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Vulnerability of Smallholder Farmers to Climate Change Across Agroecologies in Jemma Sub Basin, Ethiopia

Abirham Cherinet^{1,2*}, Belay Simane³, Abraham Mebrat Asmare¹

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Abstract Ethiopia is highly vulnerable to climate change due to its economic reliance on rain-fed agriculture. Identifying the differences in vulnerability levels within systems is crucial to propose appropriate and effective adaptation options. Thus, this study examines the agroecology-based vulnerability of smallholders' livelihoods to climate change and variability in the Jemma sub-basin. A total of 366 sample households were selected based on the proportion to sample size to collect primary data across three agroecologies, and climatic data from 1981 to 2022 were accessed from the Ethiopian National Meteorological Institute. The study result revealed significant variation in smallholders' vulnerability across agroecological zones. Lowland agroecology exhibited the highest vulnerability score (0.0610) due to its high exposure (0.6613), sensitivity (0.6723), and low adaptive capacity (0.5706). In contrast, midland agroecology was relatively the least vulnerable (-0.0768) due to its low exposure (0.51270), sensitivity (0.5746), and high adaptive capacity as compared to others. Highland agroecology had an intermediate score in all vulnerability components. The results revealed that vulnerability differences were attributable to household characteristics, lack of infrastructure, low livelihood diversification, and lack of available technologies. In light of the findings, it is suggested that resilience-building adaptation interventions like the expansion of small-scale irrigation, the establishment of effective microfinance institutions, timely information and agricultural inputs, improved extension support, engagement in non-farm sources of income, expansion of infrastructure have to be promoted thereby to increase the adaptive capacity of subsistence rainfed-dependent farmers to withstand the vagaries of the climate change/ variability risks.

Keywords: agroecology, livelihood vulnerability index, adaptive capacity, exposure, sensitivity

¹ Institute of Disaster Risk Management and Food Security Studies, Bahir Dar University, P.O. Box 79, Bahir Dar, Ethiopia

² Ethiopian Forestry Development, P.O. Box 30708, Addis Ababa, Ethiopia

³ College of Development Studies, Addis Ababa University P.O. Box 1176, Addis Ababa, Ethiopia

* Corresponding author email: aberham2010@gmail.com

1. INTRODUCTION

Climate change is one of the most serious challenges worldwide, adversely affecting human and natural systems (Addisu et al., 2019; IPCC, 2022). The global climate is changing rapidly and severely threatens development (IPCC, 2023). Climate-induced hazards such as drought, flood, rainstorms, heat waves, and cyclones lead to widespread social, economic, ecological, and psychological difficulties (Amare & Simane, 2017; Adger et al., 2017; Mekonen & Berlie, 2021). However, the impacts and severity of climate change vary across regions, countries, sectors, and communities (Balaganesh et al., 2020; Farid et al., 2019). According to Lowder et al. (2016), more than 75% of the world's agricultural lands are managed by smallholder farmers; however, they are the most vulnerable to the impacts of climate change (Berhanu et al., 2024; Zeleke et al., 2021). The livelihoods of smallholder farmers are particularly vulnerable to climate change due to their high dependence on ecosystem services and rain-fed livelihood activities, high exposure and sensitivity to climate variability, limited capacity to adapt, and often live in marginal locations (Cooper & Wheeler, 2017; Mohammed et al., 2018; Jamshidi et al., 2019).

Agriculture plays a fundamental role in the Ethiopian economy, contributing over 37.5% of the national gross domestic product (Leogrande, 2023). Additionally, it provides livelihoods for more than 80% of the Ethiopian population (Njeru, 2016). Despite its significant share of the overall economy, agriculture is predominantly rain-fed and vulnerable to climate change and extreme events (Sinore & Wang, 2024). For instance, droughts have affected nearly 2 million Ethiopians annually over the last 20 years (Simane et al., 2016). According to the World Bank (2024) report, climate change is predicted to slow the country's GDP growth by 1-1.5% of GDP and rise to 5% by the 2040s, potentially pushing millions of Ethiopians into poverty. For instance, the severe drought that occurred in 2002–2003 resulted in a 26% decrease in food output (Barnett & O'Neill, 2010). Even though climate change is a global phenomenon, its vulnerability is specific to particular regions.

Several studies have explored farmers' livelihood vulnerability and the factors influencing their vulnerability to climate variability in Ethiopia using a range of methods and approaches (Zeleke et al., 2021; Abeje et al., 2019; Assefa et al., 2022; Tessema & Simane, 2019; Dalle et al., 2024). However, due to the heterogeneity in socioeconomic capacity and livelihoods across different communities, similar climate variability could impact groups of people at different levels (Abeje et al., 2019). For instance, a region-wise study by Zeray & Demie (2015) revealed that the Afar, Somali, Oromia, and Tigray regions were among the most vulnerable, whereas, Southern Nations Nationalities and Peoples (SNNP) and the Benishangul-Gumuz region were relatively not vulnerable. Site-specific studies also revealed inconsistent results regarding the vulnerability of smallholder farmers to climate change. For instance, Asfaw et al. (2021) found that smallholder farmers in lowland agroecologies are more vulnerable than those in highland and midland agroecological zones. In contrast, Simane et al. (2016) and Asmamaw et al. (2019) found that highland areas were more vulnerable than the lowland and midland areas. Aside from that, Abeje et al. (2019) discovered that the midland agroecology was more vulnerable than highland and lowland agroecologies. However, aggregate-level assessment and

inconsistency of results might have led to intervention failure, as recent studies highlight the importance of context-specific evaluation and implementation coherence (Mogess, 2023). Besides, most studies ignore important exposure-related indicators such as the onset and cessation of the rainy season, frost, and hailstorm incidences (Zelege et al., 2023; Likinaw et al., 2024; Tessema & Simane, 2019). However, these indicators potentially determine the vulnerability levels of the agroecology (Rudiarto & Pamungkas, 2020; Fang et al., 2020; Huong et al., 2018). Although these studies have made significant contributions to our current level of knowledge and understanding of livelihood vulnerability to climate change, there are likely gaps that need to be filled.

The study area, the Jemma sub-basin, is one of the best grain producers and leading suppliers of sorghum in Ethiopia, and among the eight good-performing areas in crop production (Temeche et al., 2021; Mare et al., 2024). Hydrologically, it contributes about 14% of the annual flow and covers approximately 8% of the total area of the Upper Blue Nile basin (Yilma & Awulachew, 2009). However, the sub-basin is highly populated, with a population growth rate of 1.7, and the average population density is 144 persons/km². This rapid population growth and land-intensive development activities have led to various biophysical and socioeconomic problems in the sub-basin (Cherinet et al., 2025). Therefore, examining the extent of smallholder farmers and their underlying factors is crucial for generating research-based evidence for decision-makers. Thus, this study provides a comprehensive analysis of livelihood vulnerability among smallholder farmers across diverse agroecological zones of the Jemma sub-basin.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

The Jemma sub-basin, located in the Central Highlands of Ethiopia, is one of the largest sub-basins of the Upper Blue Nile River. The sub-basin is located at 9° 0' 0" to 11° 0' 0" Northern latitude and 38° 30' 0" to 41° 0' 0" Eastern longitude. The sub-basin has a total area of ~15,803 km² (Figure 1). The Jemma sub-basin drained the North Shewa zone of the Amhara and Oromia regions. Based on the 2007 census report, the population of Jemma sub-basin is growing at an average rate of 1.7, which means the population in 2025 will be approximately 2,175,150, resulting in a population density of 144 persons per km² (CSA, 2007). The sub-basin receives annual rainfall ranging from 697 to 1475 mm. The mean annual temperature ranges between 9 and 24°C, and the elevation varies from 1,040m to 3,814m above sea level. Crop cultivation, mainly wheat, barley, teff, maize, sorghum, and livestock rearing are the primary livelihoods of the inhabitants. Based on the FAO's soil classification, the Jemma sub-basin features a diverse range of soil types, including Eutric Vertisols (28.07%), Lithic Leptosols (37.44%), Chromic Lixisols (8.07%), Pelvic Vertisols (6.82), Haplic Luvisols (5.79%), Haplic Acrisols (6.82%). Eutric Fluvisols, Umbria Nitisols, and Alic Nitisols cover a small part of the lower basin. Sandy loam, clay, and loam are the major soil texture classes in the sub-basin (Ali et al., 2015; Worku et al., 2021).

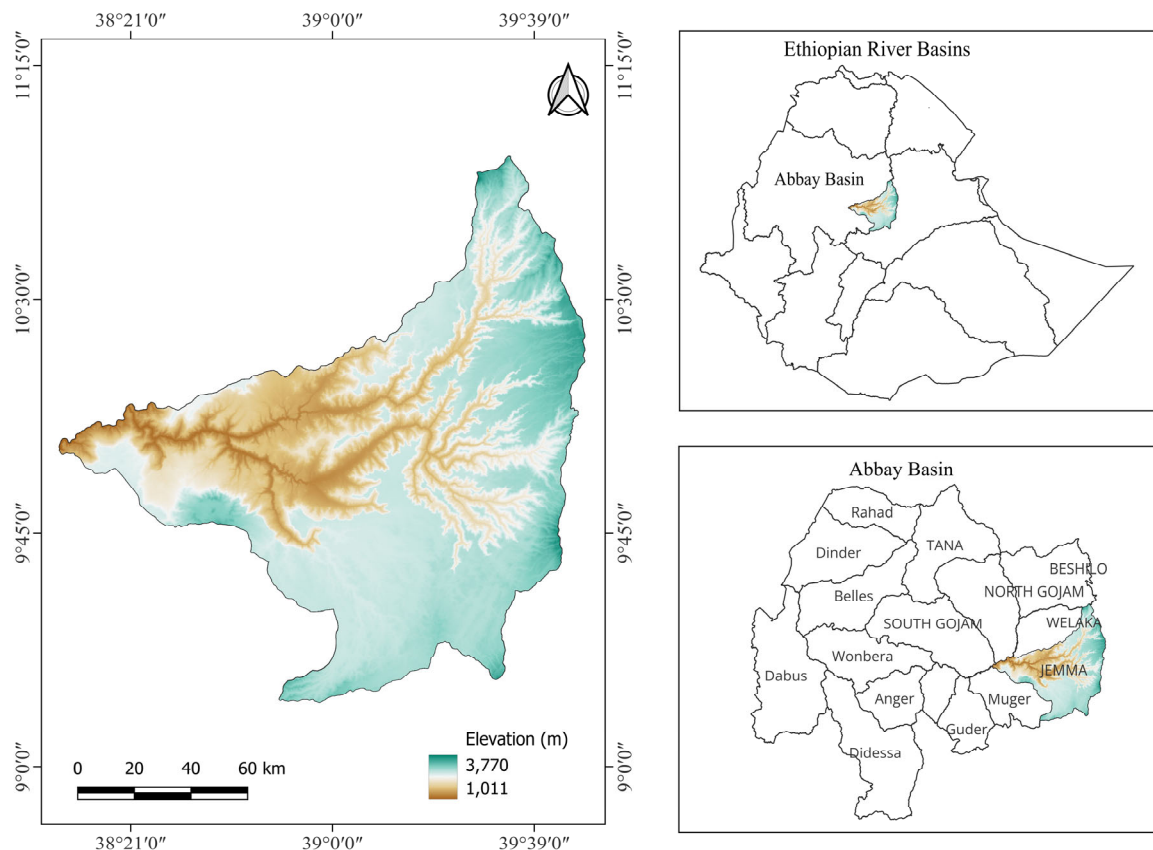


Figure 1. Map of the study area

2.2 Sample Size Determination

Both probability and nonprobability sampling techniques were applied to select the required sample households in the study area. The research employs a multistage sampling technique to determine the study area, agroecological zones (AEZs) within the sub-basin, woredas and Kebeles within the selected agroecological zone, and individuals from each Kebele for the data collection in various stages. First, we choose Menz Mama, Siyadebirna Wayu, and Merhabete woredas purposively from highland, midland, and lowland agroecology based on their dominant agroecological zones, demographics, and livelihood conditions (Table 1). Secondly, Kebeles were clustered into their respective agroecological zones, and then three highland, two midland, and three lowland kebeles were randomly selected. The list of household heads was collected from the respective kebele administrators and development agents. Finally, 366 sample households were randomly selected based on a probability proportional to size sampling technique, using Kothari, (2004) formula (Equation 1).

$$n = \frac{Z^2 * N * p * q}{e^2(N - 1) + Z^2 * p * q} \quad (1)$$

Where n = desired sample size; z = Value of standard variation (1.96), e= Acceptable error (0.05), N = total number of households in the selected AEZs=7937, p = the proportion of the target population estimated to have characteristics being measured (50% is taken or 0.5), and

$q = 1-p$. Then, $p = 0.5$, $q = 0.5$, considering a 95% confidence level, the related standard normal deviation is $z = 1.96$, and the desired accuracy is at 0.05.

$$n = \frac{1.96^2 * 7937 * 0.5 * 0.5}{0.05^2 (7937 - 1) + 1.96^2 * 0.5 * 0.5} = 366$$

Table1. Sample households in each agroecological zone of the Jemma sub-basin

Agroecology	Woredas	Sample Kebeles	Household Heads	Sample households
Highland	Menze Mama	04	1053	49
		08	856	39
		010	721	33
Midland	Siyadebirna Wayu	Senketa	778	36
		Motelemi	767	35
Lowland	Merhabete	Buyu	1350	62
		Geren	1162	54
		Arogenda	1250	58
Total		8	7937	366

Additionally, we employed a purposive sampling technique to choose Focus Group Discussants (FGD) and Key Informants (KI). The respondents were selected based on being socially respected and known to have better knowledge of the present and past environmental, social, and economic status of the area under study. The members were from different social groups, including women, men, youth, elderly religious leaders, and kebele officials. At each kebele, one focus group discussion was held with 8 participants and key-informant interviews with 15 were carried out to triangulate, supplement, and enrich the data collected from the 366 sampled households. Key indicators of exposure, sensitivity, and adaptive capacity listed in Table 2 were selected based on existing literature and prioritized by key informants and FGD participants to reflect the local condition.

2.3 Data Analysis

Both quantitative and qualitative methods are used in data analysis. The quantitative data related to exposure, sensitivity, adaptive capacity and livelihood vulnerability situation were analyzed using SPSS-20 software. The qualitative data were analysed through a process of identifying patterns, themes, and meanings in non-numeric information from FGDs, KIIs, and desk reviews, then integrated with quantitative findings to provide a more comprehensive and contextually specific picture of livelihood vulnerability at the local level. Furthermore, to substantiate the LVI results, one-way ANOVA analysis was employed.

2.4 Livelihood Vulnerability Index (LVI)

The vulnerability level of farmers' livelihoods to climate change was analyzed using the livelihood vulnerability index (LVI) developed by Hahn et al. (2009). The method used a balanced weighted average approach, ensuring that each major component contributes equally

to the overall index, despite variations in sub-components across different major livelihood asset categories (Sullivan, 2002). (Asrat & Simane, 2017; Amare & Simane, 2017; Dechassa et al., 2017). Each household was asked to provide a value for each indicator using continuous, dummy, nominal, or ordinal scales. Since the sub-components are measured on various scales, it is necessary to normalize them to obtain standard values. Finally, the integrated approach of the balanced weighted average LVI and an LVI-IPCC framework (IPCC, 2007) was used. First, the indicators were standardized to an index as in Equation (2).

$$IndexS_d = \frac{S_d - S_{min}}{S_{max} - S_{min}} \quad (2)$$

Where: $Index_{sd}$ is the standardized index for S_d , S_d (the original indicator for district d), and S_{min} and S_{max} are the minimum and maximum values, for each sub-indicator, determined by using data from the communities. These minimum and maximum values were used to transform each indicator into a standardized index. After standardizing for each indicator, the sub-components were averaged using Equation (3) to calculate the value of each major component.

$$M_d = \frac{\sum_{i=1}^n IndexS_{di}}{n} \quad (3)$$

Where: M_d = one of the major components for the woredas; index represents the sub-components, indexed by i , and n is the number of sub-components in each major component.

Once the values for each major component of a kebele were calculated, they were averaged using Equation (4) to obtain the woreda-level vulnerability index.

$$LVI_d = \frac{\sum_{i=1}^n W_{mi} M_{di}}{\sum_{i=1}^n W_{mi}} \quad (4)$$

Where: LVI_d is the Livelihood Vulnerability Index for agroecology d , equals the weighted average of the major components. The weights of each major component, W_{mi} , 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 (Geest & Warner, 2015).

$$CF_d = \frac{\sum_{i=1}^n W_{mi} M_{di}}{\sum_{i=1}^n W_{mi}} \quad (5)$$

Where: CF_d is an IPCC-defined contributing factor (exposure, sensitivity, or adaptive capacity) for agroecology d , M_{di} is the major component for agroecology d indexed by i , W_{mi} is the weight of each major component, and n is the number of major components in each contributing factor (Equation 5). Once exposure, sensitivity, and adaptive capacity are calculated, the three contributing factors are combined using Equation (6):

$$LVI - IPCC_d = (e_d - a_d) \times s_d \tag{6}$$

Where: $LVI-IPCC_d$ is the LVI for agroecology d expressed using the IPCC vulnerability framework, e_d is the calculated exposure score for agroecology d , a_d is the calculated adaptive capacity score for agroecology d , and the s_d is the calculated sensitivity score for agroecology d . The LVI-IPCC is scaled from -1 (least vulnerable) to 1 (most vulnerable). The chi-square and F-test were computed to examine the association and mean differences among the three agroecologies.

Table 2. Vulnerability factors, livelihood capitals, profiles, and indicators used for LVI analysis using the IPCC framework

Factors	Capitals	Profiles	Indicators	Units	Hypothesized functional Relationship
Exposure		Climate	Change in maximum temp.	Changes over time, °C	Larger change or frequency = high exposure
			Change in minimum temp.	Changes over time, °C	
			Change in precipitation	Changes over time, mm	
			Drought and flood incidents	Number of events over the last 20 years	
			Rainfall distribution	Normal, uniform, erratic	
			Onset and cessation of the rainy Season	% of HHs perceive delayed onset and early cessation of RF	
			Frost incidence	Normal, increased, decreased	
Sensitivity	Natural capital	Ecosystem	Hailstorm incidence	Normal, increased, decreased	More forest cover, suitable land, and access to irrigation = lower sensitivity
			Land suitability for agriculture	Average. scale values of soil depth, terrain, drainage, and fertility of (1-5)	
			Sustainability of land use system	The assumed intensity of management (high, medium, and low)	
			Land cover change (primarily deforestation)	% of HHs perceive forest cover change	
			Use of soil water conservation techniques	% of HHs practice SWC structures	
			Irrigation potentials	Ha of land suitable for irrigation	
			Annual total production (inverse)	Tons of total products harvested	
Adaptive Capacity	Financial capital	Wealth	Changes in productivity	Yield in tons/ha	Greater productivity and diversity = lower sensitivity
			Diversity of crop species	Number of crops in the system	
			Total land holding	Ha/HH	

		livestock holding	TLU/HH	Greater wealth = greater adaptive capacity
		Access to credit	% of HHs with access to credit service	
		Savings at the HH level	Amount of Birr(local currency)/HH	
		Non-agricultural income	Amount of cash obtained per year	
Physical capital	Technology	Insecticide/Pesticide supply	% of HHs using insecticide	Better access to technology = greater adaptive capacity
		Use of fertilizer	% of HHs applying fertilizer	
		Use of improved seed	% HH used an improved seed	
		Irrigation potential	% of HHs practicing irrigation	
	Infrastructure	Access to all-weather roads	% of HHs have access roads	Better access to infrastructure = greater adaptive capacity
		Access to schools	Travel time in minutes	
		Access to health care	Travel time in minutes	
		Access to markets	Travel time in minutes	
		Access to electricity	% HHs have access to electricity	
		Access to information	% of HHs have information	
		Access to savings and credit	% of HHs using credit	
Human capital	Community	Sex of household	% Male-headed HHs	More human capital, information, and services = greater adaptive capacity
		Literacy level	% HH who can read and write	
		Access to the extension service	% of HHs have gotten extension service	
		Access to training	Number of training HH heads attended	
Social capital	Social	Membership in social organizations	% of HHs who are members of any social organizations	Higher membership of CBOs and more tradition of working together = greater adaptive capacity
		Household size	Average household size/HH	
		Availability of bylaws	% of HHs have bylaws	
		Tradition of working together	% of HHs have a tradition of working together	

3. RESULTS AND DISCUSSIONS

3.1 Socioeconomic Characteristics of the Respondents

A total of 366 individuals participated in the study, with 84.7% being male, and 15.3% were from female-headed households. Among the surveyed households, 25.7% were illiterate, while 74.3% could read and write (Table 3). The average age of the respondents was 50.75 years, with a standard deviation of 11.09. The average total landholding per household was 1.69 ha (0.32 ha per capita), and the highest and lowest mean TLU were recorded in the highland (11.41) and midland (6.48), respectively. The average farming experience is 26.07 years. This study also found that households in lowland agroecological zones travel an average of two hours and forty minutes to access services such as credit institutions, schools, veterinary services, markets, and health centers, compared to highland households.

Table 3. Socioeconomic characteristics of the household

		Highland	Midland	Lowland	Total	Percentage
Sex	Male	102	66	148	310	84.7
	Female	19	11	26	56	15.3
Age	20-40	16	17	46	79	21.6
	41-60	79	40	121	219	59.8
	>61	26	12	30	68	18.6
Education	Illiterate	24	23	47	104	25.7
	Read & Write	97	48	127	262	74.3
Average family size		5.74	5.52	5.67		
Average farming experience		27.88	25.7	24.95		
Landholding Size/ hectare		2.1	1.67	1.42		
Livestock holding TLU		11.41	8.13	6.48		
Distance to credit/savings		90	150	160		
Distance to market		86.53	150	160		

3.2 Livelihood Vulnerability Analysis

3.2.1 Exposure Component of Vulnerability

The results revealed that the mean monthly maximum temperature in the Jemma sub-basin has increased over the past 42 years, with positive deviations of 0.93°C in the highland, 0.78°C in the midland, and 0.79°C in the lowland areas. Based on the overall profile index value for the exposure factors, lowland agroecology is more exposed, with an exposure score of 0.6302, while midland agroecology is the least exposed, scoring 0.5468 (Table 4). Over the last two decades, drought has affected the lowland areas more frequently, with an average score of 0.726 compared to 0.45 in the highland and 0.432 in the midland areas. Similarly, the lowland agroecology is the most exposed area to flooding (0.756), followed by the midland and highland agroecologies. From the descriptive statistics, about 96.8% of lowland and 56% of midland households responded that rain comes late and early cessation, and the distribution also varies spatially and temporally. In contrast, highlanders perceive that the cessation time is somehow extended and fairly distributed as compared to lowland and midland agroecologies.

Table 4. Exposure indices of exposure indicators across agroecologies

Components	Indicators	Highland	Midland	Lowland
Climate	Average monthly SD of max. temp. (1981- 2022)	0.93	0.78	0.79
	Average monthly SD of min. temp. (1981- 2022)	0.99	0.45	0.53
	Average monthly SD of precipitation (1981- 2022)	0.57	0.69	0.86
	Average number of drought events (1981- 2022)	0.45	0.432	0.726
	Average number of flood events (1981- 2022)	0.783	0.563	0.756
	% of HHs perceived erratic rainfall distribution	0.298	0.384	0.585
	HHs who perceive a delayed onset and early cessation of rainfall	0.457	0.621	0.785
	% of HHs who perceive frost incidence	0.621	0.273	0.223
	% of HHs who perceive hailstorm occurrence	0.678	0.421	0.697
		<i>Profile Indexed value</i>	0.6419	0.5127

3.2.2 Sensitivity Components of Vulnerability

The average sensitivity indices for the lowland, midland, and highland agroecologies were 0.5988, 0.5746, and 0.6723, respectively. These values suggest that communities in the lowland agroecology are more sensitive, whereas communities in highland agroecology exhibit comparatively lower sensitivity.

Ecosystem Profile: Irrigation potential, soil and water conservation, land suitability for agriculture (soil depth, terrain, drainage, and fertility), and sustainability of land use practices have been chosen as the indicators of the ecosystem profile. As shown in Table 5, the average sensitivity score is highest in the lowland agroecology (0.6967), followed by highland (0.6023), while the midland agroecology scored the lowest sensitivity (0.5519). Highland agroecology is highly sensitive to soil erosion (0.8808), followed by lowland agroecology (0.8603). As a result, soil and water conservation are highly practiced in these agroecologies. The sensitivity index scores revealed that households in lowland agroecological zones had the highest score of land cover change, mainly deforestation (0.3201), and highland areas had relatively low deforestation (0.2298). The analysis of land suitability for agriculture in the study area revealed that the midland agroecology has relative suitability for agriculture, followed by highland and lowland agroecologies. The land suitability is lower (highly sensitive) in lowland areas primarily due to poor soil fertility, high rate of soil erosion, and rainfall variability. Regarding irrigation potential, the highland agroecology shows the greatest potential, whereas the midland has the least potential (high sensitive). This result is consistent with the previous results by Asfaw et al. (2021) and Mekonnen et al. (2019) that lowland agroecology is more ecologically sensitive, followed by highland and midland agroecologies.

Agricultural Profile: The agricultural sensitivity profiles for the highland, midland, and lowland agroecologies are 0.5953, 0.5973, and 0.6478, respectively. Based on the average annual total production result, the lowland agroecology scored the lowest index value (0.6923), indicating the highest sensitivity, while the midland agroecology scored the highest agricultural production (0.7584). These results suggest that lowland agroecology is the most significant contributor to the overall vulnerability of the study area. This highlighted sensitivity is likely due to lower agricultural production levels in the lowland compared to the highland and midland areas. This lower production in the lowland agroecology would account for climatic

fluctuation, the lowest landhold size, low soil fertility level, high sensitivity, and fewer crop diversification, while all other factors remain constant. The focus group discussants and key informant interviews, were also indicated that frequent drought in the lowland area has caused higher asset loss as compared to the highland and midland areas. This finding also highlights that agricultural activities in the lowland agroecology are particularly sensitive to climate variability. In contrast, the midland agroecology appears less sensitive, likely due to relatively higher productivity. The inverse relationship regarding crop diversity shows, the highland agroecology is less sensitive, sowing relatively high crop species, while the lowland agroecology scored the lowest. This underscores the need for targeted research, development, and promotion of improved crop varieties in the lowland areas to help to reduce sensitivity to climate change and variability. These findings align with Tessema & Simane (2019), who reported that highland agroecology scored the highest crop diversity index compared to others. According to Bekele et al. (2020), a higher crop diversity indicates lower sensitivity to climate-related risks.

Table 5. Sensitivity indices of different indicators across agroecologies

Components	Indicators	Highland	Midland	Lowland
Ecosystem	Irrigation potential(inverse)	0.6988	0.8925	0.6397
	Inverse of soil and water conservation	0.8808	0.5966	0.8603
	Sustainability of land use system (inverse)	0.6381	0.5755	0.8656
	Inverse of land suitability for agriculture (Fertility)	0.5638	0.4821	0.7979
	Land cover change(deforestation)	0.2298	0.2128	0.3201
	Profile indexed value	0.6023	0.5519	0.6967
Agriculture	Average annual total production	0.7346	0.7584	0.7923
	Average changes in productivity per hectare	0.6529	0.6303	0.6976
	The diversity of crop species (Inverse)	0.3983	0.4032	0.4535
	Profile indexed value	0.5953	0.5973	0.6478

3.2.3 Adaptive Capacity Component of Vulnerability

A higher adaptive capacity generally corresponds to lower vulnerability in an agroecological context. Based on the overall analysis, the midland (0.6521) agroecology demonstrated the highest adaptive capacity, indicating lower vulnerability, followed by highland (0.6416), while the lowland agroecology exhibited the least adaptive capacity (0.5490), making it the most vulnerable (Table 6). These findings are consistent with Mekonnen et al. (2019), who reported that limited adaptive capacity in the lowland agroecology significantly contributed to the increased vulnerability of smallholder farmers in the Jemma sub-basin.

Wealth Profile: The analysis revealed that lowland agroecology has a lower wealth profile index (0.5104), while midland and highland agroecology have average wealth profile values of 0.6010 and 0.5626, respectively. The results show that highland, midland, and lowland agroecologies have land-holding indices of 0.5312, 0.4767, and 0.3649, respectively. Landholding size is widely recognized as a key proxy indicator of wealth, with an inverse relationship to vulnerability, meaning larger farm size generally corresponds to reduced vulnerability and vice versa. The one-way ANOVA result also proved that highland agroecologies possess the largest average cultivated land (2.1ha), while those in the lowland

agroecology have the least (1.41ha). Additionally, the analysis revealed significant differences in livestock holding and total annual income across agroecological zones ($p < 0.001$, Table 7). However, these findings suggest that vulnerability may not only be determined by farmland holding size. Other factors, such as the agricultural technological efficiency of farm management practices and livelihood diversification, also play critical roles in shaping adaptive capacity. The average Tropical Livestock Unit (TLU) further illustrates this disparity, with highland households reporting a higher score (0.5984) compared to those in lowland agroecology (0.3444). It is hypothesized that higher per capita livestock holding means higher adaptive capacity of the smallholder farmer. Despite having lower agricultural productivity, lowland households reported the highest average non-agricultural income (0.7779), while midland households scored the lowest (0.6273). In line with these findings, a study result in Catanduanes, Philippines, shows that lower-income, land-poor farmers are more inclined to seek off-farm work in response to frequent disruptions in abaca production (Marquez & Ubukata 2025). Overall, the wealth profile index underscored the low adaptive capacity of the lowland agroecology, attributed to a combination of high sensitivity to climate variability, lower saving amounts per household (0.4784), higher loan amounts per household (0.5864), and minimal average TLU (0.3444).

Table 6. Adaptive capacity indices of different indicators across agroecologies

Components	Indicators	Indexed value for each indicator		
		Highland	Midland	Lowland
Wealth	Average farm size of the HH	0.5312	0.4767	0.3649
	Average number of livestock per HH	0.5984	0.5451	0.3444
	Average Existing loans per HH (inverse)	0.4461	0.5246	0.5864
	Saving amount of Birr/HH	0.5615	0.8315	0.4784
	Average non-agricultural income	0.6759	0.6273	0.7779
	<i>Profile indexed value</i>	0.5626	0.6010	0.5104
Technology	Households that used insecticides/pesticides	0.2862	0.4403	0.2454
	HHs who used fertilizer	0.7945	0.8294	0.6805
	HHs who used improved seed	0.7687	0.8133	0.6784
	HHs who have irrigation potential	0.8588	0.7977	0.8298
	<i>Profile indexed value</i>	0.6771	0.7202	0.6085
Infrastructure	Access to all-weather roads	0.1384	0.1416	0.2473
	Average time to access schools	0.5642	0.7563	0.7804
	Average time to access health services	0.5361	0.6348	0.7673
	Average time to access markets	0.6786	0.7543	0.8787
	Access to information	0.2765	0.2045	0.1494
	HHs who have access to savings and credit	0.7252	0.6928	0.6265
	HHs that have access to electricity	0.6353	0.5851	0.4976
	<i>Profile indexed value</i>	0.5078	0.5385	0.5639
Community	Male-headed households	0.4437	0.4408	0.4104
	Household heads attended some level of school	0.7545	0.6099	0.6367
	Extension service received	0.6355	0.6549	0.4736
	Average number of training attended	0.7521	0.8404	0.6659
	<i>Profile indexed value</i>	0.6465	0.6365	0.5467
Social	Membership in social organizations	0.8563	0.8338	0.5341
	Household size	0.5192	0.5689	0.4803
	Availability of bylaws	0.7366	0.6753	0.5885
	A tradition of working together	0.7298	0.8648	0.8915
	<i>Profile indexed value</i>	0.7105	0.7357	0.6236

Table 7. Explanatory variables considered in the ANOVA analysis for the three agroecology

		Sum of Squares	df	Mean Square	F	Sig.
Distance to credit and savings in minutes	Between Groups	317315.42	2	158657.71	213.437***	0.000
	Within Groups	269832.42	363	743.34		
	Total	587147.84	365			
Distance from healthcare in minutes	Between Groups	43043.018	2	21521.51	92.675***	0.000
	Within Groups	84295.86	363	232.22		
	Total	127338.878	365			
Distance from school in minutes	Between Groups	19248.34	2	9624.17	25.52***	0.000
	Within Groups	136874.33	363	377.06		
	Total	156122.68	365			
Distance to market in minutes	Between Groups	213425.30	2	106712.65	121.30***	0.000
	Within Groups	319350.66	363	879.75		
	Total	532775.96	365			
Age of HHHs	Between Groups	1155.58	2	577.79	4.85***	0.008
	Within Groups	43272.29	363	119.21		
	Total	44427.87	365			
Livestock holding TLU	Between Groups	1744.57	2	872.29	56.45***	0.000
	Within Groups	5609.13	363	15.45		
	Total	7353.70	365			
Non-agricultural income	Between Groups	708571043.31	2	354285521.65	2.45*	0.088
	Within Groups	52509575076.91	363	144654476.80		
	Total	53218146120.22	365			
Total annual income	Between Groups	46202236886.11	2	23101118443.00	27.11***	0.000
	Within Groups	309357610934.92	363	852224823.51		
	Total	355559847821.04	365			
Irrigated land per hectare	Between Groups	0.13	2	0.06	5.53***	0.004
	Within Groups	4.15	363	0.01		
	Total	4.28	365			
Changes in productivity tons per hectare	Between Groups	1.32	2	0.66	5.18***	0.006
	Within Groups	46.32	363	0.13		
	Total	47.64	365			

Technology Profile: The level of technological adoption among farmers is crucial in determining vulnerability to climate change and variability. In other words, the increased use of agricultural technologies generally leads to higher productivity and improved adaptive capacity. The technology profile indices for the highland, midland, and lowland agroecologies were 0.6771, 0.7202, and 0.6085, respectively, indicating that the midland agroecology exhibits the highest adaptive capacity. This suggests that a greater proportion of households in the midland agroecological zone are actively utilizing agricultural technologies such as

improved seeds, chemical fertilizers, and insecticides/pesticides. Conversely, smallholder farmers in lowland agroecology demonstrate the lowest level of technology adoption, contributing to reduced adaptive capacity and the highest vulnerability. Regarding irrigation practices, highland agroecology achieved the highest index value. This may be attributed to the topography of highland agroecology, which is suitable for constructing irrigation schemes and has an adequate water supply. However, as focus group discussants and key informants noted, the prevalence of internal conflicts in the country, increased prices of fertilizers, improved seeds, water pump generators for irrigation, lack of easy access and timely delivery, and insufficient supply of these inputs present major challenges.

Infrastructure Profile: Access to roads, the average time to schools, health services, markets, access to information, electricity, savings, and credits are the selected indicators for the infrastructure profile. Time spent in accessing markets, schools, and health services has an inverse functional relationship with adaptive capacity. In other words, as the duration of service access increases, adaptive capacity decreases and vice versa. For example, the average time to access the market in highland, midland, and lowland agroecologies is 0.86, 1.5, and 1.6h, respectively. Highland, midland, and lowland agroecologies have infrastructure index values of 0.5078, 0.5385, and 0.5639, respectively, with less infrastructure in the lowland areas of the Jemma sub-basin. The higher infrastructure profile score means higher adaptive capacity, contributing to lower vulnerability, and the lower infrastructure profile score means lower adaptive capacity and higher vulnerability.

The inverse index value for average time to access all-weather roads was 0.1384 for the highland, 0.1416 for the midland, and 0.2473 for lowland agroecological zones, indicating comparatively better road infrastructure in highland areas. In contrast, the survey result revealed that the average time required to access schools was highest in the lowland (0.7804), followed by the midland (0.7563) and the highland (0.5642). Therefore, the adaptability of indicators in certain agroecological zones decreases as more time is spent and vice versa. Regarding access to information, the highland agroecology receives relatively high access to information (0.2765), reflecting better communication and extension service networks. In contrast, the lowland agroecology scored the lowest in terms of infrastructure due to the limited access to electricity, savings and credit institutions, and information, which makes the agroecology vulnerable compared to others.

Community Profile: Sex of the household head, literacy level, extension service received, and average number of training sessions attended are the key indicators to measure the adaptive capacity of the community profile. We hypothesized that there would be a greater adaptive capacity and lower vulnerability if more human capital, better access to information, and good extension services. The results reveal that the community profile indices for highland, midland, and lowland agroecologies zones are 0.6465, 0.6365, and 0.5467, respectively. This value indicates that highland agroecology possesses the highest adaptive capacity regarding community characteristics, while lowland agroecology scored the lowest. A higher community profile index is associated with stronger human and social capital, which enhances the community's ability to adapt to climate-related risks. In particular, the literacy rate varied significantly across agroecologies, with the highland agroecology scoring the highest (0.7545)

and the lowland agroecology scoring the lowest (0.6367). A study result by Antwi et al. (2014) shows that agricultural extension agents could play a critical role in creating awareness to practise early planting and harvesting in the Tolon district of Ghana. The result shows midland agroecology gets the highest extension services (0.6549), whereas the lowest value is scored in lowland agroecology. The sex of the household head, level of education, and amount of training were found to significantly influence the smallholder farmers' adaptive responses to climate change.

Social Profile: The strength of a social network is a critical component influencing a community's adaptive capacities to climate change. Recent studies highlight that active participation in community-based organizations (CBOs) and a strong tradition of collective actions significantly enhance adaptive capacity and reduce vulnerabilities to climate change (Nath, 2024). The study reveals that midland agroecology exhibits the highest social profile index, scoring 0.7357. In comparison, highland and lowland agroecologies scored 0.7105 and 0.6236, respectively. The findings highlight the importance of social capital in facilitating adaptation, with the midland communities benefiting from stronger social cohesion and institutional engagement. In contrast, the lower score in lowland agroecology indicates weaker social networks, which may limit the flow of resources, information, and mutual support. The primary goal of bylaws at the community level is to manage common resources effectively and establish rules for collective decision-making, ensuring equitable access and sustainable use of shared assets. From this point, highlanders have a higher score for bylaws (0.7366) as compared to lowlanders (0.5885). The other indicator under the social profile is a tradition of working together. Working together is not new to the Ethiopian people. Their unity and cooperation are manifest in many socio-economic settings. Farmers in Ethiopia have long practiced traditional forms of collective labor, referred to as “*Debo*” and “*Wonfel*”. All these traditional forms of cooperation have the same meaning in different local languages in Ethiopia, which is “engaging and working together,” such as hunting, farming, cultivating lands, sowing, weeding, and harvesting (ICA, 2021). According to the indexed indicator, the lowland agroecological zone scored the highest level of collective action with an average score of 0.8915, indicating a stronger tradition of working together compared to others. This robust social capital contributes significantly to the midland region's higher adaptive capacity.

3.3 Livelihood Capital and Relative Vulnerabilities

This vulnerability analysis is structured around five capitals, seven profiles, and thirty-seven indicators. Each capital represents a critical dimension of household resilience to climate change. Natural capital is the first livelihood capital described by ecosystem and agriculture profiles or sensitivity factors in the IPCC framework. The result revealed that lowland agroecology exhibited the highest vulnerability value regarding natural capital (0.6723), reflecting poor soil fertility, degraded ecosystems, and erratic rainfall patterns. In contrast, the midland agroecology was the least vulnerable regarding natural capital (0.5746). Financial capital is represented by wealth profile, and it is hypothesized that as the economic capital of a household increases, vulnerability will decrease. In terms of financial capital, the midland agroecology scored the highest value (0.6010), and the lowland agroecology is most vulnerable (0.5104). The other livelihood capital is physical capital, which includes the technological and

infrastructure profiles. From a livelihood perspective, we hypothesized that the increased uptake of agricultural technologies and accessibility to different services would reduce the vulnerability level of households in respective agroecology. Regarding physical capital, lowland agroecology is the highest vulnerable with an indexed value of 0.5862, followed by the highland (0.5925), and midland agroecology (0.6294), indicating less vulnerability (Table 8).

Human capital was assessed using four main indicators: the gender of the household head, level of education, access to extension services, and participation in training opportunities. Households that are male-headed, more educated, have regular extension services, and actively participate in training programs related to climate change adaptation are more likely to adopt effective adaptation options. The analysis revealed that the human capital vulnerability index scores vary across agroecological zones, with the highland area scoring the highest (0.6465), followed by the highland (0.6365), and the lowland (0.5467). These values indicate that the lowland householders are the most vulnerable regarding human capital. The final component of livelihood capital is social capital, which is crucial in assessing community vulnerability within agroecological zones. Membership in social organizations, family size, availability of bylaws, and tradition of working together are the selected indicators under the social profile. It is assumed that a higher indexed value of social capital indicates a lower vulnerability within the agroecological system and vice versa. In this context, social capital in midland areas shows the highest indexed value (0.7357), compared to highland (0.7105) and lowland (0.6236).

Table 8. Livelihood capital and relative vulnerability of agroecological zones

Livelihood capitals	Vulnerability factors	LVI results of Agroecologies		
		Highland	Midland	Lowland
Natural	Sensitivity	0.5988	0.5746	0.6723
Financial	Adaptive Capacity	0.5626	0.6010	0.5104
Physical	Adaptive Capacity	0.5925	0.6294	0.5862
Human	Adaptive Capacity	0.6465	0.6365	0.5467
Social	Adaptive Capacity	0.7105	0.7357	0.6236

To visually summarize the livelihood vulnerability index across components and factors, a spider diagram and vulnerability triangle were utilized. The spider diagram is scaled from zero, indicating the least vulnerable, to 0.8 at the outer edge, representing the highest vulnerabilities, with a difference of 0.2 between each successive scale (Figure 2). The visual representation closely aligns with the quantitative LVI findings, effectively illustrating the relative vulnerability of each agroecological zone across different dimensions. The diagram reveals that in the highland agroecology, community and infrastructure components contribute most significantly to vulnerability. In contrast, climate, agriculture, and ecosystems serve as the primary contributors in the lowland agroecological zone. Meanwhile, the midland agroecology shows that wealth, technology, and social components are the most influential components affecting vulnerability. The lowland agroecological zone displayed a high score in exposure and sensitivity components but showed a low score in adaptive capacity (Figure 3).

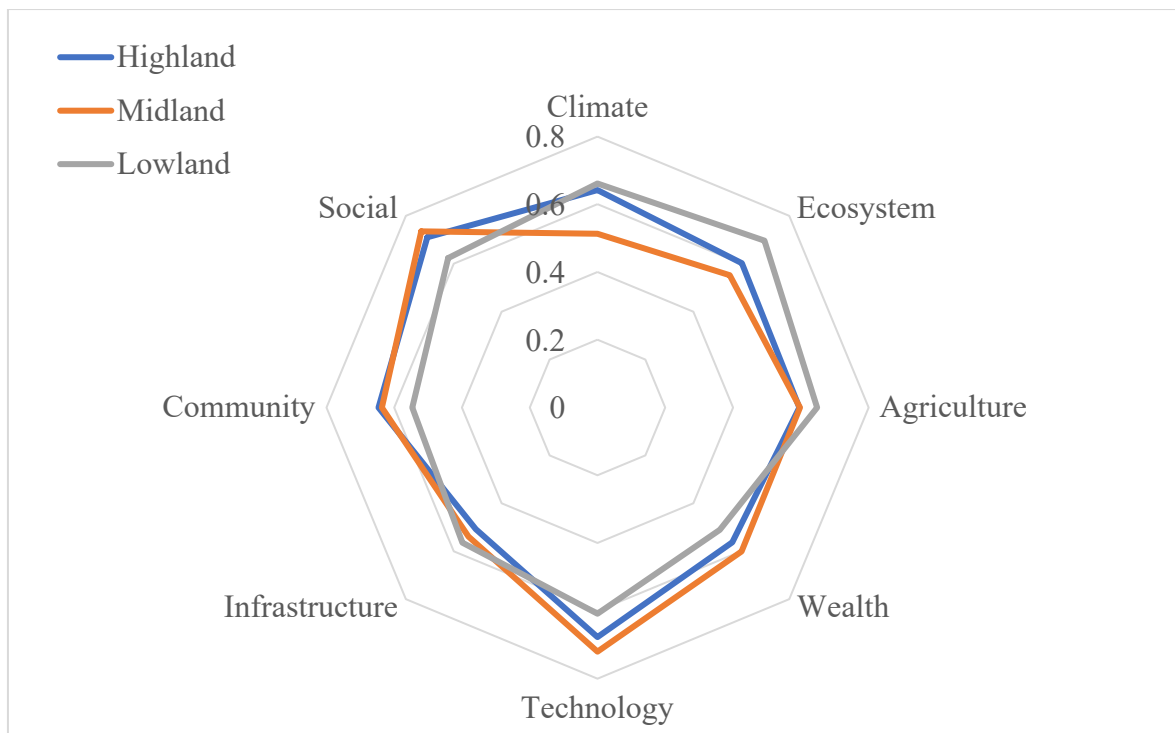


Figure 2. Radar diagram of major profiles of the Livelihood Vulnerability Index (LVI)

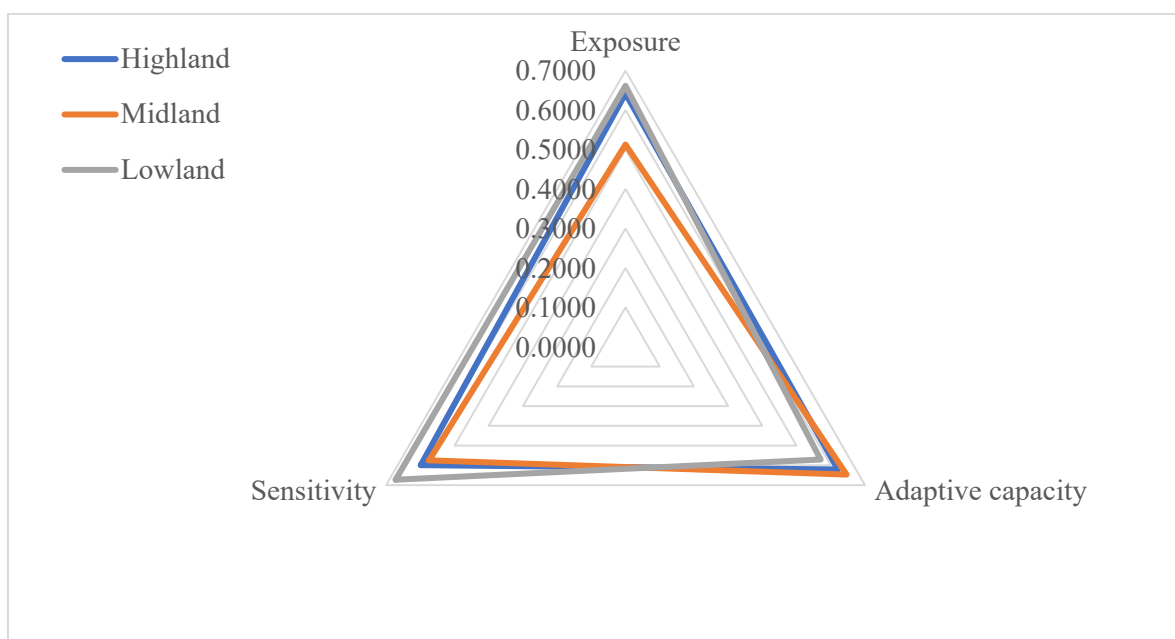


Figure 3. The vulnerability triangle of the vulnerability contributing factors

3.4 IPCC-Livelihood Vulnerability Index

According to the IPCC vulnerability framework, high exposure relative to adaptive capacity results in positive scores indicating greater vulnerability. Conversely, when adaptive capacity outweighs exposure, the relative vulnerability scores are negative, signifying lower vulnerability. In this framework, sensitivity functions as a multiplier; when sensitivity is high and exposure exceeds adaptive capacity, the overall vulnerability scores increase significantly

(Hahn et al., 2009). The study demonstrates that smallholder farmers in lowland agroecology (0.0610) are the most vulnerable, followed by highland agroecology (0.0126). In contrast, the midland agroecology exhibited the negative vulnerability score of -0.0768, indicating relatively higher resilience/least vulnerability (Table 9).

Table 9. Calculated indices for contributing factors and the Livelihood Vulnerability Index under the LVI-IPCC framework

Agroecology	IPCC contributing factors to vulnerability			IPCC-LVI
	Exposure	Adaptive Capacity	Sensitivity	
Highland	0.6419	0.6209	0.5988	0.0126
Midland	0.5127	0.6464	0.5746	-0.0768
Lowland	0.6613	0.5706	0.6723	0.0610

The result revealed that exposure is the most significant contributing factor in lowland (0.6613), and highland agroecologies (0.6419). In addition, high sensitivity (0.6723) and lower adaptive capacity (0.5706) were also recorded in lowland agroecology, showing that the overall vulnerability is estimated to be higher. This heightened vulnerability in lowland agroecology is attributed to several interrelated factors, including smaller landholdings, lower TLU, limited access to infrastructure, low amount of savings, and minimal use of agricultural inputs. In addition to climatic factors, several social and environmental indicators, such as low levels of soil fertility, high levels of loans, and the increasing frequency and intensity of environmental hazards like drought and floods, contribute significantly to heightened vulnerability. This finding is in line with Asfaw et al. (2021) and Tessema & Simane, (2019), who found that high exposure levels coupled with limited adaptive capacity have intensified the vulnerability of smallholders in lowland agroecology. The result further revealed that Midland agroecology is the least vulnerable of the study sites due to its lowest sensitivity, exposure, and high level of adaptive capacity. This could be because households in the midland area use agricultural technologies, get more extension services, have relatively fertile cultivated land, and have better savings.

4. CONCLUSIONS

Climate change impacts various communities and groups differently and on different scales due to a mix of socioeconomic and biophysical factors. Analysing livelihood vulnerability to climate change at the local level is crucial for policymakers to develop effective short-term coping strategies and long-term adaptation plans. According to the IPCC vulnerability index, households in lowland agroecology demonstrated the highest vulnerability, scoring 0.0610, while those in midland agroecology exhibited the lowest vulnerability, -0.0768. The lower overall vulnerability of households in midland agroecology is attributed to their enhanced adaptive capacity, reduced levels of exposure and sensitivity, greater asset ownership (wealth), more developed infrastructure, stronger community profiles, and well-established social networks. Likewise, the highland agroecological zone scored an intermediate result regarding livelihood capital. The indexed exposure profile indicated that the lowland agroecology

experienced the highest drought and flood exposure events. Similarly, the sensitivity profile analysis reveals that the lowland zone also scored the highest sensitivity value compared to the others. Regarding the adaptive capacity of smallholder farmers in the midland, agroecology scored the highest adaptive capacity value. Lowland agroecology scored the least adaptive capacity. This high adaptive capacity and low vulnerability in midland agroecology come through better use of agricultural technologies, livelihood diversification, training, extension services, and savings. This suggests the need to upscale these activities to smallholders in the other two agroecologies. In conclusion, variations in vulnerability to climate variability and change can be attributed to differences in household characteristics, limited access to essential infrastructure, low livelihood diversification, and the absence of available technologies. Therefore, policymakers should work with local communities and experts to develop and implement tailored adaptation techniques to address smallholder farmers' unique challenges and vulnerabilities at each agroecology.

DECLARATIONS

Data Availability Statement: The data presented in this study are available with a reasonable request from the corresponding author.

Author Contributions: Abirham Cherinet: Investigation, data collection, analysis, conceptualization, writing original draft, review, and editing. Belay Simane: Conceptualization, inspection, review, and editing. Abraham Mebrat: Conceptualization, inspection, review, and editing.

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