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Cover photo

Landscape in Halaba, Ethiopia, on June 27, 2024 (*photo*: Rediet Girma)

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Project

The "Local-Level Land Degradation Assessment Towards Sustainable Land Management for Improved Livelihoods in the Ethiopian Rift Valley (SMILE-REDAA)" project aims to develop a comprehensive understanding of land degradation by gathering evidence and actionable insights to promote sustainable land management practices. This locally-driven initiative prioritizes enhancing the capacity of local organizations by intervening in Farmer Training Centers (FTCs), schools, and tree nursery establishments, fostering community engagement to ensure long-term sustainability. Additionally, the project implements business models that support the continued success of restoration efforts while enhancing livelihoods, focusing on impactful strategies that drive meaningful change.

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Abbreviations and Acronyms

1OAO	The One-Out, All-Out
AEZ	Agroecological zone
AVHRR	Advanced Very-High Resolution Radiometer
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
DEM	Digital Elevation Model
GIMMS	Global Inventory Modelling and Mapping Studies
GPG	Good Practice Guidance
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference Information Center
LC	Land Cover
LDN	Land Degradation Neutrality
LULC	Land use and land cover
NDVI	Normalized Difference Vegetation Index
REDAA	Reversing Environmental Degradation in Africa and Asia
SEPAL	System for Earth Observation Data Access, Processing and Analysis for Land Monitoring
SLM	Sustainable Land Management
SWC	Soil and Water Conservation
UNCCD	United Nations Convention to Combat Desertification
WUE	Water Use Efficiency

Summary

Spatially customized land management strategies are crucial for mitigating land degradation and fostering effective landscape restoration. A deep understanding of local biophysical conditions ensures that interventions are both contextually relevant and impactful, promoting long-term environmental sustainability and delivering socio-economic benefits to local communities. With this consideration, this report, drawing on data collected through field surveys, GIS, and remote sensing techniques, uses Halaba, Ethiopia, as a case study to highlight the region's varied biophysical conditions and their implications for the design and planning of sustainable land management (SLM) practices. This document is intended for agricultural and natural resource management professionals involved in the design, planning, implementation, and monitoring of SLM practices.

1. Introduction

The Halaba zone in the Bilate catchment of the Ethiopian Rift Valley suffers from severe land degradation that affects both the environment and the livelihoods of local people. Working closely with farmers and advisors in this region, our Reversing Environmental Degradation in Africa and Asia (REDAA) - funded project seeks to reverse degradation through numerous biophysical interventions that also expand employment and income-generating opportunities. Multidisciplinary research and engagement activities are underway, including biophysical characterization.

Biophysical characterization of land is a fundamental step in understanding and managing natural resources, particularly in areas that face critical land degradation challenges (Reda and Abie, 2024). In regions characterized by diverse landscapes and variable climatic conditions, biophysical assessments provide essential data on landscape attributes, such as soil types, climate variables, agroecological zones, topography, land use and land cover, and land degradation neutrality (Asefa et al., 2020). These pieces of information are vital for effective land and water resources planning and management and for addressing critical environmental challenges, including soil erosion and land degradation (Reda and Abie, 2024).

Biophysical profiling of a particular study area also helps to identify critical sub-watersheds, used as input to evaluate degradation levels and prioritize areas based on ecological, social, and economic criteria (Pirani and Mousavi, 2016). In line with this, we conducted biophysical profiling of the Halaba zone[1], the study area, to characterize the diverse biophysical conditions. The characterization aimed to provide insights into the spatial and temporal distribution of landscape attributes. In addition, the characterization aimed to produce input data and information that could help the effective planning and design of targeted soil and water conservation (SWC) practices. An underlying premise of this work was that biophysical profiling, and an understanding of the spatial and temporal variability of land and water resources, are essential for the sustainable management of land and water resources. Such assessments are vital for improving management practices, addressing environmental challenges, and enhancing the livelihoods of targeted communities.

[1] Zones are a 2nd level subdivision of Ethiopia, below regions and above woredas, or districts.

2. Materials and Methods

2.1 Study Area

The study was conducted in the Halaba zone in the Bilate catchment, Abaya Chamo sub-basin of the Ethiopian Rift Valley. It lies between latitudes 7° 10'N and 7° 42'N and longitudes 38° 00'E and 38° 25'E (Figure 1). The Halaba zone consists of three woredas and one city administration, comprising 79 kebeles. Its population was estimated to be 305,555 of which 151,101 (49%) were men and 154,454 (51%) were women. The urban population accounts for 37,303 while the rural population accounts for 268,252 (CSA, 2019; Abebe et al., 2022). The economy is largely based on subsistence mixed crop-livestock agriculture (Kelbore and Gebreyes, 2022). The main cash crops include pepper, maize, teff, sorghum, haricot beans and wheat. Irrigation is practiced in some parts of the Bilate River (Abebe et al., 2022).

Declining soil fertility, severe soil erosion, reduced access to surface and groundwater, and poor water quality are the main socio-economic and environmental challenges in the Halaba zone (Mekuria et al., 2023). In response to these socio-economic and environmental challenges, the zonal department of agriculture, district agricultural offices, and local administrative bodies mobilized farmers to help with the construction of soil and water conservation measures, such as terraces, bunds, check-dams, trenches, and community ponds as well as planting indigenous and exotic plant species to restore degraded lands.

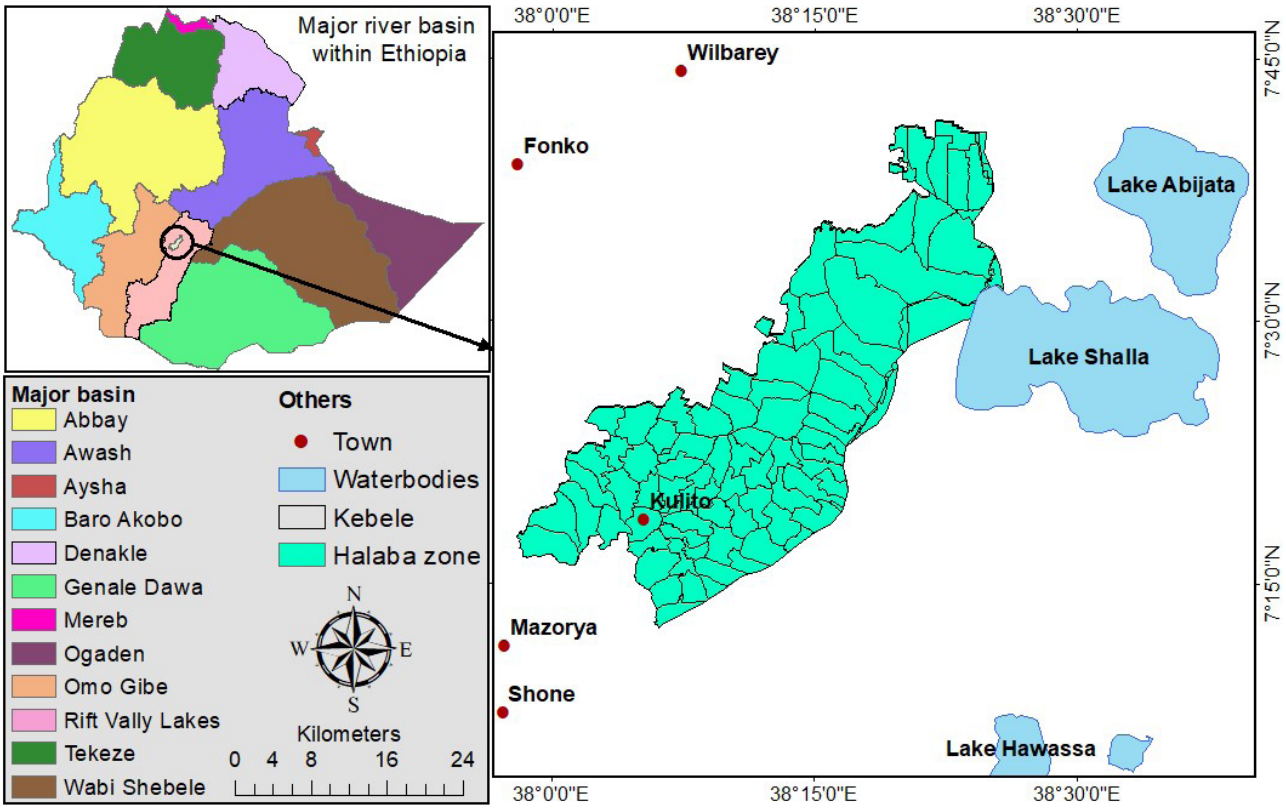

Figure 1. Location map of Halaba zone.

Note: Kebele refers to the lowest level of local government.

2.2 Data Sources and Collection Methods

GIS and remote sensing methods and literature reviews were used to characterize the biophysical features of the study area. The long-term (1985 – 2023) rainfall pattern was characterized using data retrieved from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data, available at https://data.chc.ucsb.edu/products/CHIRPS-2.0/global_annual/tifs/.

Topographic features, such as altitude and slope steepness were characterized using the freely available high-resolution (12.5m) digital elevation model (DEM) acquired from Alaskan Satellite Facility (https://search.asf.alaska.edu/#/). The traditional agroecological zones were classified using altitude and long-term mean annual rainfall (Hurni et al., 2016).

The major soils of the study area were classified using the latest FAO Harmonized World Soil Database version 2.0 (https://gaez.fao.org/pages/hwsd). SoilGrids raster layer at 250 m spatial resolution developed by the International Soil Reference Information Center (ISRIC) was used to assess soil organic carbon loss (https://soilgrids.org/). The soil erodibility value, at 250 m resolution, was acquired from the European Soil Data Centre (https://esdac.jrc.ec.europa.eu/node/115516).

To assess the long-term land use and land cover (LULC) dynamics, 30 m resolution Landsat images for 1994, 2004, 2014, and 2024 were retrieved from the System for Earth Observation Data Access, Processing and Analysis for Land Monitoring (SEPAL) open portal (https://sepal.io).

Two sources were used to acquire normalized difference vegetation index (NDVI) data, which were then analyzed to assess land productivity trends from 1994 to 2024 (Sims et al., 2021). Specifically, NDVI data from the Advanced Very-High Resolution Radiometer (AVHRR), sourced from the Global Inventory Modeling and Mapping Studies (GIMMS), were used to assess land productivity trends from 1994 to 2004. For the periods 2004 – 2014 and 2014 – 2024, NDVI data from the Terra Moderate Resolution Imaging Spectroradiometer Vegetation Indices (MOD13Q1) Version 6 were utilized to assess land productivity trends.

2.3 Data Analysis

2.3.1 Land use and land cover (LULC) analysis

Before LULC classification, image pre-processing, and enhancement techniques were applied to improve the quality of the raster images. A hybrid classification approach, combining unsupervised and supervised methods, was employed to accurately analyze larger areas with diverse biophysical characteristics (Kafy et al., 2021; Girma et al., 2022). For each identified LULC class, change in area was calculated across three time periods: 1994–2004, 2004–2014, and 2014–2024. The area of each category in the first year was subtracted from the area in the second year to determine the change. The annual rate of change for each category was then calculated by dividing the area change by the number of years between the two datasets (Girma et al., 2022). Land use and land cover transitions were analyzed using the transition matrix in ArcGIS (Zhang et al., 2018).

2.3.2 Assessing Land Degradation Neutrality (LDN)

Land Degradation Neutrality (LDN) refers to the principle of balancing land degradation with an equivalent amount of land restoration, preventing the net loss of healthy land resources (Orr et al., 2017; Cowie et al., 2018). The goal is to sustain or enhance land quality and productivity, supporting ecosystem services, agriculture, and livelihoods while curbing desertification and soil erosion. LDN emphasizes sustainable land management practices to restore and protect land, ensuring its continued productivity and resilience for future generations.

Land degradation neutrality was evaluated using the Good Practice Guidance (GPG) (Sims et al., 2019). We used GIS and remote sensing techniques to quantify the three indicators: land productivity (LP), land cover (LC), and soil organic carbon (SOC).

The change in the LP sub-indicator (kg ha^{-1} $year^{-1}$) was determined from a time series of annual NDVI datasets (Schillaci et al., 2023). One of the factors affecting the rate of change in LP within an ecosystem is the availability of water (Sims et al., 2021). Although several methods are available to calibrate time series images to minimize the influence of climate or seasonal factors on water resources, we used the Water Use Efficiency (WUE) correlation method, employing predefined datasets in Trends.Earth (Schillaci et al., 2023; Moges et al., 2023). WUE incorporates hydrological losses, such as runoff and groundwater recharge which influence the proportion of rainfall that is available for use by plants (Sims et al., 2021). The NDVI trends were adjusted for the WUE index using total actual annual evapotranspiration (Sims et al., 2021, Schillaci et al., 2023). To account for changes in WUE over time, a linear regression and a non-parametric significance test were applied (Schillaci et al., 2023).

To assess the LC sub-indicator, custom LULC data (1994, 2004, 2014, 2024) were used and reclassified to forestlands, grasslands, croplands, wetlands, artificial areas, bare land and waterbodies using the United Nations Convention to Combat Desertification (UNCCD) reporting and the Intergovernmental Panel on Climate Change (IPCC) land classifications. The land cover transition matrix between 1994–2004, 2004–2014 and 2014–2024 was then analyzed to identify the pixels that remained in the same land cover class and those that changed (Sims et al., 2019). Following this analysis, a feature of degradation typology was created based on expert knowledge to assess the dynamics of land degradation neutrality in terms of degradation, improvement or stability (Table 1). Finally, Trends.Earth combined the information from the LULC maps and the degradation typologies by LC transition to compute the status of land degradation based on the LC sub-indicator between 1994–2004, 2004–2014, and 2014–2024.

We used the relative changes in SOC, expressed in t ha^{-1}, to assess land degradation neutrality based on the SOC sub-indicator. The SOC change was determined using land use conversion coefficients, as recommended by the IPCC and the UNCCD (Yuan et al., 2022). Details of SOC estimation and the coefficients used are given in the Trends.Earth user guide and GPG (Sims et al., 2021). Areas that experienced a >10% loss in SOC during the reporting period were considered potentially degraded, and areas experiencing >10% gains were considered as potentially improved (Sims et al., 2021).

The sub-indicators were then combined using "The One-Out, All-Out (1OAO)" principle to determine the extent of land that is degraded as a percentage of the total area. The 1OAO principle implies that if any one of the indicators shows degradation (reduction or negative change), the overall assessment classifies the land as degraded regardless of positive trends in other indicators (Sims et al., 2019; Schillaci et al., 2023). 1OAO emphasizes the importance of maintaining all aspects of land health to achieve and sustain land degradation neutrality (Schillaci et al., 2023). This principle enables the identification of land degradation more accurately with three dimensions of land status, including above-ground, below-ground, and surface change (Zhao et al., 2023).

Table 1. The table of land degradation typologies by land cover transition.

Land cover in the initial year	Land cover in the target year						
	Tree-cover	Grassland	Cropland	Wetland	Artificial	Bare land	Water body
Tree-cover							
Grassland							
Cropland							
Wetland							
Artificial							
Bare land							
Water body							

Degradation Stable Improved

3. Results and Discussion

3.1 Biophysical Characterization and Implications for Land Degradation and Restoration

This sub-section summarizes the key biophysical characteristics of the Halaba zone, the study area, and implications for land degradation and restoration.

3.1.1 Topography

The elevation in the Halaba Zone ranges from 1516 to 2211 m asl (Figure 2a), with the highest elevation located in the central part of the zone. Most (52%) of the area is characterized by gentle slopes (5-15%) (Table 2, Figure 2e). Gentle slopes tend to experience lower runoff velocities, whereas moderately steep and steep slopes are more susceptible to higher velocities and runoff, which can lead to accelerated soil erosion during heavy rainfall events.

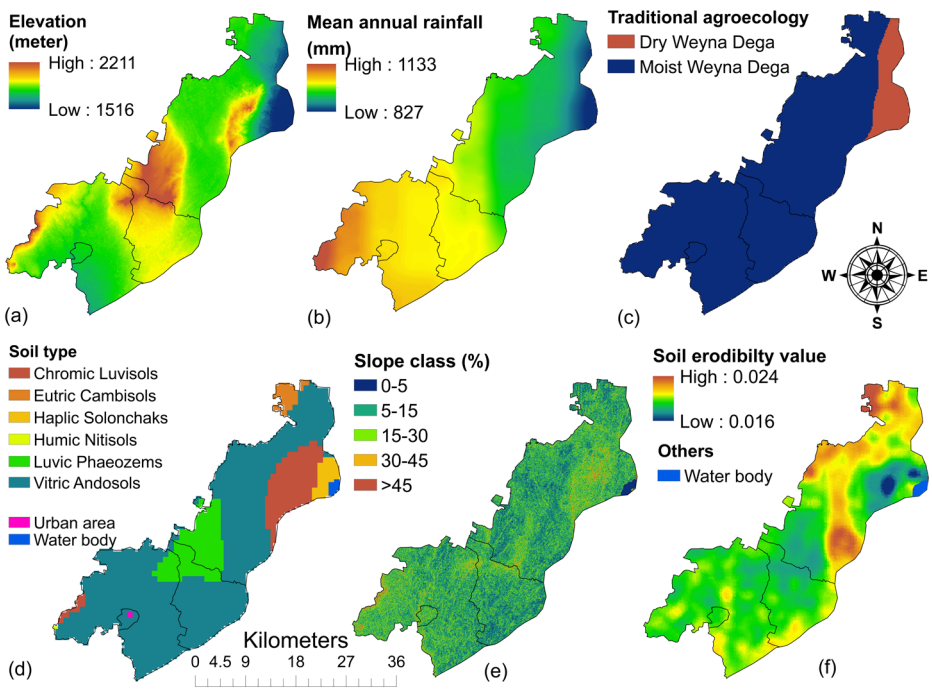

Figure 2. Selected site characteristics: (a) Elevation, (b) mean annual rainfall, (c) agroecological zone, (d) soil type, (e) slope, and (f) soil erodibility.

Table 2. Slope class of the study area.

Class	Slope range (%)	Description	year	
			Ha	%
1	0-5	Very gentle or flat	16036.6	16
2	5-15	Gentle slope	50793.3	52
3	15-30	Moderately steep slope	25776.7	26
4	30-45	Steep slope	4164.9	4
5	>45	Very steep slope (Escarpments)	1101.4	1
Total			**97873.1**	**100**

3.1.2 Rainfall distribution and agroecology

The agroecological classification of the Halaba Zone reveals that 91% of the area falls under Moist Weyna Dega, which receives between 900 and 1400 mm of rainfall annually and has an elevation ranging from 1500 to 2300 meters above sea level. The remaining 9% is categorized as Dry Weyna Dega, with less than 900 mm of rainfall and an elevation of 1500 to 2300 meters above sea level, primarily located in the northeast (Figure 2c). The mean annual rainfall in the Halaba zone varies between 827 mm and 1133 mm (Figure 2b), with higher precipitation observed in the central and southwest areas compared to the northeast. The Halaba zone has a bimodal rainfall distribution: a short rainy season, which extends from February to May, and the main rainy season, from June to September.

Adequate rainfall in the moist weyna dega zone supports agriculture and fosters better vegetation growth, which helps reduce the risk of surface erosion. However, intensive rainfall events on steep slope terrains, coupled with unsustainable land use practices, such as deforestation and overgrazing, can lead to significant soil loss. On the other hand, areas with lower rainfall will likely face challenges, such as poor vegetation cover, low organic matter, and increased soil vulnerability to erosion. This highlights the need for site-specific and locally led land management approaches that address both water retention in drier regions and erosion control in wetter areas.

3.1.3 Soil types

The result indicates that the soils of the Halaba zone can be divided into six soil groups (Figure 2d). More than 90% of the zone is covered by three soil groups (Table 3): Vitric Andosols (74%), Luvic Phaeozems (11%), and Chromic Luvisols (11%). Vitric Andosols are typically fertile and porous but are prone to erosion when vegetation cover is removed. The dominance of Andosols suggests the zone's inherent fragility and an increased risk of soil degradation especially under intensive land use and unsustainable agricultural practices. Luvic Phaeozems are also fertile and have good water-holding capacity, but improper land use can lead to nutrient depletion and structural degradation. Chromic Luvisols are generally stable but can suffer from compaction and erosion under intensive cultivation, emphasizing the need for effective vegetation management and erosion control measures.

The soil erodibility value ranges from 0.016 to 0.024, with relatively higher values in the central and northern parts of the Halaba zone (Figure 2f). The result suggests that soils in these areas are more prone to detachment and transport by erosive forces. This could be attributed to the low soil organic carbon content and coarse soil texture (Panagos et al., 2022). Consequently, these areas may require targeted soil conservation measures, such as contour farming, mulching, or enhanced vegetative cover, to reduce erosion risks.

Table 3. The soil type of the study area.

Soil type	Area	
	ha	%
Chromic Luvisols	10479.0	11
Humic Nitisols	48.2	0.05
Luvic Phaeozems	10816.2	11
Haplic Solonchaks	2264.4	1.95
Vitric Andosols	71546.1	74
Eutric Cambisols	1879.0	2
Total	**97032.9**	**100**

3.1.4 Land use and land cover

This study identified seven major LULC classes: waterbodies, grasslands, forestlands, farmlands, bare land, settlement/ built-up areas, and shrublands. The overall classification accuracy was greater than 84%, and the kappa coefficient

exceeded 80% (Table 4), suggesting that the classified maps are reliable for further analyses. Figure 3 illustrates the LULC change over the past three decades (1994, 2004, 2014, and 2024). Among the LULC classes, agriculture has remained the dominant land-cover class throughout the study period (Table 5). Over the last 30 years (1994 – 2024), the study area has undergone significant landscape alterations, with notable changes in LULC observed. The overall trends show a decrease in forestlands, shrublands, and grasslands, alongside an increase in farmlands, settlement areas, and bare land. These changes have primarily been driven by deforestation and the expansion of agricultural lands, largely due to the growing demand for farmlands in response to population increase.

Table 4. Accuracies of the classified maps showing producers accuracy (PA), users accuracy (UA) and overall accuracy (OA).

LULC Class	1994		2004		2014		2024	
	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)
Waterbodies	93.6	96.7	90.0	90.6	90.9	83.0	96.4	93.6
Forestlands	90.9	83.0	88.9	80.0	90.0	88.9	77.1	90.0
Farmlands	74.2	76.7	87.5	70.0	86.7	93.6	96.6	93.3
Bare land	78.6	83.3	83.3	83.3	80.0	87.1	86.7	93.6
Built-up areas	78.8	86.7	96.4	90.0	90.0	85.7	96.4	90.0
Grasslands	76.5	81.8	90.9	83.3	78.8	86.7	78.8	86.7
Shrublands	87.1	90.0	84.6	91.7	90.0	76.5	81.8	90.0
OA (%)	**84.3**		**85.5**		**86.3**		**87.04**	
Kappa	**0.80**		**0.84**		**0.81**		**0.87**	

Note: Kappa values < 0 refer to no agreement, 0–0.2 – slight agreement, 0.2–0.41 – poor agreement, 0.41–0.60 – moderate agreement, 0.60–0.80 – substantial agreement, and 0.81–1.0 – perfect agreement (Dey et al., 2021; Girma et al., 2022)

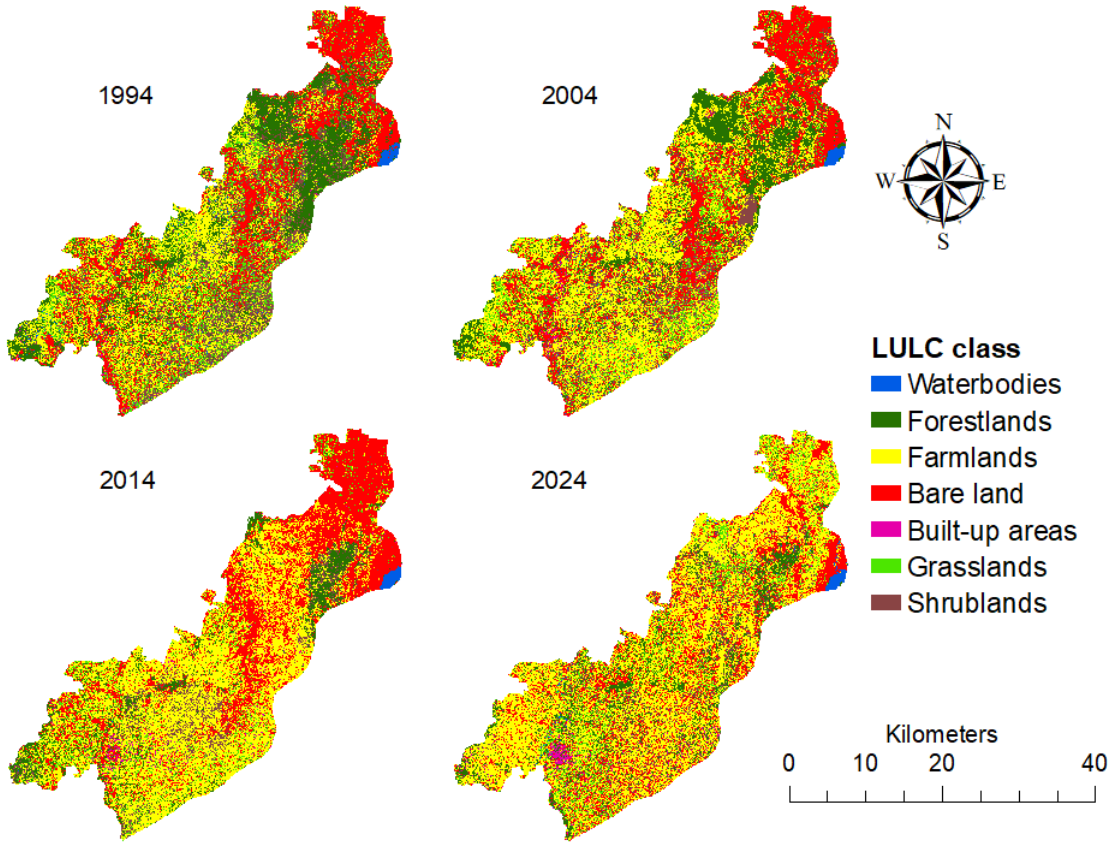

Figure 3. Land use and land cover for the years 1994, 2004, 2014 and 2024.

Table 5. Land-use and land-cover dynamics between 1994 and 2024.

LULC Class	1994		2004		2014		2024	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Waterbodies	1148.1	1.2	822.1	0.8	467.6	0.5	687.9	0.7
Forestlands	18920.3	19.3	16128.8	16.5	9235.3	9.4	11315.0	11.6
Farmlands	26315.5	26.9	35807.4	36.6	45404.6	46.4	51016.0	52.1
Bare land	25490.2	26.0	26314.7	26.9	31678.2	32.4	20905.0	21.4
Built-up areas	255.9	0.3	413.0	0.4	964.9	1.0	1283.2	1.3
Grasslands	11476.1	11.7	8763.8	9.0	5087.3	5.2	6102.9	6.2
Shrublands	14267.0	14.6	9623.3	9.8	5035.0	5.1	6563.0	6.7
Total	**97873**	**100**	**97873**	**100**	**97873**	**100**	**97873**	**100**

The patterns of LULC change reveal significant transformations across various LULC classes (Figure 4). Waterbodies experienced a net loss of 460 ha during the last three decades, largely converted to other land cover types, particularly conversions to farmlands (292 ha) and bare land (157.1 ha). The increase in water bodies from 2014 to 2024 could be attributed to the construction of water harvesting structures like community ponds as part of the implementation of community-based watershed development activities. Moreover, studies have indicated that most of the Ethiopian Rift Valley lakes experienced unstable water level fluctuations (Dadi et al., 2015, WoldeYohannes et al., 2018). Consistent with this, the expansion of water bodies might be linked to the displacement and lateral expansion of Lake Shalla due to the increase in sediment load, resulting from soil erosion. Farmland expansion was substantial, with a net gain of 24,700.1 ha, primarily at the expense of bare land (13012.9 ha), shrublands (6535.9 ha), forestlands (6043.7 ha) and grasslands (5268.3 ha). There was a 40% reduction in forestlands through a net loss of 7,604.9 ha between 1994 and 2024, primarily to shrublands, bare land, and grasslands. Grasslands exhibited a net loss of -5373.1 ha, mainly driven by the expansion of agricultural land, which gained 5268.4 ha from grasslands (Figure 4). Shrublands and bare lands showed a net decrease over the entire period, with shrublands losing 7703.9 ha and bare lands declining by 4,585.2 ha. Built-up areas, on the other hand, increased to take up an additional 1% of the land area, a net gain of 1027.3 ha.

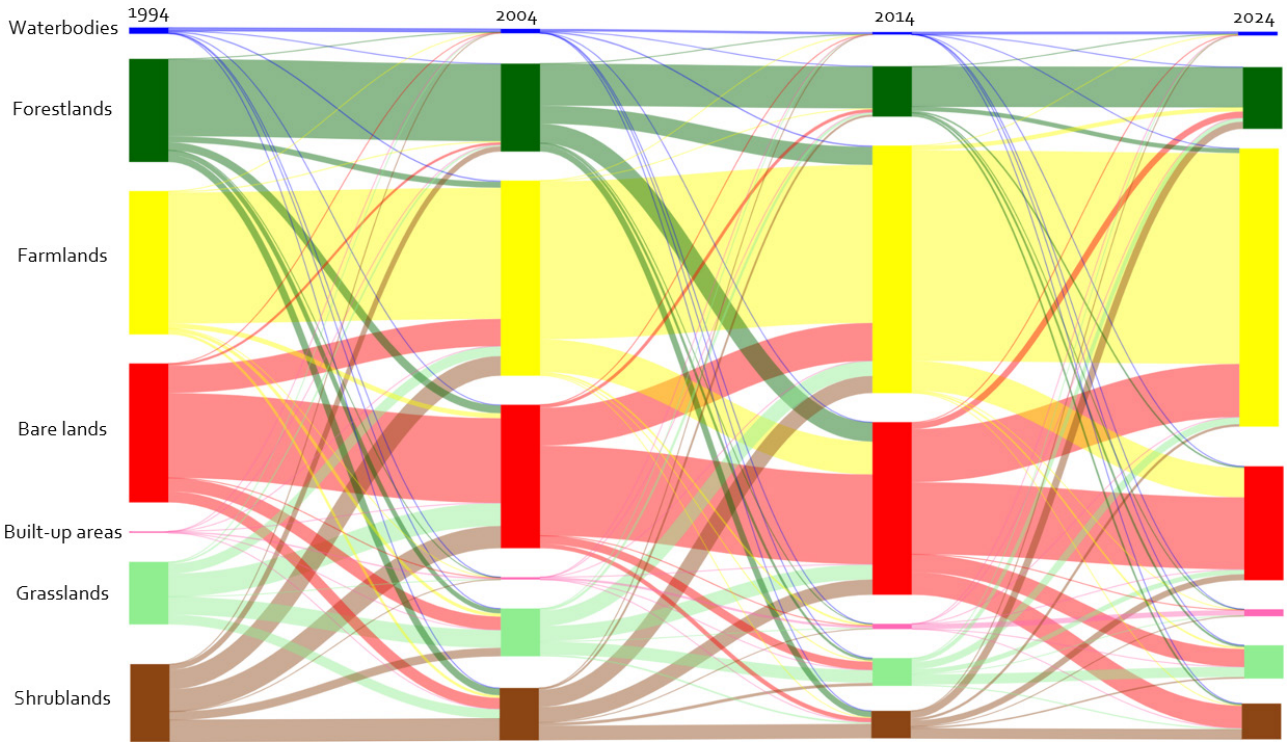

Figure 4. Sankey diagram showing LULC change transition for 1994–2024.

Note: The height of the vertical bars denotes the proportional area.

3.2 Land Degradation Neutrality

3.2.1 Land degradation neutrality in terms of land productivity

The assessment of land degradation neutrality using the land productivity (LP) sub-indicator revealed that the majority of the study area remained unchanged, accounting for 88% for 1994–2004, 74% for 2004–2014, and 83% for 2014–2024 (Table 6). However, the area showed improvements in LP trend of 8.9% for 1994–2004, 9.0% for 2004–2014, and 3.6% for 2014–2024. In contrast, areas with declining, early signs of decline, or stressed LP accounted for 1.8% for 1994–2004, 16.4% for 2004–2014, and 12.6% for 2014–2024. The spatial distribution of the LP indicator varied significantly across the study area (Figure 5a, b, c). During 1994–2004, areas with improved LP status were primarily located in the northeast (Figure 5a), while most of the degraded LP states were concentrated in the central and northeast parts during 2004–2014 (Figure 5b). By the period 2014–2024, most of the degraded LP areas were found in the northeast of the region (Figure 5c).

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

Land degradation indicator	1994-2004		2004-2014		2014-2024	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Land productivity (LP)						
Land area with improved productivity	8784.9	9.0	8816.0	9.0	3568.0	3.6
Land area with stable productivity	86544.3	88.4	72568.2	74.1	81544.3	83.3
Land area with degraded productivity	1756.6	1.8	16045.7	16.4	12336.3	12.6
Land area with no data for productivity	787.3	0.8	443.1	0.5	424.5	0.4
Total land area	**97873.1**	**100**	**97873.1**	**100**	**97873.1**	**100**
Land cover (LC)						
Land area with improved land cover	16676.7	17.0	14745.3	15.1	22039.7	22.5
Land area with stable land cover	55505.0	56.7	53526.3	54.7	47177.9	48.2
Land area with degraded land cover	25687.8	26.2	29420.0	30.1	28651.8	29.3
Land area with no data for land cover	3.5	0.004	181.6	0.2	3.5	0.004
Total land area	**97873.1**	**100**	**97873.1**	**100**	**97873.1**	**100**
Soil organic carbon (SOC)						
Land area with improved SOC	12239.6	12.5	13574.3	13.9	20522.6	21.0
Land area with stable SOC	62290.8	63.6	58682.8	59.95	49361.2	50.4
Land area with degraded SOC	21836.9	22.3	24001.5	24.5	26483.5	27.1
Land area with no data for SOC	1505.8	1.5	1614.4	1.6	1505.8	1.5
Total land area	**97873.1**	**100**	**97873.1**	**100**	**97873.1**	**100**
Combined indicators						
Land area improved	21603.7	22.1	16288.8	16.6	22760.9	23.3
Land area stable	47579.8	48.6	40566.2	41.4	38011.7	38.8
Land area degraded	26978.1	27.6	39333.7	40.2	35559.6	36.3
Land area with no data	1711.4	1.7	1684.4	1.7	1540.8	1.6
Total land area	**97873.1**	**100**	**97873.1**	**100**	**97873.1**	**100**

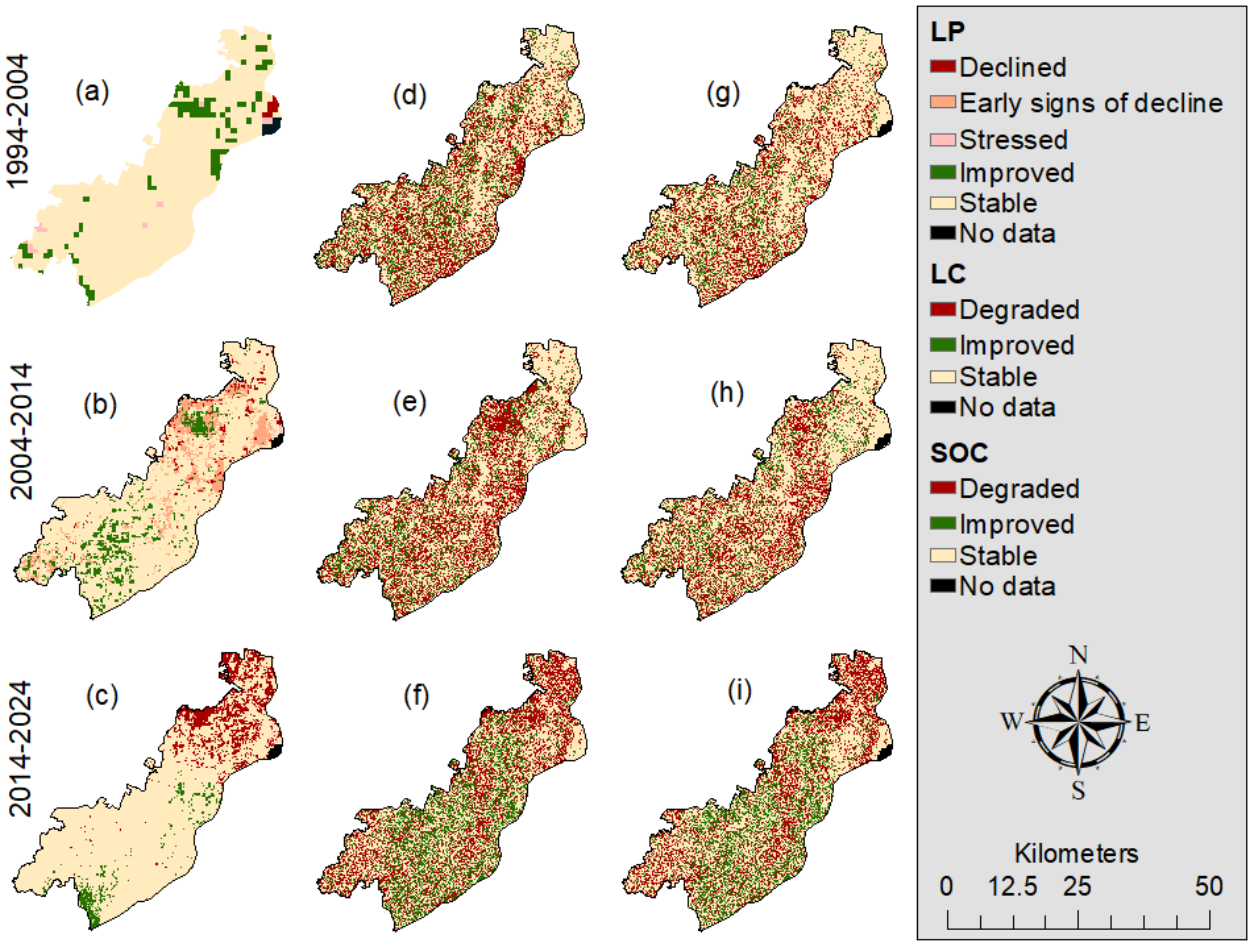

Figure 5. Land degradation sub-indicators: land productivity (LP) (a, b, c), land cover (LC) (d, e, f) and SOC (g, h, i).

3.2.2 Land degradation neutrality in terms of land cover

The assessment of land degradation neutrality, based on the land cover (LC) sub-indicator, revealed that the majority of areas were classified under stable LC status, accounting for 56%, 55%, and 48% during the periods 1994-2004, 2004-2014, and 2014-2024, respectively (Figure 5d, e, f). From the baseline period (1994) to the reporting period (2024), the proportion of the areas showing degraded conditions increased from 26% to 29% (Table 6). Conversely, the proportion of the areas demonstrating improved conditions decreased from 20% to 16% (Table 6).

The increase in degraded areas suggests that although conservation efforts may have been implemented (see study area section), their long-term success is likely compromised by a lack of follow-up, poor maintenance, and insufficient community involvement (Bayle and Muluye, 2023). To achieve land degradation neutrality, it is essential to address these challenges by incorporating local knowledge, promoting participatory approaches, and strengthening institutional capacities (Saik et al., 2024). In addition, effective watershed management strategies need to be promoted to foster sustainable development, ecological balance, and improved livelihoods (Mengistu and Assefa, 2020).

3.2.3 Land degradation neutrality in terms of loss of soil organic carbon

The assessment of land degradation neutrality, based on the SOC sub-indicator (Figure 5g, h, i) across the three periods: 1994-2004, 2004-2014, and 2014-2024 showed that 13%, 14%, and 21% of the study area improved, while 64%, 60%, and 50% displayed stable condition, respectively (Table 6). In addition, the percentage of degraded areas increased, from 22% in 1994-2004 to 25% in 2004 – 2014, and 27% in 2014-2024.

3.2.4 Land degradation neutrality in terms of combined indicators

By combining the three sub-indicators: LP, LC, and SOC, the results of the analysis reveal the following land neutrality status across the areas: 28%, 40%, and 36% of the area experienced degradation, while 49%, 41% and 39% unchanged, and 22%, 17% and 23% showed improvement over the periods between 1994-2004, 2004-2014 and 2014-2024, respectively (Table 6, Figure 6). The findings indicate persistent land degradation challenges though the proportion of improved areas is encouraging for further restoration efforts. The results suggest the need for enhanced efforts to reverse degradation trends and achieve LDN by 2030. This includes scaling up effective practices, strengthening policy enforcement and monitoring systems, prioritizing severely affected areas, and ensuring active community involvement (Solomon et al., 2024).

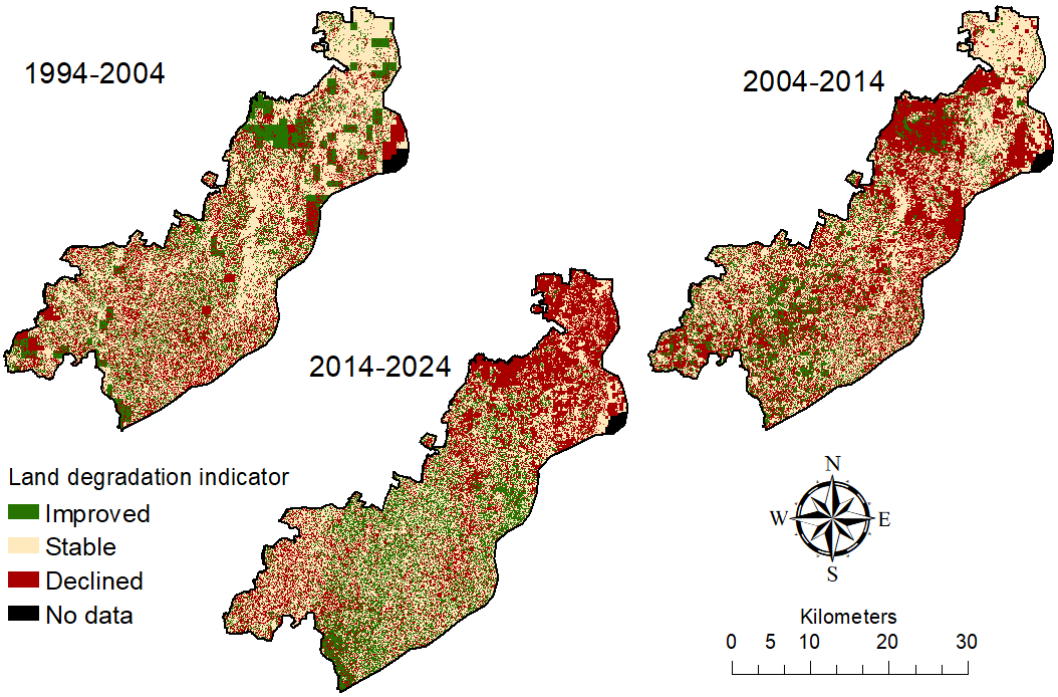

Figure 6. Land degradation indicator map.

4. Implications for Designing Sustainable Land Management Practices

The Halaba zone, the focus of this study, shows significant variations in biophysical conditions, including elevation, slope, rainfall, soil, agroecological zones, land use land cover, and land degradation neutrality. These variations play a critical role in shaping locally-led sustainable land management (SLM) practices, as they influence the suitability of land for agricultural, biodiversity conservation, and restoration efforts. The key implications of these variations for designing and planning locally-led SLM practices are as follows:

- **Elevation:** the study area's higher elevations, which include mountainous terrain, present harsher climate conditions that affect soil fertility, crop viability, and water availability. Managing these areas requires targeted strategies to prevent soil erosion and regulate water flow, such as terracing, exclosures, or agroforestry.

- **Rainfall:** The availability of water for crops and vegetation is influenced by rainfall patterns. In areas with high or adequate rainfall, such as the moist Weyna Dega agroecological zone (which covers 91% of the study area), water management techniques like drainage systems may be necessary. In contrast, areas within the dry Weyna Dega agroecological zone would benefit from practices such as drought-resistant crops, irrigation systems, and water conservation methods.

- **Slope:** The study area features both moderately steep to steep slopes (covering 32% of the land) and flatter or gently sloping areas (covering 68%). Steeper slopes are more prone to soil erosion, necessitating conservation measures like contour farming, terracing, and reforestation. Flat or gently sloping regions, while less vulnerable to erosion, may require enhanced drainage and soil fertility management practices to avoid land degradation.

- **Agroecological Zones:** These zones, defined by rainfall and altitude, greatly influence the suitability of agricultural practices in the area. Understanding the agroecological zones helps design site-specific restoration strategies, ensuring that practices are tailored to local conditions for greater sustainability.

- **Land use land cover:** The observed changes in land use and land cover, characterized primarily by the expansion of farmland at the expense of natural vegetation, highlight the urgent need for community-driven solutions. These could include participatory land-use planning, the adoption of agroforestry practices, afforestation programs, and the promotion of climate-resilient farming techniques, all aimed at balancing agricultural productivity with the preservation of ecosystems.

- **Land Degradation Neutrality:** This concept focuses on balancing land degradation and restoration. By considering spatial variations, locally-led management practices can aim to prevent, reduce, or reverse land degradation through integrated strategies that enhance soil fertility, improve water management, and promote biodiversity.

In summary, spatially tailored land management approaches are essential for addressing land degradation and promoting landscape restoration. A thorough understanding of local biophysical conditions ensures that interventions are both appropriate and effective, fostering long-term environmental health and socio-economic benefits for communities. The SMILE project will integrate this knowledge when designing and planning locally-led SLM practices, consulting with local communities, and incorporating local expertise.

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