82,845	79,169	86,922
MSF	42	1,372	284		0	0		0	0	34	11,682	16,282	13,054	16,565
P	877	28,643	5,920		0	0		0	0	1,498	514,713	717,347	543,356	723,267
BC	14	457	95		0	0		0	0	621	213,376	297,378	213,833	297,473
MLCMS	19	621	128		0	0		0	0		0	0	621	128
MGD	7	229	47		0	0		0	0		0	0	229	47
AI		0	0	38	18,511	17,956		0	0	395	135,722	189,154	154,233	207,109
ORT	52,789	1,724,089	356,326	124	60,405	58,592	92	17,003	8,283	3,101	1,065,504	1,484,976	2,867,001	1,908,177
ICAD	5	163	34	214	104,248	101,119	284	52,489	25,569	16	5,498	7,662	162,398	134,383
ICD		0	0	214	104,248	101,119	147	27,169	13,234		0	0	131,417	114,354
EBV	2,960	96,674	19,980	2	974	945		0	0		0	0	97,648	20,925
Total		3,888,990	803,756		374,611	363,368		295,158	143,778		275,8421	3,844,368	7,317,179	5,155,270

FD, food; Wa, water; RM, raw material; GR, genetic resource; MR, medicinal resource; AQR, air quality regulation; CR, climate regulation; MEE, moderation of extreme event; RWF, regulation of water flow; WT, waste treatment; WP, erosion prevention; MSF, maintenance of soil fertility; P, pollination; BC, biological control; MLCM, maintenance of life cycles of migratory species; MGD, maintenance of genetic diversity; AI, aesthetic information; ORT, opportunities for recreation and tourism; ICAD, inspiration for culture, art, and design; ICD, information for cognitive development; EBV, existence and bequest values.

[a]Stands for gain, and - stands for losses of ESVs.

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TABLE 9 Values (Int$/hectare/year; 2020 price levels) of ESVs for four LULC classes in the *Hawo* midland.

Ecosystem service[a]	Forest land			Woodland			Grassland			Cultivated land			ESV sum	
	Int$/ ha/yr	ESV 1992	ESV 2022	Int$/ ha/yr	ESV 1992	ESV 2022	Int$/ ha/yr	ESV 1992	ESV 2022	Int$/ ha/yr	ESV 1992	ESV 2022	ESV 1992	ESV 2022
FD	602	157,676	46,950	8	7	84		0	0	510	15,142	103,999	172,825	151,033
Wa	47,869	12,537,848	3,733,303		0	0	313	53	81	604	17,933	123,168	12,555,834	3,856,552
RM	11,739	3,074,679	915,525	1	1	10	637	108	166	6	178	1,224	3,074,966	916,924
GR	16	4,191	1,248		0	0		0	0		0	0	4,191	1,248
MR	3	786	234	1	1	10		0	0		0	0	787	244
AQR	309	80,933	24,099	7	6	73	8	1	2	10	297	2,039	81,238	26,214
CR	658	172,343	51,317	89	78	934	73	12	19	10	297	2,039	172,731	54,309
MEE	108	28,287	8,423		0	0		0	0	993	29,482	202,493	57,770	210,915
RWF	442	115,769	34,472	71	62	745	43	7	11	17	505	3,467	116,343	38,694
WT	12	3,143	936		0	0		0	0	40	1,188	8,157	4,331	9,093
WP	604	158,200	47,106		0	0		0	0	173	5,136	35,278	163,336	82,384
MSF	42	11,001	3,276		0	0		0	0	34	1,009	6,933	12,010	10,209
P	877	229,704	68,397		0	0		0	0	1,498	44,476	305,472	274,179	373,869
BC	14	3,667	1,092		0	0		0	0	621	18,437	126,634	22,104	127,726
MLCMS	19	4,976	1,482		0	0		0	0		0	0	4,976	1,482
MGD	7	1,833	546		0	0		0	0		0	0	1,833	546
AI		0	0	38	33	399		0	0	395	11728	80548	11761	80947
ORT	52,789	13,826,495	4,117,014	124	109	1,301	92	16	24	3,101	92,069	632,356	13,918,688	4,750,695
ICAD	5	1,310	390	214	188	2,245	284	48	74	16	475	3,263	2,021	5,971
ICD		0	0	214	188	2,245	147	25	38		0	0	213	2,283
EBV	2,960	775,283	230,850	2	2	21		0	0		0	0	775,285	230,871
Total		31,188,124	9,286,659	769	677	8,067	1,597	271	415	8,028	238,351	1,637,070	31,427,424	10,932,211

[a]For abbreviations, refer to Table 5; **+ stands for gain, and - stands for losses of ESVs.

TABLE 10 Values (Int$/hectare/yr; 2020 price levels) of ESVs for four LULC classes in the *Bekaye* lowland.

Ecosystem service[a]	Forest land			Woodland			Grassland			Cultivated land			ESV sum	
	Int$/ ha/yr	ESV 1992	ESV 2022	Int$/ ha/yr	ESV 1992	ESV 2022	Int$/ ha/yr	ESV 1992	ESV 2022	Int$/ ha/yr	ESV 1992	ESV 2022	ESV 1992	ESV 2022
FD	602	140,404	73,799	8	206	273		0	0	510	111,032	170,396	251,643	244,468
Wa	47,869	11,164,487	586,8261		0	0	313	7,747	3,321	604	131,497	201,802	11,303,730	6,073,384
RM	11,739	2,737,887	1,439,084	1	26	34	637	15,766	6,759	6	1,306	2,005	2,754,985	1,447,881
GR	16	3,732	1,961		0	0		0	0		0	0	3,732	1,961
MR	3	700	368	1	26	34		0	0		0	0	725	402
AQR	309	72,068	37,880	7	180	239	8	198	85	10	2,177	3,341	74,624	41,545
CR	658	153,465	80,664	89	2,294	3,039	73	1,807	775	10	2,177	3,341	159,743	87,819
MEE	108	25,189	13,240		0	0		0	0	993	216,186	331,771	241,375	345,011
RWF	442	103,088	54,185	71	1,830	2,425	43	1,064	456	17	3,701	5,680	109,683	62,746
WT	12	2,799	1,471		0	0		0	0	40	8,708	13,364	11,507	14,835
WP	604	140,871	74,044		0	0		0	0	173	37,664	57,801	178,535	131,845
MSF	42	9,796	5,149		0	0		0	0	34	7,402	11,360	17,198	16,509
P	877	204,543	107,511		0	0		0	0	1,498	326,130	500,497	530,672	608,008
BC	14	3,265	1,716		0	0		0	0	621	135,198	207,482	138,463	209,199
MLCMS	19	4,431	2,329		0	0		0	0		0	0	4,431	2,329
MGD	7	1,633	858		0	0		0	0		0	0	1,633	858
AI		0	0	38	979	1,298		0	0	395	85,995	131,973	86,975	133,271
ORT	52,789	12,311,978	6,471,404	124	3,195	4,235	92	2,277	976	3,101	675,119	1,036,075	12,992,570	7,512,689
ICAD	5	1,166	613	214	5,515	7,308	284	7,029	3,013	16	3,483	5,346	17,193	16,280
ICD		0	0	214	5,515	7,308	147	3,638	1,560		0	0	9,153	8,868
EBV	2,960	690,361	362,866	2	52	68		0	0		0	0	690,412	362,935
Total		27,771,862	14,597,404		19,817	26,261		39,526	16,944		1,747,776	2,682,235	29,578,981	17,322,845

[a]For abbreviations, refer to Table 7.

TABLE 11 Observed percent changes and decadal rate of changes of ESVs by ecosystem service types in the BER.

Specific ecosystem service	Highland		Midland		Lowland	
	Overall ESV change %	Gain or loss (USD yr^{-1})	Overall ESV changes %	Gain or loss (USD yr^{-1})	Overall ESV change %	Gain or loss (USD yr^{-1})
FD	+21%	1,775.764	−14%	−726.39	−3%	−239.14
Wa	−186%	−39,608.3993	−226%	−289,976.07	−86%	−174,344.88
RM	−260%	−12,124.724	−235%	−71,934.73	−90%	−43,570.11
GR	−384%	−13.8186667	−236%	−98.10	−90%	−59.01
MR	−19%	−3.07833333	−222%	−18.07	−80%	−10.78
AQR	−69%	−250.471667	−210%	−1,834.14	−80%	−1,102.61
CR	−41%	−797.231	−218%	−3,947.39	−82%	−2,397.45
MEE	28%	4,384.161	+73%	5,104.87	+30%	3,454.54
RWF	−29%	−475.554	−201%	−2,588.30	−75%	−1,564.57
WT	+27%	169.996	+52%	158.73	+22%	110.94
WP	+9%	258.4023333	−98%	−2,698.40	−35%	−1,556.31
MSF	+21%	117.032	−18%	−60.04	−4%	−22.98
P	+25%	5,997.046333	+27%	3,323.00	+13%	2,577.86
BC	+28%	2,787.997667	+83%	3,520.73	+34%	2,357.85
MLCMS	−384%	−16.4096667	−236%	−116.49	−90%	−70.07
MGD	−384%	−6.04566667	−236%	−42.92	−90%	−25.82
AI	+26%	1,762.536333	+85%	2,306.20	+35%	1,543.21
ORT	−50%	−31960.8093	−193%	−305,599.79	−73%	−182,662.68
ICAD	−21%	−933.809	+66%	131.67	−6%	−30.44
ICD	−15%	−568.760333	+91%	68.99	−3%	−9.51
EBV	−367%	−2,557.428	−236%	−18,147.12	−90%	−10,915.92
Total	−42%	−72,063.6033	−187%	−683,173.75	−71%	−408,537.87

4.2 Extent of change in ESVs across study agroecologies of the BER

Several studies on the changes in LULC and ecosystem services across time in Ethiopia have been reviewed by Haileslassie et al. (2020). However, much of the literature reviewed does not enumerate comprehensive nationwide evidence. Available information at the micro (e.g., farm fields and watersheds) and meso-scale (e.g., river basins and regions) levels indicates that the magnitude of change is enormous and that the direction of change varies across regions and the scale of studies. The result of this study illustrates similar trends: variability in magnitude and intensity of changes across agroecologies (Figures 3–5). Accordingly, population growth, climate change, and government policy-derived livelihood shifts in pastoral and agropastoral communities have incurred deforestation (Mezgebu and Workineh, 2017) and led to losses of ESVs.

The impact on ESVs is far-reaching. Several studies demonstrate the impact of the loss of biodiversity (Figure 6), decreasing crop yield (soil fertility loss), shortage of household energy, vulnerability to climate change (drought), and shortage of animal feed (overgrazing) (Hailemariam et al., 2016; Tolessa et al., 2017; Mekuria et al., 2021; Mengist et al., 2022), leading to the deteriorating state of ESVs. As reported by a survey in the Bale Ecoregion (Alemayehu et al., 2017, unpublished), 56% of those surveyed attribute decreasing soil fertility to land use change. More than 23% of the respondents consider the prevalent overgrazing to be a factor in land use change, while about 16% associated land use change with the pervasiveness of pests and diseases in the BER. The remaining 5% of the respondents attribute frequent droughts to being a significant driver of land use change (Hailemariam et al., 2016; Mengist et al., 2022). The process in the DPSIR framework is not linear. As demonstrated here, various feedback loops are prevalent that intensify the pressure. An example could be decreasing soil fertility, which forces farmers to encroach into forest land, woodland, and grazing lands, thus incurring more losses of ESVs.

The estimate of the losses in the value of general and specific ecosystem services in the BER is troubling (Tolessa et al., 2017; Mekuria et al., 2021; Mengist et al., 2022). The highest value of ESV losses was estimated for the conversion of forest land to agricultural land. This could be attributed to the diverse and stronger magnitude

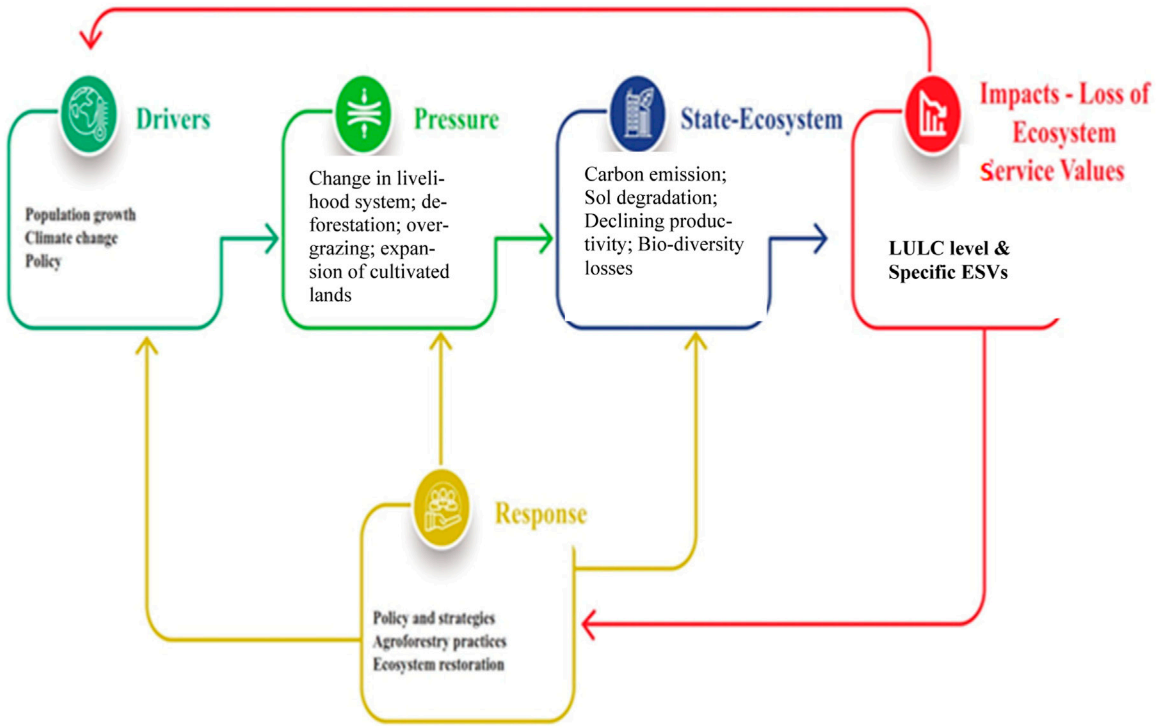

FIGURE 6
Illustration of DPSIR framework in the context of the study areas.

of ESVs of forest in TEEB database and the intensity of forest LULC changes in the study areas.

In terms of specific ESVs, the losses of water-related specific ESVs registered as one of the highest (water supply and flow regulation). Following the same, it is critical to understand how intensifying LULC conversion impacts downstream water users and uses. A review of about 10,000 publications by Acreman et al. (2021) on the effect of nature-based solutions (including forest and wetland) on water quality and availability (proxy indicator for water ESVs) for upstream and downstream water users in Africa indicated that such solutions could improve the water quality. In contrast, the evidence of their effectiveness for improving downstream water resource quantity was inconsistent, with most case studies showing a decrease in water yield where forests (particularly plantations of non-native species) and wetlands are present. Restoration of forests and floodplain wetlands can reduce flood risk, and their conservation can prevent future increases in risk and regulate base flow (ibid).

It is vital to consider the mitigation of these tradeoffs and the enhancement of shared ecosystem service benefits among the upstream and downstream users (highland, midland, and lowland areas). Addressing this through the co-designing of restoration methods for highland, midland, and dry lowland areas is important. It also substantiates the fact that highland, midland, and lowland landscapes, representing different eco-subregions, are not standalone units. They are in continuous interaction, influencing ecosystem service flows and, thus, underpinning their co-management. Significant losses in the regulation of water flow ESV in highland areas demonstrated by this study further substantiate this argument.

The magnitude of longer-term forest land impact on the base flow depends on species composition, tree density, crown–root structure, and the age of the forest stand. In the African context, longer-term monitoring is lacking (Acreman et al., 2021). These data could help separate this aggregate into fall, stem flow, interception, evaporation, etc. It can allow for an improved understanding of the flow components and its management options. The upstream–downstream connectivity of the negative impacts and benefits of land use change calls for inclusive planning mechanisms for sustainable ecosystem restoration and maintenance (Hagos et al., 2018).

Despite a substantial increase in the cultivated land, the gain in food-related ESVs from this land use type could not offset losses of food ESVs from forest and associated LULC. This is notable because of the population growth, increasing food demand, and land conversion as major drivers and pressures in the BER; it dictates the need for restoring forest-related ecosystem services (see also Mengist et al., 2022). Nature-based solutions positively impact ecological landscape quality with the provision of multiple benefits, including enhancing natural capital, promoting biodiversity, mitigating water runoff, increasing water retention, and contributing to climate change adaptations and carbon sequestration (Acreman et al., 2021).

4.3 Limitations of the study and future direction

Mekuria et al. (2023) provided an extensive explanation of the gaps in using the global value of the ecosystem services index. Tolessa et al. (2017) also suggested that ESVs are non-quantifiable and context-specific, and this may imply the underestimation/overestimation of actual values; thus, readers are encouraged to judiciously understand the empirical values. Mekuria et al. (2023) summarized that to address these gaps, the ESVD has been modified several times (2010, 2012, 2014, and 2020). While the persistent improvement implies the added value of the ESVD and the place it has in informing policymakers, it also urges the scientific community to develop ecosystem service value coefficients for local conditions that consider biophysical and social settings. In this paper, the overarching interest is to illustrate the observed trend that provides a scientific underpinning for understanding the LULC change and impacts on ESVs and supports the policy and planning of national programs such as REDD+, Ethiopia's voluntary commitment to the Bonn Challenge.

5 Conclusion

The objectives of this study were to provide empirical evidence on the LULC conversion rate and pattern across time and space for three study watersheds and to estimate the LULC conversion effect and trends on ESVs. Based on existing practices and empirical evidence, the study also proposes management options and approaches to aid in restoring ecosystem services.

In view of the results, we concluded that diverse magnitudes, trends, and patterns of LULC changes in the study areas considerably impact ESVs. The estimated significant losses of water ESVs and ESVs for water flow regulation in the midland and highland areas can impact livelihood activities in drier lowland areas, which depend on the midland and highland areas for water ecosystem service provision. Increased ESVs for cultivated land could not offset losses in food ESVs at the scale of agroecology. Thus, restoring forest-related ecosystem services is vital. While the stark variation in the impact and response among the study sites entails the need for context-specific conservation, connectivity between the highland and lowland areas through different ecosystem services (such as water) calls for the highland, midland, and lowland stakeholders to co-plan and co-manage the BER.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

AH: conceptualization, formal analysis, funding acquisition, writing–original draft, and writing–review and editing. MT: writing–review and editing, conceptualization, methodology, and supervision. MD: data curation, formal analysis, methodology, software, validation, visualization, and writing–review and editing. WM: conceptualization, formal analysis, methodology, validation, visualization, and writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The project is financed by EU.

Acknowledgments

The authors thank the project partners for their constructive comments during the presentation of the draft version at the stakeholders' workshop. The authors thank Farm Africa and SOS Sahel Ethiopia coordinators working on the Bale Ecoregion and Alemayehu Wudneh for their support during the fieldwork. The authors acknowledge the project "Scaling out integrated and multi-sectoral eco-regional approach in the Bale Ecoregion" (SHARE BER Phase II), for supporting the accomplishment of this activity.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author disclaimer

The views expressed in this manuscript are solely attributed to the authors and not to the funding agency.

Publisher's note

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