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Research article

Smallholder farmers' vulnerability to climate change and variability: Evidence from three agroecologies in the Upper Blue Nile, Ethiopia

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ABSTRACT

This study delves into the profound impact of climate change on agriculture in Ethiopia, particularly the vulnerabilities faced by smallholder farmers and the resulting implications for poverty. Focusing on three distinct agroecologies, namely: highland, midland, and lowland zones. The study employed a robust methodology, combining a cross-sectional survey, spatial-temporal trend analysis using GIS, and the development of an overall vulnerability index through the balanced weighted average method. The study, encompassing 646 households, combines data from a variety of sources and analytical tools like the vulnerability index, ArcGIS 10.8, and ERDA's IMAGINE 2015. Utilizing the LVI-IPCC scale, the study shows that climate change is an immediate vulnerability in all agroecological zones. It identifies highland areas as the most sensitive and exposed regions, while lowland households are found to be the most vulnerable in terms of overall vulnerabilities. The research reveals specific challenges faced by communities, such as inadequate health facilities and insufficient food and water supplies in both highland and lowland agroecosystems. Additionally, our investigation has observed a significant alteration in land use practices, specifically the shift from communal grazing land to private cultivation and plantations, emphasizing eucalyptus. This alteration enhances the ecosystem's vulnerability to climate disturbances. The study suggests targeted interventions, such as advocating for sustainable land-use practices, afforestation, and adopting climate-smart agriculture practices. It is important to implement policy measures that prioritize conserving and restoring shrubland, grazing land, and natural forests to ensure both long-term socio-economic and ecosystem resilience. The study's nuanced insights are instrumental in understanding the diverse challenges posed by climate change in Ethiopian agriculture, supporting informed policymaking and sustainable interventions.

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1. Introduction

Climate change is a major threat to both natural and human systems, leading to lasting harm and losses for ecosystems and humans shortly (2021–2040) [1]. Agriculture is particularly affected by these threats [2,3,4]. The rise in average temperature by 1.5 °C in the near term (2021–2040), attributed to a lack of commitment to reducing greenhouse gases and human inefficiency [1], has led to climatic extremes with adverse effects on ecosystems, biodiversity, and human systems [5,6,7].

Climate change poses a threat to the livelihoods of individuals worldwide, especially in developing countries, where agriculture serves as a primary source of income [2,8,9,10]. Agriculture and the livelihoods of smallholder farmers are significantly influenced by weather and climate variables, including temperature, precipitation, floods, droughts, and storms [11,12,13]. Smallholder farmers in Sub-Saharan Africa, relying on subsistence agriculture with limited adaptive capacity, face heightened vulnerability [14,15,16]. Ethiopia, where agriculture contributes 32.6% to GDP, 77% of exports, and employs 72.7% of the labor force, is particularly exposed to the impacts of climate change and variability [17]. The smallholder farming households, constituting around 95% of total agricultural production, are particularly at risk. The agricultural practices in the region, characterized by small-scale, traditional, rain-fed, and subsistence-oriented methods, encounter substantial productivity challenges linked to rainfall variability [18,19].

Climate-related crises in Ethiopia, spanning from the 2000s to the 2010s, have significantly disrupted the lives of nearly 38 million people [20]. Since 1960, Ethiopia has witnessed an average temperature increase of 1 °C, equating to a decade-by-decade rise of 0.25 °C. This warming trend has resulted in heightened evapotranspiration and reduced soil moisture, impacting agricultural productivity. Future projections for temperatures and precipitation from 2040 to 2059 anticipate a sustained increase ranging from +1.2 °C to +2.6 °C, coupled with a variation in rainfall between −16.8 mm and 27.4 mm. These projections exacerbate the adverse impact of climate change on the livelihoods of smallholder farmers [21].

The repercussions of climate change extend to food and nutritional insecurity in Africa, resulting in reduced crop yields, animal production, and rangeland productivity, leading to high prices and restricted access to agricultural products and services [22,1,23,24]. Disasters such as species extinction, food and energy insecurity, malnutrition, and the loss of livelihood have ensued due to decreasing food production [2,25,26,27], exacerbating poverty, hindering economic development, and increasing inequality [28,1,29]. Sub-Saharan African nations, including Ethiopia, face heightened vulnerability to climate-related dangers compared to other regions of the world [1,30,16]. In Ethiopia, farmers, particularly, are compelled to deplete their irreplaceable assets to withstand these challenges, resulting in heightened poverty and food insecurity among families [31,32,33,34].

Frequent occurrences of floods and droughts in Ethiopia have led to loss of life, property, and mass displacement [35,36,37,38]. Notably, 19 drought episodes were recorded in Ethiopia between 1900 and 2002, with increasing frequency over the years [39]. The vulnerability of Ethiopia's agriculture to climate change is evident through the detrimental effects of droughts, floods, seasonal shifts, heat waves, and windstorms on production and economic growth [40,38,41]. The country's vulnerability is further compounded by high poverty levels, dependence on primary sectors, topographic nature, and vulnerability to non-climatic stresses such as inadequate infrastructure [32,36,42,43]. Despite efforts to reduce reliance on rain-fed agriculture, enhance innovation, and support smallholder

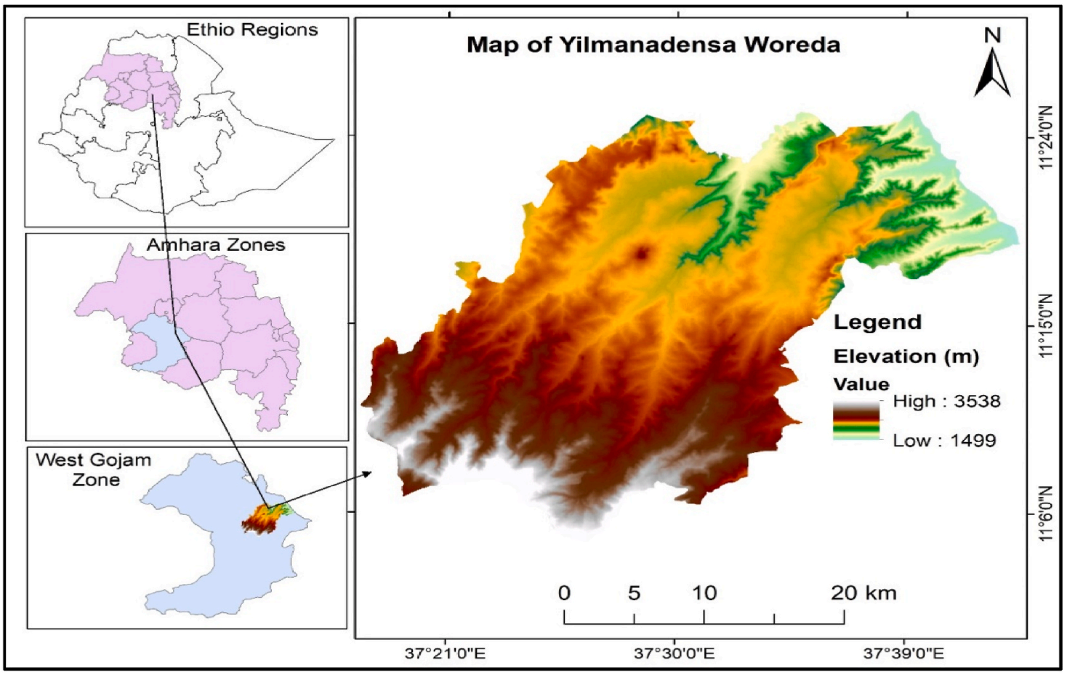

Fig. 1. Map of Ethiopia, Amhara Region, West Gojjam zone, and the Study area; Yilmana Danas.
(Source: Authors' compilation using ArcGIS, 2022)

farmers through agricultural development policies, the challenges persist [44,17].

Numerous studies in Ethiopia have assessed smallholder farmers' vulnerability to climate change, with varying conclusions on the most vulnerable agroecologies [8,45,46]. Scholars consistently advocate for conducting vulnerability assessments specific to location and agroecology contexts to formulate effective response strategies against climate change hazards and enhance resilience [20,3,47]. Thus, this finding provides insights into factors influencing vulnerability, encompassing exposure to rainfall, temperature, floods, and biophysical patterns trends over time with consideration of agroecology contexts. The multidimensional insights into smallholder farmers' vulnerability in Ethiopia's Upper Blue Nile basin bear significant implications for policymakers and practitioners working towards a green economy, environmental sustainability, and socio-economic development in the region. Moreover, it adds valuable knowledge to the resilience of smallholder farmers in the face of climate change. This study uniquely contributes to vulnerability assessment by innovatively examining exposure and sensitivity trends over time, integrating both socioeconomic and biophysical factors. The significance of the paper is emphasized through its comprehensive analysis, which encompasses a thorough evaluation of these trends, considering both socio-economic and biophysical environmental factors. This innovative approach provides a nuanced understanding of vulnerability, offering insights into the specific impact of climate-induced shocks on different agroecologies within Ethiopia. Notably, the study contributes to the existing body of knowledge by shedding light on the multidimensional factors influencing the vulnerability of smallholder farmers in the region, encompassing exposure to rainfall, temperature, floods, and biophysical patterns.

This paper is structured as follows: Section 2 provides a comprehensive overview of the materials and methods employed. Section 3 encompasses both the presentation of results and the ensuing discussion. Finally, Section 4 includes the conclusion along with outlines for policy recommendations.

2. Material and methods

2.1. Study area

As shown in Fig. 1 the study was carried out in Yilmana Denesa *Woreda*, located in the Upper Blue Nile Basin of Ethiopia. The area is divided into three agroecologies—highland, midland, and lowland - with altitudes ranging from 1499 to 3538 m above sea level. The *Woreda* has a total area of approximately 92,587.4 ha and covers an altitude range of >2400 m.a.s.l for the highlands, between 1800 and 2400 m s l for the midlands, and 1500–1800 m s l for the lowlands [48]. Fig. 1 shows the coordinates of the study area, which falls between 11^0 6' 0 " and 11^0 24' 0" N and 37^0 21' 0" to 37^0 39' 0" E. The Midland agroecology covers the largest area, accounting for 61% of the total study area. This is followed by highland s (32%) and lowlands (7%). According to the Central Statistics Authority, the total population of Yilmana Denesa *Woreda*[1] is 214,850, out of which 106,967 are males [49]. The total number of households is 44,437, of which 8056 are female-headed and the remaining are male-headed households [50].

The study area encompasses 92,914.06 ha, with land cover distribution as follows: shrub land covers 14,282.8 ha (15.37%), cultivated land spans 64,423 ha (69.34%), settlement areas occupy 1157.58 ha (1.25%), plantations encompass 9896.1 ha (10.65%), natural forests cover 343.71 ha (0.37%), and grazing land extends over 2810.87 ha (3.03%) (computed using ArcGIS, 2022). The mean annual temperatures in the highland, midland, and lowland areas are 13.710 °C, 17.60 °C, and 22 °C, respectively (calculated from monthly temperature data obtained from ee. ImageCollection ("IDAHO_EPSCOR/TERRACLIMATE, 2022"). In the highland agroecology, rainfall ranged from 1303.34 mm to 1853.3 mm, with an annual average of 1534.3 mm. The midland agroecology experienced rainfall quantities between 997.9 mm and 1515.2 mm, with an average annual rainfall of 1282.7 mm. In the lowland agroecology, recorded rainfall varied from 883.3 mm to 1339.9 mm, with an average of 1141.9 mm (computed from Image Collection ("UCSB-CHG/CHIRPS/DAILY, 2022").

2.2. Sampling and data Collection procedure

In this study, we investigated the vulnerability of smallholder farmers using both a cross-sectional survey and a GIS spatial-temporal trend analysis. We followed [51] recommendations by employing a stratified sampling technique, aiming for a representative sample across various agroecologies. A multistage sampling procedure was used, starting with the identification of a vulnerable *Woreda* with three distinct agroecologies. Randomly selecting four *Kebeles*[2] from midland, two from highland, and two from lowland agro-ecologies, they ultimately surveyed 646 respondents, with 326 households from midland, 160 from highland, and 160 from lowland agroecology.

The sample size of respondents in this study was determined following the methods proposed by Ref. [52], which consider the margin of error and confidence interval. If adequate information on p isn't available from earlier studies or a pilot sample [53] suggest using a confidence coefficient of 0.95 and an error margin of 0.04 to determine a suitable sample size. In this study, the confidence coefficient is 0.95, and the marginal error is 0.04 Eq. (1)

$$n = \frac{\text{Nz2pq}}{\text{e2 (N} - 1) + \text{z2pq}} = \frac{\mathbf{44437}(\mathbf{1.96})^2(\mathbf{0.5})(\mathbf{0.5})}{(\mathbf{0.04})^2(\mathbf{44436}) + \mathbf{0.9604}} = 592 \text{ small householder farmers'}\ldots\ldots \quad (1)$$

[1] *Woreda* is medium level administrative unit of Ethiopia that comprises 25–35 *Kebeles* that equivalent to district.

[2] *Kebeles* are smaller administrative units that comprise 5–10 villages in Ethiopia next to *Woreda*.

Where n is the desired sample size, N is the population size, z is at the z statistic for a level of confidence set at 1.96 for a 95% confidence level, p is the expected proportion of an attribute that is present in the population (0.5); q is the estimated proportion of an attribute that is not present in the population (1-p) (0.5); and we = precision level (0.04). 10% of the sample size was added to account for people who could not be contacted and questionnaires returned, and 646 households were surveyed.

To collect the socio-economic data, we prepared a survey questionnaire. The questionnaire was evaluated by the Bahir Dar University Institutional Review Board and got amendments. After getting amendments we get an approval certificate from the Bahir Dar University Institutional Review Board and then loading on KOBO TOOL BOX and collect that data through this software. The institutional board review committee approval date and serial number are presented at the end of this paper.

2.3. An integrated approach to assessing vulnerability

This study involved a survey of 646 households, 7 focus groups, and 8 key informant interviews. The key informants were chosen specifically for their knowledge of agricultural practices and climate patterns in the area of the *Woreda* level. Six farmer key informants, two from each agroecology, participated in the study. A semi-structured questionnaire was used during the interviews and data collected was analyzed using thematic analysis.

2.3.1. Composite index approach vulnerability index analysis

The vulnerability status of farm households was evaluated through a vulnerability index developed using a balanced, weighted average technique to assess their overall vulnerability [54,55]. LVI comprises three key indicators: exposure, sensitivity, and adaptive capacity. Each sub-component contributes equally to the total index using a balanced, weighted average technique [55,56]. The LVI formula is adapted from the life expectancy index, calculating the ratio of actual life expectancy to specified maximum and minimum life expectancies [57,58]. The LVI formula uses a balanced, weighted average technique where each sub-component contributes equally to the total index to create an assessment tool used by a wide range of users [59,60]. Since the sub-components are measured on various scales, it was required to first standardize each as an index. This conversion formula differs from the one used to calculate the life expectancy index, which is the ratio of the difference between the actual life expectancy and a minimum and range of defined maximum and minimum life expectancies [54,57,58]. For each indicator, households were asked to provide an effect value based on continuous, nominal, or ordinal scales, and then the data were normalized using Eq. (2) To provide standard values ranging from 0 to 1.

$$\text{Index VI} = \frac{(\text{Maxi} - \text{xi})}{(Maxi - Minxi)} \tag{2}$$

Where VI is the normalized value of the indicator; Maxi is the maximum value of indicator I; Minxi is the minimum value of indicator I and xi is the ith value of an indicator for the earth household.

After each was standardized, and obtaining values of sub-components, the sub-components were averaged using Eq. (3) To calculate the value of each major component:

$$\text{MA} = \frac{\sum_{i=1}^{n} index\ SAi}{n} \tag{3}$$

Where: MA = one of the major components of study agroecology index SAi = subcomponent, n = number of subcomponents in each major component of this agroecology. Then the overall LVI AI the Livelihood Vulnerability Index for agroecology 'A', equals the weighted average of the 3 major components. The weights of each major component, WMi, are determined by the number of sub-components that make up each major component and are included to ensure that all sub-components contribute equally to the overall LVI [54,57,56]. Eq. (4)

$$\text{CFA} = \frac{\sum_{i=1}^{n} WMiMAi}{\sum_{i=1}^{n} WMi} \tag{4}$$

Where: where CFA is an IPCC-definite contributing factor (exposure, sensitivity, or adaptive capacity) for agroecology A, MAi are the major components for agroecology A indexed by this formula. WMi is the weight of each major component, and n is the number of major components in each contributing factor. After getting one LVI the overall smallholder farmers' vulnerability status was calculated using Eq. (5) through IPCC-definitely contributing factors (exposure, sensitivity, and adaptive capacity) combined using the following equation:

$$\text{LVI-IPCCA} = (\text{eA–aA}) * \text{sA} \tag{5}$$

Where: LVI–IPCCA = the LVI for agroecology 'A' expressed using the IPCC vulnerability framework.

EA = the calculated exposure score for agroecology 'A'

AA = the calculated adaptive capacity score for agroecology 'A'

SA = the calculated sensitivity score for agroecology 'A'

In this study, we scaled the LVI–IPCC from −1 (least vulnerable) to 1 (most vulnerable) [34,43,45,46].

2.3.2. Data sources and analysis of ecological vulnerability through land use/land cover change

For this study, data from various sources were collected, including satellite imagery, field data, and information from local experts and residents. Four-time series (1992, 2003, 2013, and 2022) Landsat images were obtained from the Earth Explorer data archive, using different Landsat sensors (thematic mapper, enhanced thematic mapper, and operational land imager) (4–5, 7, and 8–9). Various software and materials were used to achieve the study's goals. During fieldwork, a GPS Garmin 12 was used as a global posting system. The corresponding satellite images are shown in Table 1. Factors such as availability, cost, spatial resolution, capture date, and cloud cover were taken into consideration when selecting satellite data.

We employed Geographic Information System (GIS) and Remote Sensing Analysis (RS) to monitor changes in land use and land cover, aiming to enhance understanding of ecosystem vulnerability. The selected years for classification were based on data availability and the study's objectives post-1992. Ground control points were collected during fieldwork using GPS to support image classification. While most data were extracted from satellite images, continuous field observations provided training data for image interpretation. Clear conditions and dry grass facilitated satellite data interpretation. Field observations characterized quantitative aspects of each land use/land cover class. The study compared current practices, forest conditions, and conservation efforts with participant statements from focus groups and key informant interviews to validate findings (https://earthexplorer.usgs.gov).

We collected data from multiple sources, including local communities and satellite imagery. We used ArcGIS 10.8 and ERDAS IMAGINE 2015 to analyze the data and prepare maps. Six LULCC classes were identified and classified, and land use/land cover change analysis was conducted for the years 1992, 2003, 2013, and 2022 (see Table 2).

To classify the satellite images, we used unsupervised and supervised classification methods. The unsupervised classification was employed to identify features in pixel form, while the supervised classification used ground control points and identifiable coordinate points from Google Earth [61]. Ultimately, we collected 110 ground control points for image classification. The accuracy of the product classification was assessed, and the area coverage of each LULCC class on classified images [62,63] was developed using ERDAS IMAGINE 2015.

3. Results and discussion

3.1. Smallholder farmers' vulnerability to climate change and variability

The vulnerability status of smallholder farmers to climate change is outlined in Appendix table A1, determined through a systematic process of standardization, weighing, subcomponent division, and regrouping of the main components: exposure, sensitivity, and adaptive capacity. Following IPCC-LVI standards, smallholder farmers can assess their climate vulnerability within each agroecology by computing the composite LVI score. This innovative vulnerability assessment provides a comprehensive framework for evaluating the climate vulnerability of smallholder farmers, integrating exposure, sensitivity, and adaptive capacity components within a unified index. The balanced weighted average technique ensures equitable consideration of each sub-component, aligning with established IPCC standards [56]. The adaptation of the LVI formula from the life expectancy index offers a robust and adaptable method for quantifying vulnerability [57,58].

The systematic process in Appendix table A1enhances transparency and trustworthiness for stakeholders to effectively understand and utilize the methodology. Detailing smallholder farmers' vulnerability status in each agroecology, the assessment not only provides a nuanced understanding of challenges but also empowers farmers for informed decisions in their unique context. This practical tool significantly contributes to the field, addressing the complexities of vulnerability assessments in diverse environments. The study's rigorous methodology and clarity establish a foundation for future research and policymaking, emphasizing the importance of a standardized yet adaptable approach to vulnerability assessments in the context of climate change and agriculture.

3.1.1. Smallholder farmers' exposure

The exposure component of the study encompasses eight sub-components related to natural disasters and climate variability: changes in maximum and minimum temperatures, precipitation, runoff, climate-related hazards such as floods and droughts, households without warning, households with injuries, and households with deaths. A 40-year analysis reveals that the lowland agroecological zone had the highest score for changes in maximum temperature, indicating greater exposure to heat stress. Meanwhile, the midland had the highest change in minimum temperature. Changes in precipitation over 40 years were highest in lowland zones, followed by midland and highland zones, suggesting varied contributing factors.

Table 1
Description of Satellite images.

Year	Sensor	Path/Row	Date of acquisitions	Spatial Resolution
1992	Landsat 4–5 TM	170/051	1992/02/28	30 m*30 m
2003	Landsat 7 ETM+	170/051	2003/01/30	30 m*30 m
2013	Landsat8-9 OLI/TIRS	170/051	2013/02/27	30 m*30 m
2022	Landsat8-9 OLI/TIRS	170/051	2022/03/27	30 m*30 m

Source download from: https://earthexplorer.usgs.gov*, (2022)*

Table 2
Specification of Land use-land cover change classification parameters.

Classification	Description
Shrub/ bushland	Areas covered by small trees, bushes, and shrubs, in some cases, mixed with grasses; less dense than forests
Cultivated land	Areas allotted to rain-fed and irrigated cultivation for crop production and scattered rural settlements usually associated with cultivated lands
Settlements	Areas covered with buildings, and houses in urban or semi-urban areas
Plantation	Areas covered with woodlots grown on small individual farm plots or plantations in communal lands dominated by Acacia decurrence and Eucalyptus species
Natural Forest	Areas covered with forests of both natural indigenous tree and riverine vegetation species.
Grazing land	Areas covered by grasses and used for grazing, as well as bare land that has little grass or no grass cover

Source: own computation, (2022)

Furthermore, the study identifies that the number of climate-related hazards was highest in the lowlands, followed by the highlands, with the midlands being the least exposed. Highland areas had the highest percentage of households with injuries due to natural disasters, while lowlands had the highest percentage of households not receiving warnings about impending disasters. The weighted exposure index shows that all three agroecologies exhibit similar levels of exposure weight, with highlands experiencing the highest exposure (0.338), followed by lowland (0.329), and midland (0.328), indicating critical vulnerability to climate change in highland areas compared to other zones (Annex table A1).

Contrary to findings from various studies, including those conducted by Refs. [8,25,64] which suggest that lowland agroecology is the most exposed to climate variability followed by highland agroecology [65]. Found different results. They reported that the midland agroecology was the most exposed when compared to the lowland and highland agroecologies. A critical literature review at the country level by Refs. [20,47] revealed that lowland and highland agroecologies are more vulnerable than midland agroecology, aligning with the current study's findings. This suggests that, in most parts of Ethiopia, lowland and highland agroecologies are more vulnerable to the adverse impacts of climate change than midland agroecology.

3.1.2. Smallholder farmers' sensitivity

The study underscores the vulnerability of farmers' assets and resources to the risks associated with climate change and variability [55]. According to the sensitivity index, households in highland areas exhibited the highest vulnerability compared to lowland and midland households, with values of 0.421, 0.413, and 0.331, respectively (Annex table A1). This indicates that highland households are the most prone to the impacts of climate change compared to their counterparts in other regions. The study further identified four major components under this indicator, namely ecosystem, health, food, and water.

Ecosystem: The sensitivity index scores revealed that households in lowland agroecological zones had the highest score of 0.538, indicating relatively less contribution to the ecosystem management activities compared to highland and midland agroecological zones with scores of 0.434 and 0.425, respectively (Annex table A1). This may be associated with the topographical nature characterized by cliffs and gorges; smallholder farmers in lowland and highland agro-ecologies do not engage in tree plantation. Furthermore, in lowland agroecology, the combination of high temperature and a high evapotranspiration rate renders the land more barren, exposing the soil to increased erosion. These factors contribute to the heightened sensitivity of the lowland agroecology, followed by the highland agroecology. Empirical studies and literature reviews in Ethiopia consistently designate lowland agroecology as more ecologically sensitive, followed by highland and midland agro-ecologies [8,65]. Critical literature reviews, as presented by Refs. [20,47], consistently identify lowland agroecology as more ecologically sensitive, followed by highland and midland agro-ecologies, aligning with the current study's findings.

Health: The health component of the study, comprising four sub-components, identified households in lowland agroecological zones as the most vulnerable (score of 0.332), with focus group discussions revealing the prevalence of typhoid, malaria, and other waterborne diseases in lowlands. Despite increased health facility availability, the distance to health facilities was highest for households in the highlands, contributing to a decrease in the overall health index. Lowland households also had the highest percentage of households with chronic illnesses (0.3%) (Annex table A1).

Food: The study highlighted concerns about food access for households in highland areas, with a vulnerability index of 0.382, while lowland households showed relatively lower vulnerability with a contributing factor of 0.291. Additionally, households in both highland (0.289) and lowland (0.152) areas struggled to find food for a longer duration compared to households in midland (0.15) areas. Farmers in highland areas grew the lowest number of crop types, indicating lower crop diversity compared to midland and lowland areas (Annex table A1).

Water: The vulnerability index revealed that households in highland areas are the most vulnerable to water-related issues (0.517), while households in midland areas are the least susceptible (0.408). Conflicts over water resources were more commonly reported by households in highland areas, attributed to mountainous terrain and natural resource degradation, making it difficult for households to access sufficient water throughout the year (Annex table A1). This aligns with previous studies confirming less accessible water sources, particularly in lowland and highland agroecological zones [45,57].

Overall, the findings highlight the vulnerability of households in the study area to climate change impacts on water resources, with highland areas being the most at risk. Several studies, including [8,25,36,65,64], have explored the relationship between ecosystem sensitivity to climate change and agroecological vulnerability. They emphasize that lowland and highland areas are more sensitive to climate change impacts than midland agroecology. Given this variability across agroecologies, targeted interventions should be developed, accounting for specific vulnerabilities and sensitivities associated with each one. Such interventions could involve advocating for sustainable land management practices and conservation strategies tailored to the characteristics of each agroecology to reduce vulnerability and increase resilience in the face of climate change. In line with findings by Ref. [33,36] in Ethiopia [11] in Pakistan [66], in Ghana [67], in Mali, and [68] in Kenya, policymakers and practitioners must consider these insights and formulate policies that promote sustainable development while mitigating the risks posed by environmental stresses to vulnerable communities in Sub-Saharan Africa.

3.1.3. Smallholder farmers' adaptive capacity

Adaptive capacity: It measures resilience and the ability to adjust to current or anticipated climatic changes, and was assessed using the Livelihood Vulnerability Index (LVI) in the Upper Blue Nile Basin [54,55]. The study reported that midland households demonstrated the highest overall adaptive capacity score (0.507), surpassing highland (0.456) and lowland (0.443) households (Annex table A1). The six major components influencing adaptive capacity were identified as livelihood strategies, financial assets, socio-demographic profile, agricultural capacity, social network, and access to services.

Livelihood Strategy: Smallholder farmers in highland areas were identified as particularly vulnerable to climate change impacts. The study indicated that midland households exhibited the highest adaptive capacity score, with highland households being the least adaptive due to limited livelihood options and a lack of initial capital (Annex table A1). These findings diverge from earlier conclusions by Refs. [45,23], emphasizing the need for targeted interventions that consider specific vulnerabilities across agroecologies and non-climatic environmental stresses.

Financial Assets: Lowland households showed slightly better financial assets (0.413) than midland (0.395) and highland (0.325) zones. However, midland households had superior per capita income ($USD), with the highest percentage living above the poverty line. These results align with [69] the findings, emphasizing the low adaptive capacity of smallholder farmers in Ethiopia concerning financial and agricultural aspects (Annex table A1).

Socio-demographic Profile: Midland households exhibited the highest socio-demographic profile score (0.544), followed by highland (0.517) and lowland households (0.503), indicating their superior adaptive capacity. The study delved into family dependency ratios, revealing that midland households had fewer family members below 15 years and above 65 years. Additionally, midland households had a higher proportion of male-headed households compared to highland and lowland households (Annex table A1).

Agricultural Capacity: The findings highlighted midland agroecology's superior adaptation capabilities in terms of land size, a crucial factor in vulnerability reduction. Large land holdings and livestock ownership were associated with lower vulnerability, aligning with [55] observations. Midland households possessed the largest farm size, making them less vulnerable in agricultural capacity compared to highland and lowland households. This emphasizes the need for interventions promoting sustainable land management, adaptive farming practices, and increased livestock ownership in vulnerable regions (Annex table A1).

Social Network: Comprising four sub-components, the analysis identified midland households as the least susceptible in terms of social networks (0.734), with lowland (0.553) and highland households (0.609) following. Most households across agro-ecologies did not seek assistance from the local government in the past 12 months, emphasizing the importance of enhancing access to information and support. This aligns with [69] findings on smallholder farmers' intermediate adaptive capacity regarding social networks (Annex table A1).

Access to Services: A crucial factor in enhancing resilience, access to services was highest in midland households (0.506), followed by lowland (0.458) and highland households (0.429) (Annex table A1). The proximity of markets and input resources, climate-specific extension services, and access to credit services were considered vital contributors to adaptive capacity. Focused interventions, such as improving access to marketplaces, input resources, financing facilities, and extensive services, are crucial for assisting vulnerable families in becoming more resilient to climate change effects.

3.1.4. Smallholder farmers' overall vulnerability status based on LVI–IPCC

Table 3 presents the comprehensive vulnerability status of smallholder farmers utilizing the LVI-IPCC framework [56]. It details the contributing factor scores for exposure, adaptive capacity, and sensitivity. The vulnerability assessment reveals distinct patterns among highland, midland, and lowland households.

Exposure: Highland households emerge as the most exposed (0.338) to climate change impacts, surpassing midland (0.328) and lowland households (0.329). This emphasizes the critical vulnerability of highland areas to the adverse effects of climate change. These findings align with the observations of [8,65].

Sensitivity: The study identifies highland agroecology as the most sensitive, followed by lowland and midland agroecologies,

Table 3
LVI–IPCC smallholder farmers' vulnerability status among different agro-ecologies.

IPCC contributing factors of vulnerability	Highland	Midland	Lowland
Adaptive capacity	0.456	0.507	0.443
Sensitivity	0.421	0.331	0.413
Exposure	0.338	0.328	0.329
LVI-IPCC	**−0.050**	**−0.059**	**−0.047**

Source: own computation, (2022)

respectively. This indicates that highland households are more susceptible to the impacts of climate change, underscoring the need for targeted interventions in these areas. These findings are consistent with previous research by Refs. [44,70].

Adaptive Capacity: In terms of adaptive capacity, midland households exhibit better resilience (0.503) compared to highland (0.456) and lowland (0.443) agroecologies. This suggests that midland areas are more equipped to adjust to current or anticipated climatic changes. The adaptive capacity rankings follow a pattern of midland, highland, and lowland agroecologies. This reinforces the significance of considering adaptive capacity in developing climate change mitigation strategies. The results align with the insights provided by Refs. [44,70,65].

The Livelihood Vulnerability Index (LVI-IPCC), scaled from −1 (least vulnerable) to 1 (most vulnerable) [56], indicates immediate vulnerability to climate change impacts across all agroecological zones (highland: −0.050, midland: −0.059, lowland: −0.047) (Table 3). Despite small differences among agroecologies, relatively lowlands are the most vulnerable, followed by highland agro-ecology households. It emphasizes the need for comprehensive climate resilience strategies. Distinct variations in LVI subcomponents among agroecologies, detailed in Appendices Annex table A1, further highlight the nuanced vulnerabilities.

Several studies, including [25,64], align with this study, emphasizing the vulnerability of lowland agroecology to climate change impacts. Highland areas follow as the second most vulnerable, with midland areas exhibiting relatively lower vulnerability, consistent with findings by Refs. [45,57]. However, opposing results by Ref. [46] suggest midland and lowland vulnerability. Additional research conducted in Ethiopia, such as empirical studies conducted by Refs. [8,65] and critical literature reviews presented by Refs. [20,47], consistently identify lowland agroecology as being more ecologically sensitive. This is followed by highland and midland agro-ecologies, which aligns with the findings of the current study. The study concurs with various authors, such as [66] in Ghana and [67] in Mali, highlighting Sub-Saharan Africa's vulnerability due to low adaptive capacity.

The assessment contributes nuanced insights into smallholder farmers' exposure, sensitivity, and adaptive capacity across diverse agro-ecologies. The urgency for targeted interventions in highly exposed and sensitive highland areas is emphasized. Conversely, midland areas present opportunities for resilience-building strategies. Building on [44,70], this study enriches the discourse on smallholder farmers' climate vulnerabilities. Policymakers, practitioners, and researchers can leverage these findings to design tailored climate resilience strategies, considering the unique challenges faced by farmers in each agroecological zone. The study advocates for adaptive capacity improvement in vulnerable zones, acknowledging the importance of addressing specific vulnerabilities and sensitivities..

Focus Group Discussions (FGDs) were also conducted across diverse agroecologies, participants from the highland agroecology affirmed the region's heightened exposure to high-intensity rainfall, resulting in flooding and erosion. Factors such as lack of weather information, limited awareness of climate change impacts, and restricted livelihood options were identified as exacerbating vulnerabilities. In the midland agroecology, participants noted exposure to irregular rainfall, rendering crops susceptible to pests and diseases. Vulnerability in this area was attributed to a lack of agricultural innovations and awareness of climate change impacts.

Box 1
Unveiling Smallholder Farmers' Vulnerability Among Agroecological Zones

In this vulnerability case study, key informants (K1 and K2) in highland areas, (K3 and K4) in midland areas, and (K5 and K6) in lowland areas were interviewed using an obstacle diagnosis model to identify factors hindering smallholder farmer resilience. All informants universally recognized climate change, attributing it to both divine acts and imprudent environmental resource use. The region, classified as highly vulnerable, faces various climatic shocks, including, high rainfall variation, floods, erratic rainfall, erosion, and temperature increments. Vulnerability is exacerbated by limited livelihood options, financial resources, and inadequate climate change information. Climatic shocks have intensified, leading to significant crop yield reductions (30%–50%) and diminished forage productivity.

Key informants emphasized the vulnerability of highland areas to floods and erosion, midland areas to adverse cereal crop (Teff, Finger millet, and Potato) impacts, and lowland areas to damage to Maize and Soybean production. Shared obstacles identified by all informants encompass a shortage of livelihood options, a weak social network to adopt climate-smart agricultural innovations, limited financial access, lack of agricultural innovations, unresponsive institutions, and insufficient climate information. Recommendations put forth include irrigation development, the introduction of shock-resistant crop innovations, and the implementation of tailored adaptation measures. The proposed solutions advocate for institutional and economic reforms, increased resource allocation, awareness initiatives, and the provision of accessible credit services to strengthen smallholder farmers' climate resilience across diverse agroecological zones.

This case study significantly enhances our understanding of smallholder farmers' vulnerability, offering detailed insights into challenges in highland, midland, and lowland areas. The obstacle diagnosis model allows a comprehensive examination of resilience impediments, revealing the intricate interplay between climatic shocks, environmental factors, and socio-economic constraints. Emphasizing tailored adaptation measures for each agroecological zone, the study adds practical value to the climate resilience discourse. Policymakers, practitioners, and researchers can use these findings to design targeted interventions addressing the unique vulnerabilities of smallholder farmers in distinct geographical contexts. The study stresses the importance of holistic, region-specific strategies to enhance climate resilience and mitigate the impact of climatic shocks on vulnerable communities.

Source: own Key informant Interview

Participants from the lowland agroecology reported high exposure to rainfall variability and temperature increments, primarily due to deforestation for farming practices. This region exhibited a low adaptive capacity, limited access to services (extension and credit), and few livelihood strategies, making it one of the most vulnerable agroecologies to climate change impacts.

Furthermore, these findings align with studies in Australia where farmers believe climate change is natural rather than a result of human actions [71]. Additionally, various studies in Ethiopia by Refs. [69,72,70] emphasize the influence of natural disasters, climate variables, and unsustainable land use on climate risk. Studies at the Sub-Saharan Africa (SSA) level, as shown by Refs. [26,27], reveal that smallholder farmers in Sub-Saharan Africa heavily depend on subsistence agriculture and are vulnerable to the negative effects of climate change. SSA countries' vulnerabilities are associated with their reliance on rain-fed agricultural practices and limited socio-economic and institutional capacity, leading to a poverty trap that is challenging to escape [73,9,14,15]. Similarly, studies in Ethiopia have shown that smallholder farmers are vulnerable to climate change, not only due to exposure but also because of weak institutional services. Examples include a lack of climate information, extension services for climate-smart agricultural innovations, and credit services, along with constraints associated with the availability of livelihood resources and infrastructure [20,47].

3.2. Spatial temporal ecosystem vulnerability of smallholder farmers

3.2.1. Overall study area ecosystem sensitivity trend to climate change and variability

To assess vulnerability trends in the study area, a comprehensive analysis was conducted over thirty years, from 1992 to 2022, divided into three phases: 1992–2003, 2003–2013, and 2013–2022, with 1992 serving as the benchmark. These phases were dedicated to specific ecosystem sensitivity analyses. An examination of satellite images revealed six major land-use and cover types persisting throughout the study period: shrubland, cultivated land, settlement, plantation, natural forest, and grazing land. The dominant land use and land cover types over time are summarized in Table 4.

In 1992, cultivated land emerged as the largest class, covering 67.26% of the area, with shrubland following at 19.56%. Natural forests and settlements represented the smallest classes. By 2003, cultivated land continued to dominate at 67.75%, accompanied by an increase in grazing land to 8.5%. Shrubland and plantations accounted for 17.23% and 5.68%, respectively, while natural forests and settlements remained the smallest classes. This trend persisted in 2013 and 2022, with cultivated land consistently covering over two-thirds of the area, followed by shrubland, grazing land, plantations, and natural forests. This pattern is also depicted in a visual representation (Annex fig. A1 and A2).

These trends underscore the need for a more nuanced understanding of the challenges posed by changes in land use. The reduction in shrubland and grazing areas implies increased vulnerability of the ecosystem to climate change shocks, such as erosion and flooding. This vulnerability is associated with the diminished capacity of these areas to act as natural buffers against environmental stressors. Moreover, the rise in cultivated land and settlement areas adversely affects both land and livestock production, exacerbating sensitivity to climate change hazards.

Notably, improvements in plantation areas offer a positive dimension to ecosystem dynamics. Enhanced stability in these regions contributes to a reduction in vulnerability by providing the capacity to absorb carbon dioxide, aligning with mitigation efforts against climate change. This indicates that strategic land-use planning, particularly emphasizing the promotion of plantation areas, can serve as a valuable tool in climate resilience.

To fortify these insights and contribute meaningfully to the existing knowledge base, it is crucial to integrate socio-economic dimensions into the analysis. Understanding how land-use decisions are influenced by human activities, economic considerations, and policy interventions will offer a more comprehensive perspective on the intricate relationship between land-use dynamics and vulnerability trends in the study area. Furthermore, future research endeavours should explore the interconnectedness between land-use patterns and specific climate change impacts, providing a more detailed and context-specific understanding of the challenges faced by the ecosystem. This holistic approach will facilitate the development of targeted and effective strategies for climate change adaptation and mitigation.

3.2.2. Rate of Land use Land cover change

The Dynamics of Land Use/Cover Index serves as a valuable tool to gauge changes in land use types over time, shedding light on the influence of both human activities and environmental factors. Analyzing the results from Table 5, it is evident that significant shifts

Table 4
Land use-land cover trends in the study period.

LULC Types	Area (Ha)							
	1992	%	2003	%	2013	%	2022	%
Shrub land	18169.9	19.56	16008.6	17.23	14162.6	15.24	14282.8	15.37
Cultivated land	62492.9	67.26	62952.2	67.75	63767	68.63	64423	69.34
Settlement	174.69	0.19	381.6	0.41	548.55	0.59	1157.58	1.25
Plantation	3630.6	3.91	5273.55	5.68	6423.76	6.91	9896.1	10.65
Natural Forest	382.68	0.41	399.42	0.43	417.33	0.45	343.71	0.37
Grazing Land	8063.37	8.68	7898.76	8.50	7594.91	8.17	2810.87	3.03
Total	92914.14	100	92914.13	100	92914.15	100	92914.06	100

Source: own computation (2022); supporting from https://earthexplorer.usgs.gov,

Table 5
Rate of Land Use Land Cover Change (ha, ha/yr, and %).

LULC types	1992–2003 (11 years)			2003–2013 (10 years)			2013–2022 (9 years)			1992–2022 (30 years)		
	Ha	Ha/year	%	Ha	Ha/year	%	Ha	Ha/year	%	Ha	Ha/year	%
Shrub land	−2161.30	−196.48	−11.8	−1846.00	−184.6	−11.5	120.2	13.36	0.85	−8887.10	−296.24	−21.39
Cultivated	459.30	41.75	0.73	814.80	81.48	1.3	656	72.89	1.03	1930.10	64.34	3.09
Settlement	206.91	18.81	118.4	166.95	16.695	43.8	609.03	67.67	111.03	982.89	32.76	562.65
Plantation	1642.95	149.36	45.2	1150.21	115.021	21.8	3472.34	385.82	54.05	10265.50	342.18	172.57
N. Forest	16.74	1.52	4.37	17.91	1.791	4.5	−73.62	−8.18	−17.64	−38.97	−1.30	−10.18
Grazing land	−164.61	−14.96	−2.04	−303.85	−30.385	−3.8	−4784.04	−531.56	−62.99	−4252.50	−141.75	−65.14

Source: own computation (2022); supporting from https://earthexplorer.usgs.gov

have occurred in the landscape.

The index results highlight notable increases in settlement and plantation areas, signifying a substantial transformation of land for urban and agricultural purposes. Understanding the driving forces behind these changes is crucial, involving factors such as population growth, economic development, or policy interventions. Additionally, natural forests and cultivated land have experienced growth, with an expansion of cultivated land potentially signifying agricultural intensification and the growth of natural forests suggesting positive conservation efforts or natural regeneration processes. Distinguishing between these scenarios is vital for comprehensive land management strategies.

However, a concerning trend emerges when examining the decline in grazing land and shrub areas during the initial period (1992–2003), which may have multifaceted implications. Reductions in grazing land could indicate challenges for livestock-dependent communities, affecting their livelihoods and adaptive capacity. Simultaneously, shrinking shrub areas might contribute to increased vulnerability to environmental hazards like erosion, given the protective role shrubs play in preventing soil degradation. For instance, the expansion of settlement areas might indicate increased exposure to climate risks for the local population, while the growth in plantation areas could contribute positively to adaptive capacity by enhancing carbon sequestration.

Between 2003 and 2013, Ethiopia's Upper Blue Nile Basin witnessed significant shifts in land use, marked by annual decreases in shrubland and grazing land by 11.5% and 3.8%, respectively. In contrast, cultivated land, settlement areas, plantations, and natural forest coverage experienced increments. Specifically, cultivated land increased by 1.3%, settlement coverage grew by 43.8%, plantation area increased by 21.8%, and natural forest coverage increased by 4.5%. The subsequent period from 2013 to 2022 saw a continuation of these trends, with plantation and settlement areas expanding by 54.05% and 111.03%, while natural forest and grazing areas significantly declined by 18.64% and 62.99%, respectively. A detailed examination from 1992 to 2022 revealed an annual increase of 64.3 ha of cultivated land, 32.6 ha in settlements, and 342.18 ha in plantations. Conversely, grazing land, shrubland, and natural forest areas witnessed annual decreases of 141.71 ha, 296 ha, and 1.31 ha, respectively. These transformations underscore the profound alterations in the landscape over the study period.

Moreover, focus group discussions identified communal grazing land being converted to privately cultivated land and private plantations, primarily focused on eucalyptus. Smallholder farmers shifted their focus from cereal crop production to plantations, leading to reductions in grazing land, shrubs, and natural forests. This trend aligns with visual image interpretation, reinforcing the reliability of the findings. The conversion of communal grazing land to private use poses a threat to the traditional practices of communities, affecting their livelihoods and adaptive capacities. The dominance of eucalyptus plantations, at the expense of diverse crops and natural vegetation, indicates a potential risk to food security and biodiversity. The observed reduction in grazing land, shrubland, and natural forests amplifies vulnerability to climatic shocks and hazards.

3.2.3. Land use Land cover change matrix

The comprehensive analysis spanning from 1992 to 2022 illuminates substantial land use and land cover changes in the Upper Blue Nile Basin. This period witnessed transformations, including the conversion of certain areas to cultivate land, plantations, or grazing land. Notably, the shift from shrubland to cultivated land was particularly noteworthy. However, despite this conversion, there was an overall net loss of shrubland. The identified net loss of shrubland signifies a potential threat to the ecological balance and resilience of the ecosystem (see Table 6).

Between 1992 and 2022, a noteworthy transformation occurred with a substantial conversion of grazing land to cultivated land. The predominant expansion of cultivated land, particularly at the expense of grazing land and shrubland, resulted in the depletion of these natural areas. The shift toward exotic plant species, notably Eucalyptus, further contributed to the diminishing expanse of grazing lands, raising concerns about the long-term sustainability of ecosystems and livelihoods. The observed conversion dynamics, especially the encroachment on grazing lands, pose multifaceted challenges. The loss of natural areas, including shrubland, natural forests, and plantations, indicates environmental degradation, jeopardizing biodiversity and disrupting the delicate balance of ecosystems. Additionally, dependence on exotic species like Eucalyptus raises questions about the ecological compatibility of such plantations and their impact on traditional livelihoods.

The study reveals annual rate changes in plantations, settlements, and agricultural land, coupled with a reduction in shrubland, grazing land, and natural forest. These changes, depicted in Annex fig. A1& fig. A2, illustrate similar trends with some variations across the overall study area. The findings highlight significant land alterations, emphasizing urban and agricultural expansion, along with an

Table 6
Land Use Land Cover Change matrix as observed between the years 1992 and 2022.

1992	2022								
		Shrub land	Cultivated	Settlement	Plantation	N Forest	Grazing	Row Total	Loss
	Shrub land	**7433.8**	8268.21	12.78	1953.99	28.98	472.14	18169.9	*−10736.1*
	Cultivated	3927.42	**44868.27**	612.54	10667	185.04	2232.63	62492.9	*−17624.6*
	Settlement	0	0	**174.69**	0	0	0	174.69	*0*
	Plantation	23.94	808.83	1.98	**2763.09**	0.27	32.49	3630.6	*−867.51*
	N Forest	11.97	83.79	5.76	23.76	**254.79**	2.61	382.68	*−127.89*
	Grazing	788.13	5775.75	110.25	1131.39	16.11	**241.74**	8063.37	*−7821.63*
	Column Total	12185.26	59804.85	918	16539.23	485.19	2981.61	**92914.14**	*−37177.8*
	Gain	*4751.46*	*14936.58*	*743.31*	*13776.14*	*230.4*	*2739.87*	*37177.76*	

Source: own computation (2022); supporting from https://earthexplorer.usgs.gov

Table 7
Overall average per decade Land use Land cover change across three AEZs.

LULCTypes	Unitofmeasurement	Lowland				Changesinthedecade	Midland				Changesinthedecade	Highland				Changesinthedecade
		1992	2003	2013	2022	y =	1992	2003	2013	2022	y =	1992	2003	2013	2022	y =
Shrub land	Area in ha	2016.24	2009.45	2210.37	2113.11	0.75x + 29.92	9454.43	8418.24	8570.9	7780.8	−0.867x +17.37	4874.87	3651.93	4544	3570.93	−1.005x + 16.355
	% Change	30.71	30.61	33.67	32.19	R^2 = 0.4498	16.8	14.96	15.23	13.82	R^2 = 0.831	16.22	12.15	15.12	11.88	R^2 = 3607
Cultivated land	Area in ha	3691.13	4093.74	4142.16	4236.54	2.56x + 55.13	40178.8	40712	39937	38542	−1.011x + 73.31	19391.4	20532.8	21032	19957.3	0.73x + 65.47
	% Change	56.22	62.35	63.09	64.53	R^2 = 0.8175	71.38	72.33	70.95	68.47	R^2 = 0.6288	64.51	68.31	69.97	66.39	R^2 = 0.159
Settlement	Area in ha	13.14	31.9	33.03	53.46	0.184x + 0.04	144.72	311.67	436.95	955.08	0.455x −0.315	17.91	40.59	80.46	154.8	0.148x-0.125
	% Change	0.2	0.49	0.5	0.81	R^2 = 0.9091	0.26	0.55	0.78	1.7	R^2 = 0.8904	0.06	0.14	0.27	0.51	R^2 = 0.9433
Plantation	Area in ha	52.65	26.1	56	87.57	0.204x + 0.335	2297.52	2953.89	4422.6	7552.5	3.063x −0.005	1291.14	2316.15	1025	4351.39	2.624x + 0.915
	% Change	0.8	0.4	0.85	1.33	R^2 = 0.478	4.08	5.25	7.86	13.42	R^2 = 0.9049	4.3	7.71	3.41	14.48	R^2 = 0.4546
Natural Forest	Area in ha	7	6.5	10	12	0.026x + 0.07	188.1	165.6	141.66	117.18	−0.04x + 0.37	207.18	244.98	289.17	237.96	0.044x + 0.705
	% Change	0.11	0.1	0.15	0.18	R^2 = 0.8244	0.33	0.29	0.25	0.21	R^2 = 1	0.69	0.82	0.96	0.79	R^2 = 0.2595
Grazing Land	Area in ha	785.16	398.08	113.76	62.64	−3.736x + 14.515	4026.69	3728.79	2780.9	1342.3	−1.559x + 9.27	4276.06	3272.13	3088.3	1786.14	−2.549x + 16.705
	% Change	11.96	6.06	1.73	0.95	R2 = 0.9118	7.15	6.62	4.94	2.38	R^2 = 0.9252	14.23	10.89	10.27	5.94	R^2 = 0.9336

This pattern is also present in figurative illustration (Appendix Fig, 3, 4, and 5).
NB: The LULCC trends underscore the urgency of addressing the challenges posed to ecosystems and communities in the Upper Blue Nile Basin.
Source: own computation (2022); supporting from https://earthexplorer.usgs.gov

increase in plantation areas. However, it is noteworthy that communities dependent on livestock face challenges in terms of adaptation and sustenance. Despite the challenges faced by livestock-dependent communities, areas with plantations show potential for enhancing carbon sequestration, particularly in the midland agroecology.

Previous literature assessing vulnerability has consistently pointed to population pressure on ecosystem resources, manifesting in the expansion of cultivated land and settlements [20,47]. A prevalent phenomenon among Ethiopian smallholder farmers is land fragmentation, driven by high population pressures [25].

Addressing the challenges posed by land conversion requires a paradigm shift toward sustainable land use practices, prioritizing the conservation and rehabilitation of grazing lands and other natural areas as a crucial imperative. Sustainable practices should balance agricultural needs with ecological preservation, ensuring the resilience of ecosystems while safeguarding the dependent livelihoods. This finding underscores the urgent need for sustainable land use practices, emphasizing strategies that prioritize the conservation and rehabilitation of shrubland areas. These efforts are crucial not only for ecosystem resilience but also for maintaining delicate ecological equilibrium. The observed land use changes call for strategic interventions in sustainable land management, focusing on practices that mitigate further loss of shrubland while facilitating the rehabilitation of affected areas. Conservation initiatives must align with broader ecological goals to ensure the preservation of the unique functions of shrubland ecosystems.

3.2.4. Per decade Land use Land cover change among three AEZs

Table 7 provides a comprehensive overview of the average per-decade LULCC rates for each land use type within the three distinct agroecologies. This breakdown allows for a nuanced understanding of how LULCC manifests differently in highland, midland, and lowland areas. Such granularity is instrumental for targeted interventions and policy formulations catering to the specific needs of each agroecological zone.

Land Use Trends Across Agroecological Zones: Lowland AEZ: A marginal increase (0.75% per decade) in shrubland may contribute to reduced ecosystem sensitivity. However concurrent expansion of cultivated land (2.56% per decade) raises concerns about increased vulnerability to climate change. Midland AEZ: A continuous decrement in shrubland (0.867% per decade) highlights the pressing need for interventions, while a population-driven expansion of settlements necessitates sustainable management practices. Highland AEZ: Decreasing shrubland (1.005% per decade) and expanding plantation coverage (2.624% per decade) emphasize the need for targeted afforestation initiatives to mitigate the vulnerability.

Challenges and Implications: Cultivated Land Expansion: The significant expansion of cultivated land in lowland and highland AEZs raises concerns about heightened vulnerability to climate change impacts, emphasizing the urgency of sustainable land management practices. Settlement Growth: Observed higher population growth in midland AEZ necessitates interventions to manage population strain, ensuring sustainable development and minimizing environmental impacts. Natural Forest Dynamics: While natural forest coverage increased in highland and lowland AEZs, a decrease in midland AEZ underlines the need for conservation efforts to maintain biodiversity and ecological balance. Grazing Land Decline: A significant decline in grazing land across all AEZs, particularly in lowland AEZ, highlights the heightened ecological sensitivity. This underscores the importance of sustainable land use practices in vulnerable areas.

While no prior research has specifically addressed the trend analysis of ecosystem vulnerability, several cross-sectional studies focusing on ecosystem sensitivity have been conducted in various regions of Ethiopia. Studies by Refs. [6,7,40,47,49] have demonstrated that ecosystems in Ethiopia are highly sensitive to the impacts of climate change and variability shocks. In ecological terms, lowlands are identified as more ecologically sensitive, followed by highland and midland agroecologies [8,65], aligning with the current study's findings. However, these studies did not examine changes in land use over time or explore how such changes have contributed to the overall vulnerability of the ecosystem.

4. Conclusion

This study, using the LVI-IPCC scale, found that households in highland, midland, and lowland agroecological zones are immediately vulnerable to climate change, with lowland agroecology households being the most vulnerable, followed by highland agroecology. Midland agroecology shows relatively lower overall vulnerability because it has better adaptive capacity than other agroecologies. The weighted exposure and sensitivity index emphasized critical vulnerability in the highlands, signalling the need for targeted interventions to address agroecological challenges. Sensitivity analysis showed highland households were most susceptible to climate change impacts on health, food, and water, while lowland households had a relatively lesser contribution to ecosystem management. This underscores the importance of understanding agroecology-specific vulnerabilities for targeted interventions in sustainable land management and conservation. Midland households exhibited the highest overall adaptive capacity due to factors such as diversified livelihood options, better demographic profiles, and improved access to services. Highland households, identified as the most exposed and sensitive, require comprehensive strategies for enhancing adaptive capacity and resilience.

Our study, spanning from 1992 to 2022 and divided into three phases, highlights substantial changes in land use and cover types within Ethiopia's Upper Blue Nile Basin. Over this period, cultivated land consistently dominated the region, exhibiting an annual increase of 64.3 ha. Concurrently, plantations and settlements expanded, whereas grazing land, shrubland, and natural forests experienced notable declines, indicating high vulnerability to climate-related shocks. The transition from communal grazing land to private cultivation and plantations, particularly eucalyptus, signifies a dynamic transformation in land use practices. This shift negatively impacts grazing land, shrubs, and natural forests, contributing to an increased sensitivity to climate shocks. To mitigate these changes and enhance ecosystem resilience, the study recommends adopting sustainable land use practices, afforestation, and climate-smart agriculture. Emphasizing the need for interventions to reverse trends, the study underscores the importance of conserving and rehabilitating shrubland, grazing land, and natural areas.

Addressing these issues becomes imperative for maintaining ecological balance, sustaining livelihoods, and ensuring the long-term resilience of ecosystems. It highlights the dynamic nature of land use changes and their implications for ecosystem vulnerability. However, the study acknowledges limitations, particularly in its geographical scope, as it does not cover large areas. Additionally, the study acknowledges a limitation in the availability of sufficient previous research findings to assess the trend status changes of ecosystem sensitivity over time.

This study analyzes socio-economic, climatic, and ecosystem sensitivity trends over 30 years in the Upper Blue Nile Basin, providing insights for future interventions. It emphasizes the need for tailored climate change adaptation strategies, including financial provision, institutional linkage, improved access to services, and social network strengthening, to reduce vulnerability and promote resilience among smallholder farming communities. The findings are crucial for policymakers and practitioners aiming for a green economy, environmental sustainability, and socio-economic development in sub-Saharan Africa. The study provides valuable guidance for formulating effective strategies to support vulnerable communities' livelihoods.

Ethical clearance statement

The investigation actively engaged smallholder farmers through participation in surveys, focus group discussions and key informant interviews. The questions employed in these research methods underwent a thorough evaluation and received approval from the Institutional Review Board committee at Bahir-Dar University. This approval ensured adherence to ethical standards throughout the study. Ethical clearance was obtained by submitting an application to Bahir Dar University using form BDU 03–008, and it was approved under meeting number November 2022 on July 7th, 2022. The ethics approval reference protocol number assigned to the study was 05/IRB/22, with an assigned number of 05/22/04.

Declaration of consent for participation

I, [Enumerator Full Name], am the data enumerator for the Study on Smallholder Farmers' Vulnerability to Climate Change and Variability: Evidence from Three Agroecologies Upper Blue Nile, Ethiopia. This research is being conducted as part of a third-degree postgraduate qualification program at Bahir Dar University, and your valuable input is crucial to the success of this study. I am reaching out to you to request your participation in this study on behalf of your family. The information you provide will contribute significantly to our understanding of farmers' resilience to climate change in the region. The outcomes of this study aim to benefit the local community, the country, and the international community in their collective efforts to address the challenges posed by climate change.

If you choose to participate, it will require approximately 40 min of your time to complete the questionnaire.

Confidentiality: Please be assured that any information you provide will be treated with the utmost confidentiality. Your name and any other identifying details will not be disclosed or used for any purpose beyond the scope of this study.

Voluntary Participation and Withdrawal: Your participation in this study is entirely voluntary. You have the freedom to decide whether or not to participate, and you may withdraw at any point, without any repercussions. Additionally, you can request that your responses and information not be included in the study after completing the questionnaire. If you have any questions or concerns about the study, you may contact the main researcher, Mr Assefa Abelieneh, at +251(0)937403010. Questions and Clarifications: If you have any questions about the questionnaire, I am available to provide explanations and address any concerns you may have.

This consent is read for respondents or research participants and requests their response on whether they agree to participate or not participate. If they agree, they are requested to sign on the signatory attendance sheet. In this sheet participants' codes and signatures are documented.

Your cooperation is immensely appreciated, and your contribution to this study is invaluable.

Data Enumerator.

Declaration of availability of data

While the research data linked to this study has not yet been deposited into a publicly accessible repository, it has been gathered using KOBO TOOLBOX Software. Access to the data can be provided upon a reasonable request.

CRediT authorship contribution statement

Assefa A. Berhanu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Zewdu B. Ayele:** Visualization, Validation, Supervision. **Dessalegn C. Dagnew:** Visualization, Validation, Supervision, Methodology, Data curation, Conceptualization. **Tadele Melese:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Investigation, Conceptualization. **Abeje B. Fenta:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Koyachew E. Kassie:** Visualization, Validation, Supervision.

Declaration of competing interest

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

Appendices.

Annex Table A1
Smallholder farmers' vulnerability to climate change and variability

Vulnerability	Profile	Indicator	Unit	Highland	Midland	Lowland
		Weighted Exposure	**Index**	**0.338**	**0.328**	**0.329**
Exposure	Exposure to natural disasters and Climate Variability	Change in Maximum temperature	0C	0.568	0.570	0.575
		Change the Minimum temperature	0C	0.577	0.588	0.573
		Change in precipitation	Mm	0.405	0.546	0.552
		Change in runoff	Mm	0.486	0.382	0.317
		Climate-related hazards: flood/drought	No	0.091	0.025	0.120
		Households that did not receive a warning	% hh	0.413	0.426	0.431
		Households' injuries recorded	% hh	0.1	0.055	0.056
		Households with death	% hh	0.069	0.030	0.012
		Weighted Sensitivity	Index	**0.421**	**0.331**	**0.413**
		Ecosystem sensitivity	Index	**0.434**	**0.425**	**0.538**
Sensitivity	Ecosystem	Do not have Irrigation access	% hh	0.8	0.846	0.856
		Do not have a tree plantation	% hh	0.423	0.388	0.613
		agroecology NDVI value less or equal to 0.1	% Bare land	0.133	0.21	0.327
		Land does not protect from erosion	% hh	0.381	0.255	0.356
		Food	Index	**0.382**	**0.320**	**0.291**
	Food	Number of months HHs struggle to find food	No	0.289	0.15	0.152
		Crop diversity index	Inverse	0.53	0.527	0.441
		Do not save crops	% hh	0.375	0.304	0.306
		Do not save seed	% hh	0.335	0.298	0.263
		Health	Index	**0.326**	**0.151**	**0.332**
	Health	Distance from health facility	Km	0.372	0.027	0.264
		Family member Chronic illness associated with weather hazard	% hh	0.183	0.011	0.3
		Family member Miss works due to illness	% hh	0.156	0.0132	0.15
		Do not have an Improved sanitation facility	%hh	0.594	0.554	0.613
		Water	Index	**0.517**	**0.408**	**0.476**
	Water	Reported Water conflict	% hh	0.281	0.221	0.219
		Utilizing natural water systems as the water source	% hh	0.685	0.332	0.65
		Distance to water source	Km	0.25	0.233	0.269
		Do not have consistent water availability	% hh	0.419	0.298	0.325
		Water storage capacity (in litres)	Inverse	0.949	0.954	0.918
Adaptive capacity		**Weighted Adaptive Capacity**	Index	**0.456**	**0.507**	**0.443**
		Livelihood Strategies	Index	**0.515**	**0.559**	**0.535**
	Livelihood Strategies	Do Adopt cc adaptation measures	%hh	0.581	0.785	0.637
		Households' family members do not work outside the community	%hh	0.6	0.643	0.4
		Household diversified Livelihoods	%hh	0.375	0.54	0.462
		Households practising money saving in the bank	%hh	0.356	0.652	0.419
		Women participate in decision-making	%hh	0.662	0.687	0.756
		Financial assets	Index	**0.325**	**0.395**	**0.413**
	Financial assets	Households above the Poverty line	Hh %	0.331	0.503	0.537
		Household per capita Income $USD	No	0.089	0.119	0.134
		Households have quality housing & roofing materials	%hh	0.556	0.563	0.569
		Socio-demographic profile	Index	**0.517**	**0.544**	**0.503**
	Socio-demographic	The household head had attended school	% hh	0.4	0.469	0.306
		Dependency ratio (inverse)	Ratio	0.67	0.69	0.66
		HH with no orphans	% hh	0.862	0.905	0.906
		HH Percent of the male HH	% hh	0.856	0.902	0.956
		Households get training about weather and climate	% hh	0.119	0.08	0.044
		Adult women in the household attend education	% hh	0.194	0.215	0.144

(*continued on next page*)

Annex Table A1 (*continued*)

Vulnerability	Profile	Indicator	Unit	Highland	Midland	Lowland
		Agricultural capacity	Index	**0.341**	**0.301**	**0.198**
	Agricultural capacity	Land size	No	0.318	0.333	0.211
		Farming experience	No	0.409	0.375	0.204
		Livestock ownership in TLU	No	0.297	0.195	0.178
		Social Network	Index	**0.609**	**0.734**	**0.553**
	Social Network	Household member in the local organization	% hh	0.367	0.471	0.462
		The household does not receive help/aid/assistance from others	% hh	0.675	0.709	0.512
		The household does not borrow money from others for immediate consumption	% hh	0.675	0.691	0.675
		Households do not apply to the local government for assistance in the last 12 months	% hh	0.719	0.801	0.562
		Access to services	Index	**0.429**	**0.506**	**0.458**
	Access to services	Distance to market (km)	Inverse	0.632	0.791	0.798
		Distance to road (km)	Inverse	0.711	0.900	0.799
		Households have Credit Access	% hh	0.325	0.239	0.194
		Households do have access to Climate information	% hh	0.438	0.528	0.425
		Frequency of extended visit	No	0.039	0.07	0.075
		LVI–IPCC **Overall Index**		**−0.050**	**−0.059**	**−0.047**

Source: own computation (2022)

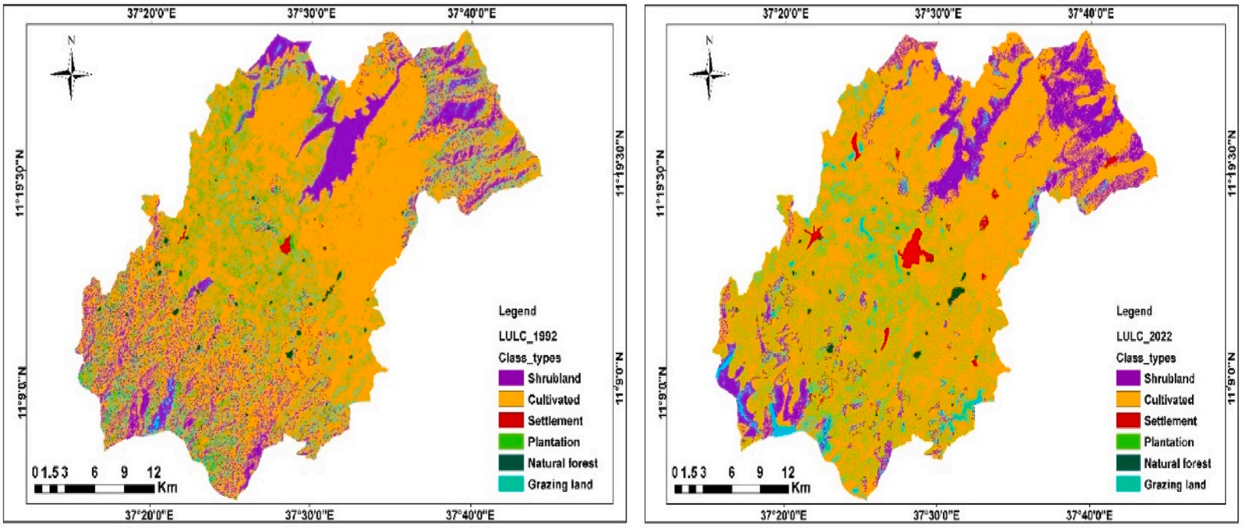

Fig. A1. LULC's area (ha) in different years across the study area.
(Source: own computation (2022); supporting from https://earthexplorer.usgs.gov)

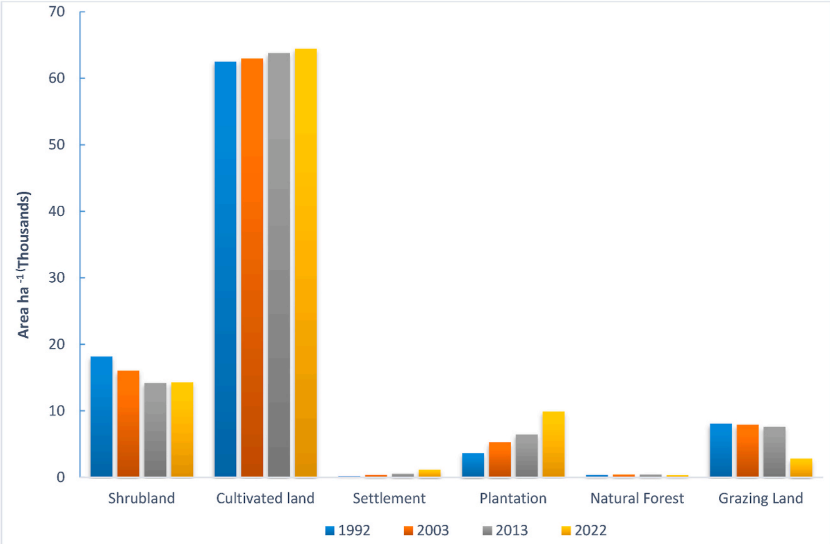

Fig. A2. LULC's area (ha) in different years across the study area.
(Source: own computation (2022); supporting from https://earthexplorer.usgs.gov)

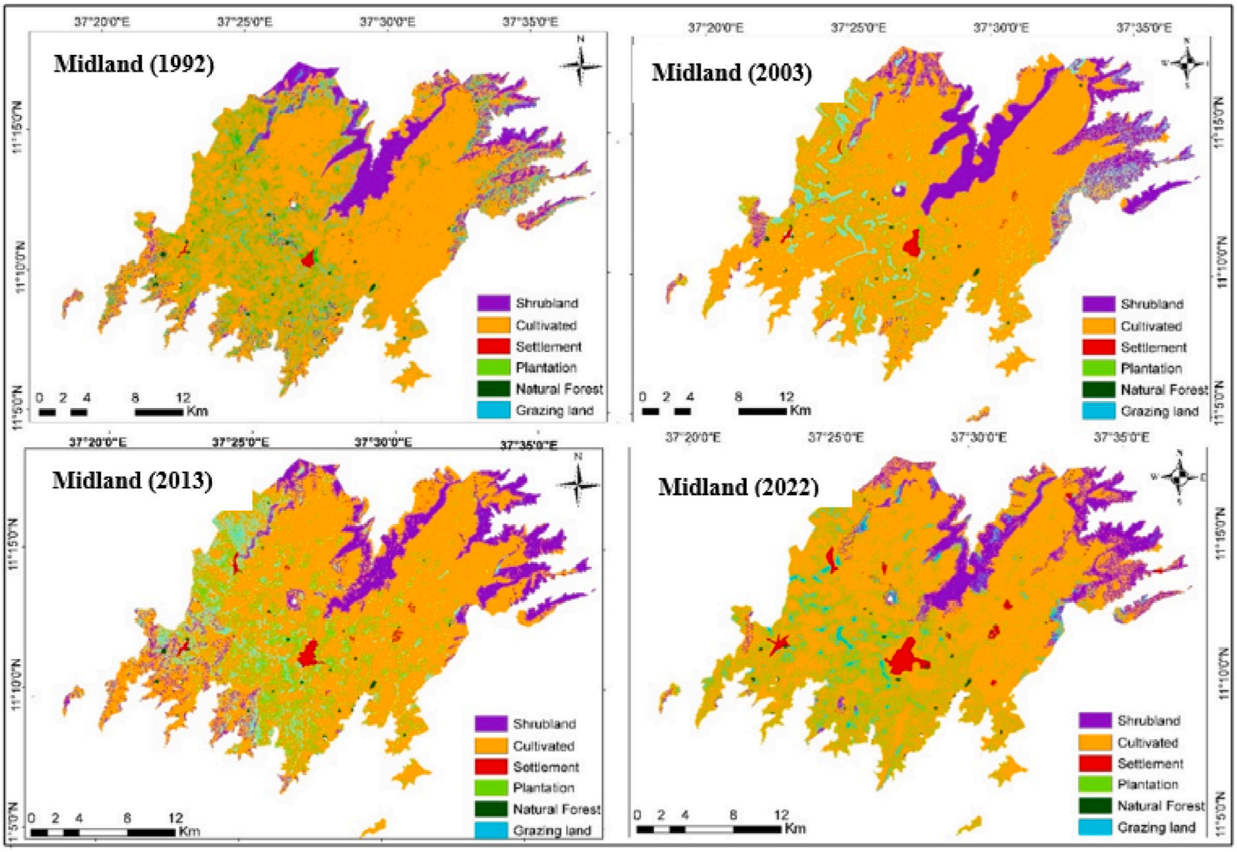

Fig. A3. LULCC midland agroecology for the year 1992–2022.
(Source: own computation (2022); supporting from https://earthexplorer.usgs.gov)

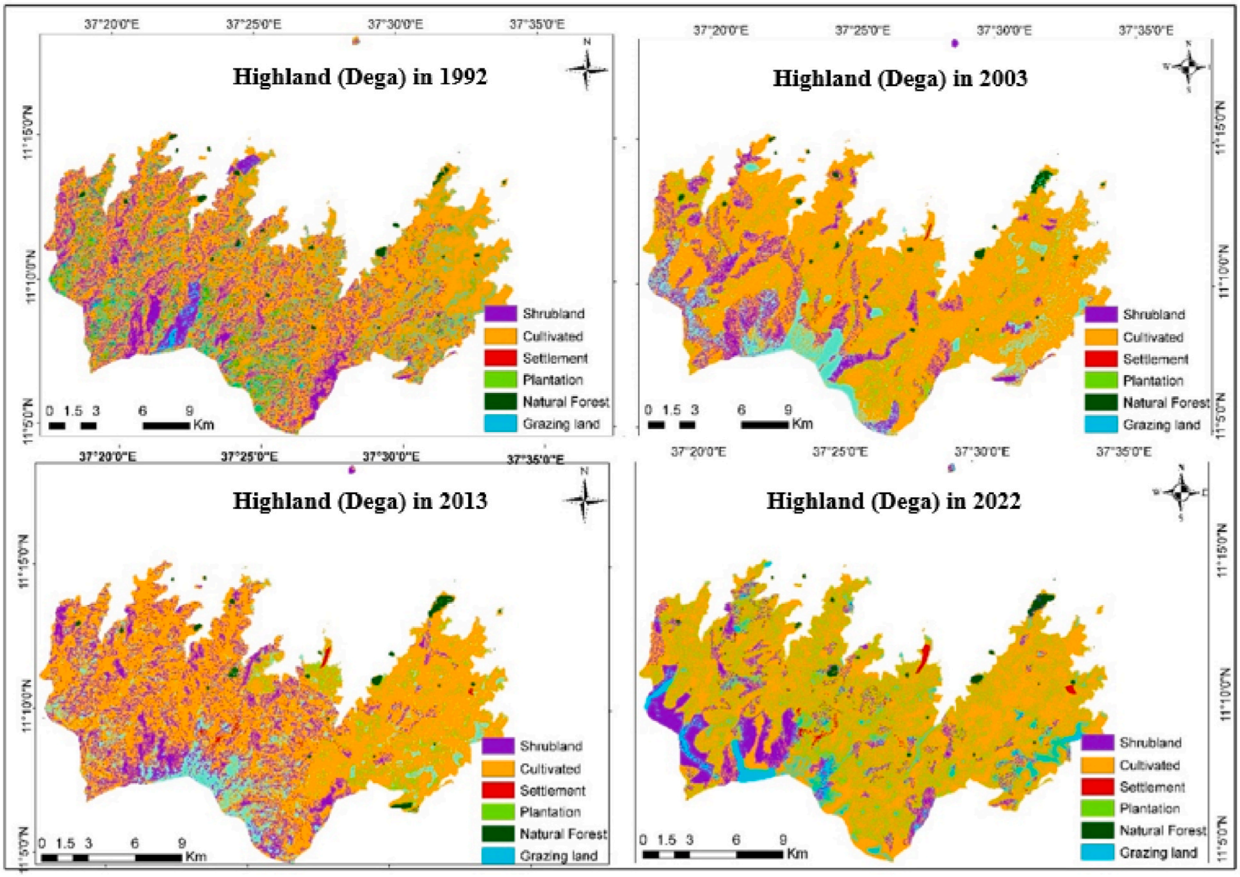

Fig. A4. LULCC in highland agroecology for the year 1992–2022.
Source: own computation (2022); supporting from https://earthexplorer.usgs.gov*)*

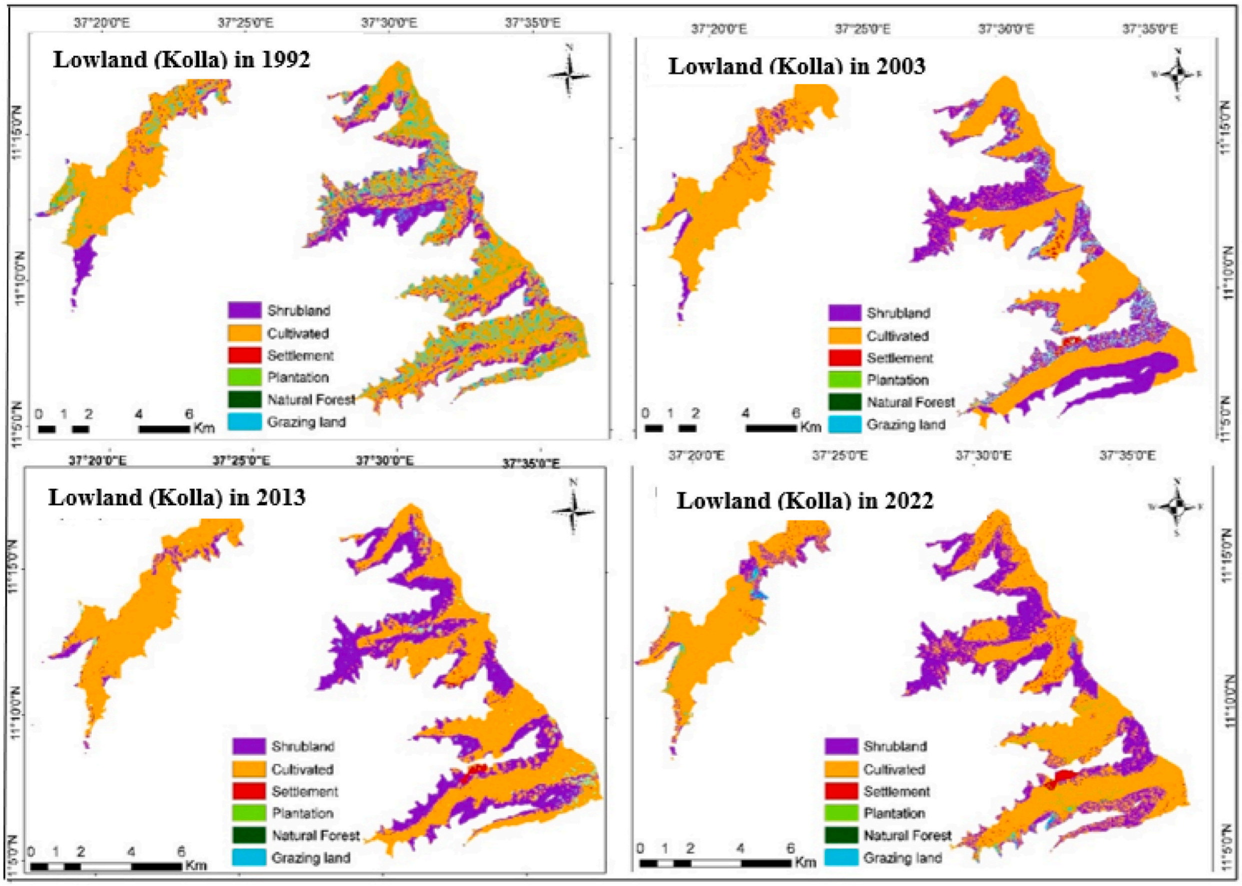

Fig. A5. LULCC in lowland agroecology for the year 1992–2022.
Source: own computation (2022); supporting from https://earthexplorer.usgs.gov*)*

References

[1] S. Cooley, D. Schoeman, L. Bopp, P. Boyd, S. Donner, S.I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.F. Racault, B. Rost, InIPCC AR6 WGII, in: Oceans and Coastal Ecosystems and Their Services, Cambridge University Press, 2022 Feb 28.

[2] A. Abdulkadir, A.M. Lawal, T.I. Muhammad, Climate change and its implications on human existence in Nigeria: a review, Bayero Journal of Pure and Applied Sciences 10 (2) (2017) 152–158.

[3] M.W. Priyanto, J.H. Mulyo, H.P. Irham, Farmer AWARENESS, RISK perception and adaptation to climate change: IS the INDONESIANS' climate program make a difference? Journal of Sustainability Science and Management 18 (2) (2023 Feb) 34–50.

[4] A. Raza, A. Razzaq, S.S. Mehmood, X. Zou, X. Zhang, Y. Lv, J. Xu, Impact of climate change on crops adaptation and strategies to tackle its outcome: a review, Plants 8 (2) (2019 Jan 30) 34.

[5] O.A. Adeagbo, T.O. Ojo, A.A. Adetoro, Understanding the determinants of climate change adaptation strategies among smallholder maize farmers in South-west, Nigeria, Heliyon 7 (2) (2021 Feb 1) E06231.

[6] S.K. Jha, S. Mishra, B. Sinha, J.M. Alatalo, R. Pandey, Rural development program in tribal region: a protocol for adaptation and addressing climate change vulnerability, J. Rural Stud. 51 (2017 Apr 1) 151–157.

[7] A. Thomas, A. Baptiste, R. Martyr-Koller, P. Pringle, K. Rhiney, Climate change and small island developing states, Annu. Rev. Environ. Resour. 45 (2020 Oct 17) 1–27.

[8] A. Asfaw, A. Bantider, B. Simane, A. Hassen, Smallholder farmers' livelihood vulnerability to climate change-induced hazards: agroecology-based comparative analysis in Northcentral Ethiopia (Woleka Sub-basin), Heliyon 7 (4) (2021 Apr 1) E06231.

[9] T. Dube, P. Moyo, M. Ncube, D. Nyathi, The impact of climate change on agro-ecological based livelihoods in Africa: a review, J. Sustain. Dev. 9 (1) (2016) 256–267. Dube T, Moyo P, Mpofu M, Nyathi D (2016), The impact of climate change on agro-ecological based livelihoods in Africa: A review.

[10] E. Workie, J. Mackolil, J. Nyika, S. Ramadas, Deciphering the impact of COVID-19 pandemic on food security, agriculture, and livelihoods: a review of the evidence from developing countries, Current Research in Environmental Sustainability 2 (2020 Dec 1) 100014.

[11] S. Ali, Y. Liu, M. Ishaq, T. Shah, Ilyas A. Abdullah, I.U. Din, Climate change and its impact on the yield of major food crops: evidence from Pakistan, Foods 6 (6) (2017 May 24) 39.

[12] F. Leippert, M. Darmaun, M. Bernoux, M. Mpheshea, A. Müller, M. Geck, M. Herren, W. Irungu, M. Nyasimi, J.M. Sene, M. Sow, The Potential of Agroecology to Build Climate-Resilient Livelihoods and Food Systems, 2020.

[13] J. Zscheischler, O. Martius, S. Westra, E. Bevacqua, C. Raymond, R.M. Horton, B. van den Hurk, A. AghaKouchak, A. Jézéquel, M.D. Mahecha, D. Maraun, A typology of compound weather and climate events, Nat. Rev. Earth Environ. 1 (7) (2020 Jul) 333–347.

[14] T.M. Mashizha, Adapting to climate change: Reflections of peasant farmers in mashonaland west province of Zimbabwe, Jàmbá: Journal of Disaster Risk Studies 11 (1) (2019 Jan 1) 1–8.

[15] L. Pereira, Climate Change Impacts on Agriculture across Africa, Oxford research encyclopedia of environmental science, 2017 Mar 29.
[16] O. Serdeczny, S. Adams, F. Baarsch, D. Coumou, A. Robinson, W. Hare, M. Schaeffer, M. Perrette, J. Reinhardt, Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions, Reg. Environ. Change 17 (2017 Aug) 1585–1600.
[17] Federal Democratic Republic of Ethiopia: Plan and Development Commission (FDRE-PDC). Ten Years Development Plan: Path Way to Prosperity 2021-2030: Plan and Development Commission, Addis Ababa, Ethiopia, 2020.
[18] A.M. Chanie, K.Y. Pei, Z. Lei, C.B. Zhong, Rural development policy: what does Ethiopia need to ascertain from China rural development policy to eradicate rural poverty, American Journal of Rural Development 6 (3) (2018) 79–93.
[19] C. Falco, F. Donzelli, A. Olper, Climate change, agriculture and migration: a survey, Sustainability 10 (5) (2018 May 3) 1405.
[20] M.S. Demem, Impact and adaptation of climate variability and change on small-holders and agriculture in Ethiopia: a review, Heliyon9, 5 (2023 Aug) E06231, 1-8.
[21] Climate Risk Profile: Ethiopia (CRPE), The World Bank Group, 2021.
[22] F. Baarsch, M. Schaeffer, Climate Change Impacts on Africa's Economic Growth, Africa Development Bank, Abidjan, 2019 Feb 13.
[23] A. Egeru, B. Barasa, J. Nampijja, A. Siya, M.T. Makooma, M.G. Majaliwa, Past, present and future climate trends under varied representative concentration pathways for a sub-humid region in Uganda, Climate 7 (3) (2019 Feb 26) 35.
[24] T.E. Epule, A. Chehbouni, V. Ongoma, Y. Brouziyne, D. Etongo, E.L. Molua, A new index on agricultural land greenhouse gas emissions in Africa, Environ. Monit. Assess. 194 (9) (2022 Sep) 598.
[25] A.A. Ebrahim, B.A. Miheretu, A. Alemayehu, Vulnerability of smallholder farmers to climate variability and change across different agro-ecological Zones in Oromo Nationality Administration (ONA), North east Ethiopia, PLoS One 17 (6) (2022 Jun 22) e0268094.
[26] M.S. Gizaw, T.Y. Gan, Impact of climate change and El Niño episodes on droughts in sub-Saharan Africa, Clim. Dynam. 49 (1–2) (2017 Jul) 665–682.
[27] B. Stuch, J. Alcamo, R. Schaldach, Projected climate change impacts on mean and year-to-year variability of yield of key smallholder crops in Sub-Saharan Africa, Clim. Dev. 13 (3) (2021 Mar 16) 268–282.
[28] D.M. Baptista, M.M. Farid, D. Fayad, L. Kemoe, L.S. Lanci, M.P. Mitra, T.S. Muehlschlegel, C. Okou, J.A. Spray, K. Tuitoek, F. Unsal, Climate Change and Chronic Food Insecurity in Sub-saharan Africa, International Monetary Fund, 2022 Sep 15.
[29] M.R. Maino, D. Emrullahu, Climate Change in Sub-saharan Africa Fragile States: Evidence from Panel Estimations, International Monetary Fund, 2022 Mar 18.
[30] B.W. Muleta, Climate Change and Food Security in Sub-saharan Africa, 2022.
[31] T. Alemu, A. Mengistu, Impacts of climate change on food security in Ethiopia: adaptation and mitigation options: a review. Climate Change-Resilient Agriculture and Agroforestry: Ecosystem Services and Sustainability, 2019, pp. 397–412.
[32] Y.T. Ayinu, D.Y. Ayal, T.T. Zeleke, K.T. Beketie, Impact of climate variability on household food security in Godere District, Gambella Region, Ethiopia, Climate Services 27 (2022 Aug 1) 100307.
[33] A. Belay, C. Oludhe, A. Mirzabaev, J.W. Recha, Z. Berhane, P.M. Osano, T. Demissie, L.A. Olaka, D. Solomon, Knowledge of climate change and adaptation by smallholder farmers: evidence from southern Ethiopia, Heliyon 8 (12) (2022 Dec 1) E06231.
[34] R. Solomon, B. Simane, B.F. Zaitchik, The impact of climate change on agriculture production in Ethiopia: application of a dynamic computable general equilibrium model, Am. J. Clim. Change 10 (1) (2021 Feb 10) 32–50.
[35] Z.A. Alemu, M.O. Dioha, Climate change and trend analysis of temperature: the case of Addis Ababa, Ethiopia, Environmental Systems Research 9 (1) (2020 Dec) 1–5.
[36] G.W. Gebru, H.E. Ichoku, P.O. Phil-Eze, Determinants of smallholder farmers' adoption of adaptation strategies to climate change in Eastern Tigray National Regional State of Ethiopia, Heliyon 6 (7) (2020 Jul 1) E06231.
[37] D.O. Gemeda, D.H. Feyssa, W. Garedew, Meteorological data trend analysis and local community perception towards climate change: a case study of Jimma City, Southwestern Ethiopia, Environ. Dev. Sustain. 23 (2021 Apr) 5885–5903.
[38] National Adaptation Plan Ethiopia Nap-Eth, Ethiopia's Climate Resilient Green Economy: National Adaptation Plan. Addis Ababa, Ethiopia: Federal Democratic Republic of Ethiopia, 2019 May.
[39] H. Zegeye, Climate change in Ethiopia: impacts mitigation and adaptation, International Journal of Research in Environmental Studies 5 (1) (2018 Apr) 18–35.
[40] T. Ginbo, Heterogeneous impacts of climate change on crop yields across altitudes in Ethiopia, Climatic Change 170 (1–2) (2022 Jan) 12.
[41] H. Teshome, K. Tesfaye, N. Dechassa, T. Tana, M. Huber, Smallholder farmers' perceptions of climate change and adaptation practices for maize production in Eastern Ethiopia, Sustainability 13 (17) (2021 Aug 26) 9622.
[42] G.B. Tesfahunegn, T.A. Gebru, Climate change effects on agricultural production: insights for adaptation strategy from the context of smallholder farmers in Dura catchment, northern Ethiopia, Geojournal 86 (1) (2021 Feb) 417–430.
[43] G. Zerssa, D. Feyssa, D.G. Kim, B. Eichler-Löbermann, Challenges of smallholder farming in Ethiopia and opportunities by adopting climate-smart agriculture, Agriculture 11 (3) (2021 Feb 26) 192.
[44] S.B. Bedeke, W. Vanhove, M.G. Wordofa, K. Natarajan, P. Van Damme, Vulnerability to climate change among maize-dependent smallholders in three districts of Ethiopia, Environ. Dev. Sustain. 22 (2020 Feb) 693–718.
[45] D. Chala, S. Belay, A. Bamlaku, H. Azadi, Agro-ecological based small-holder farmer's livelihoods vulnerability to climate variability and change in Didesa sub-Basin of Blue Nile River, Ethiopia, Acad. J. Agric. Res. 4 (5) (2016) 230–240.
[46] T. Zeleke, F. Beyene, T. Deressa, J. Yousuf, T. Kebede, Vulnerability of smallholder farmers to climate change-induced shocks in East Hararghe Zone, Ethiopia, Sustainability 13 (4) (2021 Feb 18) 2162.
[47] Sinore T., Wang F., Impact of climate change on agriculture and adaptation strategies in Ethiopia: a meta-analysis, Heliyon 10(2024 Feb 13) E06231.1-12.
[48] Ministry of Agriculture MoA, Agro-ecological zones of Ethiopia. Addis Ababa, Ethiopia, 1998.
[49] Central Statistics Authority Csa, Ethiopian Central Statistics, Population Census Result of Yilemana Densa Woreda, Addis Ababa Ethiopia, 2007.
[50] Yilmana Densa Woreda agriculture office, Yilmana Densa Woreda Agriculture Office Annual Report. Adet, Ethiopia June, 2022.
[51] C.R. Kothari, Research Methodology: Methods and Techniques, New Age International, 2004.
[52] R.V. Krejcie, D.W. Morgan, Determining sample size for research activities, Educ. Psychol. Meas. 30 (3) (1970 Sep) 607–610.
[53] W.W. Daniel, C.L. Cross, Biostatistics: a Foundation for Analysis in the Health Sciences, Wiley, 2018 Nov 13.
[54] M.B. Hahn, A.M. Riederer, S.O. Foster, The Livelihood Vulnerability Index: a pragmatic approach to assessing risks from climate variability and change—a case study in Mozambique, Global Environ. Change 19 (1) (2009 Feb 1) 74–88.
[55] N.A. Khan, Q. Gao, M. Abid, A.A. Shah, Mapping farmers' vulnerability to climate change and its induced hazards: evidence from the rice-growing zones of Punjab, Pakistan, Environ. Sci. Pollut. Control Ser. 28 (2021 Jan) 4229–4244.
[56] J.J. McCarthy (Ed.), Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2001 Jul 2.
[57] A. Marelign, S. Addisu, A. Mekuriaw, Observed and perceived climate change and variability and small holder farmers' vulnerability: the case of janamora district, Northwestern Ethiopia, J. Environ. Earth Sci. 8 (9) (2019 Aug 31) 33–44.
[58] A. Mekasha, K. Tesfaye, A.J. Duncan, Trends in daily observed temperature and precipitation extremes over three Ethiopian eco-environments, Int. J. Climatol. 34 (6) (2014 May) 1990–1999.
[59] H. Il Choi, Assessment of aggregation frameworks for composite indicators in measuring flood vulnerability to climate change, Sci. Rep. 9 (1) (2019 Dec 18) 19371.
[60] R.K. Pachauri, M.R. Allen, V.R. Barros, J. Broome, W. Cramer, R. Christ, J.A. Church, L. Clarke, Q. Dahe, P. Dasgupta, N.K. Dubash, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Ipcc, 2014.
[61] M. Mekonnen, T. Sewunet, M. Gebeyehu, B. Azene, A.M. Melesse, GIS and remote sensing-based forest resource assessment, quantification, and mapping in Amhara Region, Ethiopia, Landscape Dynamics, Soils and Hydrological Processes in Varied Climates (2016) 9–29.
[62] R.G. Congalton, A review of assessing the accuracy of classifications of remotely sensed data, Rem. Sens. Environ. 37 (1) (1991 Jul 1) 35–46.

[63] C.A. Vieira, P.M. Mather, P. Aplinb, Assessing the positional and thematic accuracy of remotely sensed data, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. ISPRS Arch. 35 (6) (2004 Jul).

[64] I. Tessema, B. Simane, Vulnerability analysis of smallholder farmers to climate variability and change: an agroecological system-based approach in the Fincha'a sub-basin of the upper Blue Nile Basin of Ethiopia, Ecological Processes 8 (2019 Dec) 1–8.

[65] Z. Mekonnen, T. Woldeamanuel, H. Kassa, Socio-ecological vulnerability to climate change/variability in central Rift Valley, Ethiopia, Adv. Clim. Change Res. 10 (1) (2019 Mar 1) 9–20.

[66] E.K. Derbile, D. Chirawurah, F.X. Naab, Vulnerability of smallholder agriculture to environmental change in North-Western Ghana and implications for development planning, Clim. Dev. 14 (1) (2022 Jan 2) 39–51.

[67] A.C. Segnon, E. Totin, R.B. Zougmoré, J.C. Lokossou, M. Thompson-Hall, B.O. Ofori, E.G. Achigan-Dako, C. Gordon, Differential household vulnerability to climatic and non-climatic stressors in semi-arid areas of Mali, West Africa, Clim. Dev. 13 (8) (2021 Sep 14) 697–712.

[68] C.K. Ndung'u, F.W. Muriu-Ng'ang'a, Assessment of farmers' vulnerability to climate variability and extreme events: evidence from dry Kitui, Kenya, International Journal of Environment, Agriculture and Biotechnology 6 (1) (2021 Feb 16).

[69] P. Asrat, B. Simane, Characterizing vulnerability of crop-based rural systems to climate change and variability: agro-ecology specific empirical evidence from the Dabus watershed, north-West Ethiopia, Am. J. Clim. Change 6 (4) (2017 Oct 24) 643–667.

[70] A.A. Mekonen, A.B. Berlie, Rural households' livelihood vulnerability to climate variability and extremes: a livelihood zone-based approach in the Northeastern Highlands of Ethiopia, Ecological Processes 10 (2021 Dec) 1–23.

[71] E.K. Austin, J.L. Rich, A.S. Kiem, T. Handley, D. Perkins, B.J. Kelly, Concerns about climate change among rural residents in Australia, J. Rural Stud. 75 (2020 Apr 1) 98–109.

[72] S.A. Legese, O.A. Olutayo, H. Sulaiman, P. Rao, Assessing climate change impacts in the Lake Tana Sub-Basin, Ethiopia using livelihood vulnerability approach, J. Earth Sci. Climatic Change 7 (368) (2016), 1-0.

[73] L. Connolly-Boutin, B. Smit, Climate change, food security, and livelihoods in sub-Saharan Africa, Reg. Environ. Change 16 (2016 Feb) 385–399.