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Research Article

Smallholder farmers' vulnerability to climate change and variability in Gedeo Zone, Southeastern Rift Valley escarpments of Ethiopia

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Abstract

The Southern Rift Valley escarpments of Ethiopia are highly vulnerable to climate change, with smallholder farmers in the Gedeo Zone disproportionately affected. However, comprehensive studies on these impacts remain limited. This study investigated the socio-economic consequences of farmers' vulnerability to climate-related hazards using mixed methods. Data were collected from 384 farming households. Quantitative data were analysed through descriptive and inferential statistics, specifically the Propensity Score Matching (PSM) model, while qualitative data were examined thematically. Results revealed that 72.65% of smallholder farmers in the study area were highly vulnerable for impact of climate change, with food security and economic stability severely undermined. Although drought and temperature shifts were widely recognized, rainfall variability emerged as the most critical threat among vulnerable households. This heightened sensitivity translated into statistically significant reductions in household income ($p<0.001$), consumption ($p<0.001$), and agricultural production ($p<0.001$) compared to non-vulnerable farmers. Disparities in adaptive capacity were evident, as non-vulnerable farmers had significantly better access to credit and financial resources $p<0.001$) and moderately stronger social networks ($p<0.001$). Both groups, however, faced systemic barriers in accessing information and training. Specifically, vulnerable farmers' income, consumption and production decreased by 40, 19 and 47% ($p<0.001$) respectively lower than no-vulnerable farmers. The study revealed that coffee producing smallholder farmers in the study region are vulnerable to climate change. This calls urgent extension intervention focusing on scaling of accessible, tailored financial services and climate-adaptation funds.

KEYWORDS
Climate Change; farmers; variability; Vulnerability; Gedeo Zone, Ethiopia

1 Introduction

The complex interplay between global climate change and agricultural systems poses profound risks, particularly for smallholder farmers who are central to global food security (Intergovernmental Panel on Climate Change (IPCC), 2021). These farmers, concentrated in developing regions, are disproportionately exposed due to their reliance on rain-fed agriculture, limited resource access, and heightened vulnerability to extreme weather events (Food and Agriculture Organization (FAO), 2018; Müller et al., 2021). In Sub-Saharan Africa, where agriculture is predominantly rain-fed and institutional support remains weak, climate variability intensifies existing challenges of food insecurity and poverty (Abate et al., 2022; Niang et al., 2014). Ethiopia, with its economy heavily dependent on agriculture, is especially susceptible, frequently experiencing recurrent droughts, floods, and erratic rainfall that threaten millions of smallholder livelihoods (Gebreyesus et al., 2023; Tadesse et al., 2021). These shocks undermine food security and erode development gains, perpetuating cycles of poverty (Bedru et al., 2023; Worku and Singh, 2021).

The Gedeo Zone in southern Ethiopia represents a distinctive agro-ecological system, characterized by intensive multi-strata agroforestry dominated by enset and coffee (Dullo et al., 2022; Geda and Kebede, 2016. Despite its ecological richness, the zone faces mounting pressures from climate variability, including shifts in rainfall seasonality, intensity, and temperature, leading to crop failures, soil erosion, and resource degradation (Dullo et al., 2022; Osman et al., 2022. Smallholders, often cultivating small plots with limited access to inputs and credit, are highly sensitive to these impacts (Abate et al., 2022; Alemayehu and Bewket, 2017. Understanding their vulnerability defined by exposure to hazards, socio-economic sensitivity, and adaptive capacity is essential for designing effective, context-specific adaptation strategies (Deressa et al., 2009; Intergovernmental Panel on Climate Change (IPCC), 2021).

Critical resource gaps exacerbate vulnerability in the Gedeo Zone. Farmers lack affordable financial services necessary for investing in adaptive measures, purchasing inputs, or recovering from shocks (Abate et al., 2022; Dullo et al., 2022). This constraint limits adoption of climate-resilient technologies and livelihood diversification, increasing sensitivity to income and production losses (Bedru et al., 2023; Worku and Singh, 2021). Access to improved technologies such as drought-tolerant crops, efficient irrigation, and modern tools remains inadequate (Gebreyesus et al., 2023; Osman et al., 2022). Equally, farmers face deficits in localized climate information, early warning systems, and training in climate-smart practices, which are vital for informed decision-making and resilience building (Gebremariam et al., 2021; Nigussie et al., 2020; Tadesse et al., 2021. Institutional support, though present, is fragmented and under-resourced, limiting the reach of extension services and coordinated adaptation programs (Deressa et al., 2009; Simane et al., 2016).

Infrastructure deficiencies further constrain resilience. Limited market access, storage, and processing facilities reduce profitability, exacerbate post-harvest losses, and discourage production expansion (Dullo et al., 2022; Geda and Kebede, 2016). Moreover, inadequate support for integrated resource management has accelerated soil erosion, fertility decline, and water scarcity, intensifying climate-related risks (**osman2022smallholde**; Intergovernmental Panel on Climate Change (IPCC), 2021). Addressing these systemic gaps through targeted interventions, stronger institutions, and community empowerment is critical for fostering sustainable, climate-resilient livelihoods.

Although numerous studies have examined climate vulnerability among Ethiopian smallholders, disaggregated analyses within distinct agro-ecological zones such as Gedeo remain limited (Molla et al., 2020; Simane et al., 2016. Existing research generalizes vulnerability, overlooking intra-regional differences in socio-economic conditions, adaptive capacities, and livelihood outcomes (Gebremariam et al., 2021; Nigussie et al., 2020). Rigorous quantitative assessments that identify and measure drivers of vulnerability and their differential impacts on household income, consumption, and production are scarce (Tadese et al., 2020; Worku and Singh, 2021). Such granular insights are essential for moving beyond broad generalizations and informing precise, contextually relevant policy interventions (Bedru et al., 2023).

This study addresses these gaps by conducting a localized, comparative assessment of smallholder vulnerability to climate change in the Gedeo Zone. It systematically examines exposure, sensitivity, and adaptive capacity, differentiating vulnerable from non-vulnerable households through robust statistical analyses (Mean, Standard Deviation, T-value, p-value). The research quantifies disparities in socio-economic conditions and adaptive capacities, while measuring the direct impacts of vulnerability on household income, consumption, and agricultural production. Findings are expected to provide strong empirical evidence and actionable insights for targeted policy design, localized adaptation planning, and efficient resource allocation, thereby enhancing resilience and livelihoods in the Gedeo Zone and contributing to broader climate adaptation discourse.

2 Materials and methods

2.1 Description of study area

This study was carried out in selected districts within Gedeo Zone, Southern Ethiopia Regional State. Geographically, the Zone is located north of the equator from 5°53'N to 6° 27'N latitude and from 38° 8' to 38° 30'east longitude (Negash, 2010). On the main highway from Addis Ababa to Moyale towards Kenya, 365 kilometers from Ethiopia's capital city Addis Ababa. Slope gradient reaches up to 70% in some areas and almost 50% of the landscape is steep, with slope gradient above 10% (Mesele, 2011; Meteorological Climate and Technical Agency (MCTA), 2020). The majority of the soil type in the area is nitosol (Abiyot, 2013), typically made up of volcanic rocks. The Zone has three agro-ecological zones whose mid altitude agro-ecology occupies the largest area (62.2%) followed by high land (37.1%) and low altitude (0.7%) (Bogale, 2007). The study districts, namely Kochore, Yirgachefe and Wonago are one of the districts in the Gedeo Zone SNNPRS (Figure 1). Kochore district is found between 6'09' N latitude and 38'16'E longitude. Elevations range from 1,500 to 3,100 meters above sea level (masl), and the study area comprises two agro-climate zones: Dega (with elevations between 2,300 and 3,700 masl, accounting for 26%) and Weyna Dega (ranging from 1,500 to 2,300 masl, constituting 74%) according to Yibrah (2014). The average annual temperature falls between 25°C and 31°C, while the annual rainfall ranges from 1,000 to 1,200 millimeters.

Yirgachefe district is located between 6°09'N and 6°32'N and 38°08'E and 38°32'E, with an altitudinal range of 1501–2500 masl (Negash, 2007). The annual rainfall ranges between 1200 and 1800 mm, with a bimodal distribution, and the mean annual temperature varies from 15°C to 20°C (Asnake, 2021). Wonago district is found between 6°20'E and 6°32'E, and 38°14'N and 38°24'N, with an undulated type of landscape and an altitude ranging from 1601 to 2875 masl. The district receives rainfall of 800 to 1400 mm per annum and annual temperatures ranging from 11°C to 29°C (Negash, 2007). All study districts are categorized as mid and highlands based on elevation, with a range of 1500–3700 masl.

2.2 Site selection

The study focused on three districts Kochere, Yirgachefe, and Wonago purposefully selected to capture the dimensions of vulnerability related to climate hazards, socio-economic sensitivity, and adaptive capacity. These districts lie within the coffee-producing belt of the Zone, where indigenous agroforestry practices are highly prevalent. From each district, three kebeles were randomly chosen: two from the midlands and one from the highlands, yielding a total of nine kebeles (six midland and three highlands). Specifically, Jeldo and Anchabi (midlands) along with Gololicha (highland, representing Woina dega and dega) were selected in Kochere. In Yirgachefe, Tutit and Wote (midlands) and Udesa (Woina dega) were included. Similarly, Deko and Hase Haro (midlands) and Wotiko (Woina dega) were chosen in Wonago. This stratified selection ensured representation across agro-ecological zones, thereby enabling a comprehensive assessment of smallholder vulnerability within the study area.

2.3 Research Design

A research design outlines the procedures for achieving research objectives and testing hypotheses (McDaniel & Gates, 2006). This study employed an explanatory research design to investigate how vulnerability components (independent variable) affect smallholder farmers' farming practices (dependent variable).

2.4 Research Approach

To achieve the study's objective, researchers used a mixed research approach, combining quantitative and qualitative methods. Quantitative data were collected via structured questionnaires from smallholder farmers, addressing vulnerability components like exposure, sensitivity, and adaptive capacity. Qualitative data were gathered through in-depth interviews and focus group discussions with a subset of the surveyed farmers. This comprehensive approach aimed to provide a deeper understanding of farmers' vulnerability.

2.5 Data type and sources

This study utilized both primary and secondary data. Primary data were collected through household surveys, key informant interviews, and focus group discussions. Secondary data were gathered from government reports, academic journals, published and unpublished materials, and websites.

2.5.1 *Sampling techniques and sample size determination*

Multiple-stage stratified sampling methods were used in the study. First, districts were selected due to high climatic change and variability. Second, the district is grouped by their agro-ecology (strata) on the basis of their elevation, where 1500–2300 masl is midland and above 2300 masl is high land. Third, kebeles were chosen from each agro-ecology stratum for data uniformity, and finally, households were randomly selected from selected kebeles using proportional sampling. The sample size of sampled households was determined following Yamane (1967) sampling techniques. The number of respondents included in the study was as follows:

$$n = \frac{N}{1 + N\ (e)\ 2} = n = \frac{9662}{1 + 9662\ (0.05)\ 2} = \frac{9662}{25.155} = 384 \quad (1)$$

Where n, N and e represent the sample size (number of respondents), total number of households and level of precision (allowable error, 5%), respectively. For sample size allocation at kebele level the proportional allocation formula was used as

$$ni = \frac{Ni\ x\ n}{N} \quad (2)$$

Where; ni = the sample size proportion of each kebele, Ni= the population proportion in the stratum (kebeles), n= the sample size of the districts and N = the total population of the districts.

2.6 Data collection methods

Surveys: Structured questionnaires administered to smallholder farmers involved demographic information, vulnerability components and socioeconomic conditions of farmers.

Key informants' interviews: To gather insights on the vulnerability of smallholder farmers in the Gedeo zone, key informants were selected based on knowledge or experience in agriculture, climate resilience, or rural development related to smallholder farming. individuals with direct experience working with smallholder farmers, such as extension workers, agricultural officials, and NGO staff

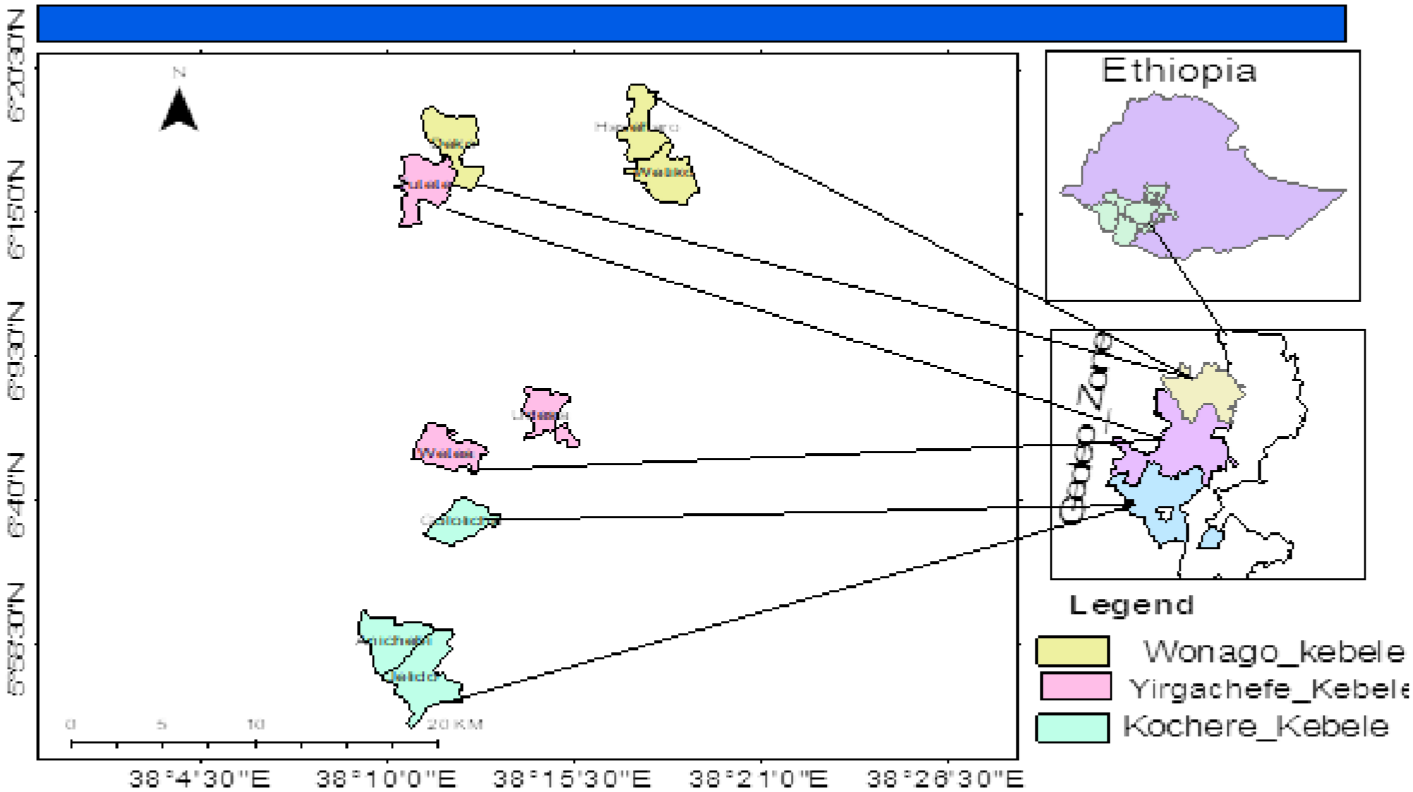

Figure 1: Location map of study area

Table 1: Total household and sample size of the study area

Name of districts	Name of Kebeles	Total households	Sampled households	
			Numbers	Percentage
Kochere	Jeldo	1073	43	11.19
	Anchabi	1024	41	10.79
	Gololcha	1253	50	13.02
Yirgachefe	Tutit	801	32	8.33
	Wote	970	39	10.15
	Udesa	1014	40	10.41
Wonago	Deko	1002	40	10.41
	Hase Haro	880	35	9.11
	Wotiko	1645	64	16.66
Total	**9**	**9662**	**384**	**100**

were preferred. Informants were to understand the local socio-economic context and agricultural challenges in the region. The selection included a diverse range of stakeholders, including farmers, community leaders, policymakers, researchers, and NGO representatives to ensure varied perspectives. We conducted 15 key informant interviews to gather diverse insights in a manageable manner, ensuring a rich data set for analysis. These interviews' perceptions about the vulnerability of farmers derived from climate change and variability engaged in this practice (Yin, 2018) .

Focus Group Discussions: focus groups discussions were conducted with smallholder farmers. Farmers who provided rich qualitative insights into the vulnerability of farmers derived from climate change and variability. The discussions were undertaken with 9 groups' of farmer's i.e. one group from each kebele. One group consists of 8 to 12 members

2.7 Methods of data analysis

The analysis and presentation of the study was both quantitative and qualitative. Quantitative data obtained through structured questionnaire were analyzed by descriptive statistics (such as frequency, percentages, means, Chi-squares and p-values) and inferential statistics specifically, multivariate probit regression model with the help of STATA software version 15.0. Qualitative data obtained through interviews and focus group discussions were analyzed thematically.

2.7.1 *Measures of farmers Vulnerability to climate change and variability*

Vulnerability of smallholder farmers was measured by exposure, sensitivity, and adaptive capacity of smallholder farmers. The vulnerability of a household Vi can be expressed mathematically as:

$$V_i = f(E_i, S_i, A_i) \tag{3}$$

Where:

V_i : Vulnerability of household i

E_i : Exposure of household i

S_i : Sensitivity of household i

A_i : Adaptive capacity of household i

Exposure: This refers to the degree to which farmers are subjected to climate-related hazards such as drought frequency, flood incidence, rainfall variability, temperature changes, impact on crop yields, livestock health and soil erosion.

Thus, the researcher can represent exposure as:

$$E_i = f(D_{\text{freq}}, R_{\text{var}}, T_{\text{chang}}) \tag{4}$$

Where,

D_{freq} : Drought frequency

R_{var} : Rainfall variability

T_{chang} : Temperature changes

Sensitivity: This indicates how susceptible farmers are to these hazards based on their socio-economic conditions. It reflects how changes in drought impact income, Food Security, and production. Thus, sensitivity can be represented as:

$$S_i = f(\text{Inc, FS, Prod})$$

Where,

Inc = households income

FSI = households food Security

Prod = households production

Adaptive Capacity: This reflects the ability of farmers to adjust their practices in response to changing conditions. It reflects farmers' Access to Information, Financial Resources, Social Networks, Training and Education, Access to Technology, Institutional Support and Community Engagement to adjust their practices in response to climate change impacts. Thus, Adaptive Capacity can be represented as:

$$AC_i = f(\text{Ainf, FR, SN, TE, Atech, IS, CE})$$

Where,

Ainf = Access to Information

FR = Financial Resources

SN = Social Networks

TE = Training and Education

Atech = Access to Technology

IS = Institutional Support and

CE = Community Engagement

2.7.2 *Methods of characteristics of farmers vulnerability to climate change and variability*

Vulnerability of smallholder farmers were characteristics based computed mean scores as 1.00 - 1.49 = very low, 1.50 - 2.49 = low, 2.50 - 3.49 = medium, 3.50 - 4.20 = high and 4.21 - 5.00 = very high. Accordingly, vulnerable farmers are those farmers exposed to different risks while non vulnerable farmers are relatively not vulnerable due to their adaptive capacity.

2.8 Model specification

Propensity Score Matching (PSM) Model: Investigating the impact of farmers' vulnerability to climate-related hazards on their socio-economic conditions

Propensity Score Matching (PSM) is a statistical technique used to control confounding variables when estimating the effect of a treatment or intervention. The core idea is to estimate the probability (propensity score) of receiving the treatment based on observed covariates and then match treated and untreated subjects with similar propensity scores. The derivation of the

The propensity score e(X) is defined as the conditional probability of receiving treatment given a set of observed covariates X:

$$e(X) = P(T = 1|X) \tag{5}$$

Where T is the treatment indicator (1 if treated, 0 otherwise)

After estimating the propensity scores using logistic regression or other methods, treated units are matched with control units that

Table 2: Variables definition and measurement

Variables	Variables Definition	Variables measurement
	Treatment Variable (FVCH)	
Farmers' vulnerability to climate-related hazards (FVCH)	Farmers' vulnerability to climate-related hazards (FVCH) refers to the degree to which a farming household is susceptible to, and unable to cope with	Binary (1 if Farmer's were vulnerable to climate-related hazards; 0 otherwise)
	Outcome Variables	
Households income	Total income generated by the household	Continuous (Monetary units, ETH Birr per year)
Households consumption	Total consumption expenditure of the household	Continuous (Monetary units, ETH Birr per year)
Households production	Total quantity of agricultural produce harvested by the household	Continuous (Kilograms per year)
	Independent Variables (Covariates)	
Age	Age of Household Head	Continuous (Years)
Gender	Gender of Household Head	Binary (1 = Male, 0 = Female)
household size	Number of members	Continuous
Total Farm Size	Total cultivated land area managed by the household	Continuous (Hectares)
Farming Experience	Number of Years Farming Experience of the household head	Continuous (Years)
Agro-ecological Zone	The specific agro-ecological zone where the farm is located	Categorical(1=Dega (highland), 2=Weina Dega (midland), 3=Kolla (lowland)
Initial Climate Exposure	Pre-existing conditions that might drive the need for adaptive capacity.	Ordinal scale (e.g., 1=Very Low, 5=Very High)
distance to the nearest market	Accessibility influences input costs and market access for outputs.	Continuous (Kilometers)
Climate Risk Perception	Household head's subjective assessment of the severity of climate change impacts	Ordinal Scale (e.g., 1=Low to 5=Very High)

have similar scores. This can be done using various matching techniques such as nearest neighbor matching, caliper matching, or kernel matching . Outcome Estimation: The average treatment effect on the treated (ATT) can be estimated as:

$$ATT = E[Y(1)|T = 1] - E[Y(0)|T = 1] \quad (6)$$

Where $Y(1)$ is the outcome for treated units and $Y(0)$ is the outcome for matched control units (Imbens, 2009).

Hypotheses of the study

Farmers' Vulnerability to Climate-Related Hazards (FVCH)

Null Hypothesis (H0): There is no significant relationship between farmers' vulnerability to climate-related hazards and household income, consumption, and production.
Alternative Hypothesis (H1): There is a significant relationship between farmers' vulnerability to climate-related hazards and household income, consumption, and production. Studies have shown that increased vulnerability to climate-related hazards negatively impacts agricultural productivity and household income (Mastrorillo et al., 2016) .

Household Income

Null Hypothesis (H0): Household income is not significantly affected by farmers' vulnerability to climate-related hazards.
Alternative Hypothesis (H1): Household income is significantly affected by farmers' vulnerability to climate-related hazards. Research indicates that vulnerable households often experience reduced income due to lower agricultural yields and increased costs of adaptation.

Household Consumption

Null Hypothesis (H0): Household consumption expenditure is not significantly influenced by farmers' vulnerability to climate-related hazards.
Alternative Hypothesis (H1): Household consumption expenditure is significantly influenced by farmers' vulnerability to climate-related hazards. Vulnerable households may increase consumption expenditures to cope with climate impacts, leading to higher overall consumption costs (Alderman Haque, 2006).

Household Production

Null Hypothesis (H0): There is no significant relationship between farmers' vulnerability to climate-related hazards and the total quantity of agricultural produce harvested.

Alternative Hypothesis (H1): There is a significant relationship between farmers' vulnerability to climate-related hazards and the total quantity of agricultural produce harvested. Vulnerability to climate change can adversely affect crop yields, thereby reducing overall agricultural production.

3 Results

3.1 Characteristics of farmers' vulnerability to climate-related hazards

Based on the vulnerability index analysis, there was a significant level of vulnerability among farmers to climate-related hazards, with 72.65% of respondents were vulnerable and 27.35% of respondents were none vulnerable to impact of climate change (Table 3). Most vulnerable farmners justified that they felt the impacts of climate change due to recurrent droughts, floods, and changing weather patterns, which undermine their food security and economic stability.

Table 3: Proportion of extent of farmers vulnerability status in the Gedeo Zone, Southeastern Rift Valley escarpments of Ethiopia

Farmers' vulnerability to climate-related hazards	Frequency	percent
Vulnerable farmers	279	72.65
Non-vulnerable farmers	105	27.35

3.2 Characterization of farmers climate-related hazards (Exposure) among vulnerable and none-vulnerable farmers

The results presented in Table 4 provide significant insights into the exposure to climate-related hazards among vulnerable and non-vulnerable farmers.

Drought Frequency: Vulnerable farmers reported a mean drought frequency of 3.83, classifying their perceived exposure as high, accompanied by a standard deviation of 0.79. In contrast, non-vulnerable farmers perceived drought frequency as medium with a mean of 2.51 and a standard deviation of 0.64. Despite notable difference in intensity, the Chi-square test (Chi2 = 19, p = 0.415) indicated no statistically significant difference between the two groups concerning drought frequency, suggesting that though vulnerable farmers sense the impact more intensely, the occurrence of drought events is generally pervasive across the farming community.

Flood Incidence: Both vulnerable and non-vulnerable farmers perceived flood incidence as medium, with means of 3.07 (Std. Dev. = 0.63) and 2.82 (Std. Dev. = 0.59) respectively. However, no statistically significant differences were reported between the two groups regarding their perceived exposure to floods. This suggests that floods, like droughts, are experienced across the community without a distinct perception gap between vulnerable and non-vulnerable farmers in terms of their occurrence. The medium perception indicates that while floods are a concern, they might not be as overwhelmingly frequent or impactful as other hazards for these farming communities.

Rainfall Variability: There was a tendence of differences on perceived responses on rainfall variability between vulnerable and non-vulnerable farmers (Chi2 = 23, p = 0.076), showing that rainfall variability is a profoundly impactful and differentiating factor for vulnerable farmers. This also makes it the highest perceived exposure indicator for vulnerable groups, highlighting their acute sensitivity to unpredictable rainfall patterns.

Temperature Changes: Both vulnerable and non-vulnerable farmers perceived temperature changes as high, indicating that the rising in temperatures are a universally perceived challenge within the farming community, irrespective of their vulnerability status. The respondents indicated that they observed the impact of high temperature on their crops, livestock, and overall farming systems.

Soil Erosion: Vulnerable farmers reported a mean score of 3.3 (high), while non-vulnerable farmers had a mean of 2.94 (medium), although the difference was not significant (Chi2= 2.7, p= 0.393)

3.3 Characterization of farmer's socio-economic conditions among vulnerable and non-vulnerable farmers

In-depth analysis of key socio-economic indicators (income, consumption, and production) that reflect the sensitivity of vulnerable and non-vulnerable farmer groups to external shocks, particularly climate-related hazards were conducted (Table 5). Household Income: There was significant difference between non-vulnerable and vulnerable farmers in terms of income (p<0.001). The mean household income of non-vulnerable farmers was 40% higher than the vulnerable farmers (Table 5), showing that non-vulnerable farmers possess considerably greater financial resources, which inherently reduces their sensitivity to economic shocks and allows for more robust adaptive capacity.

Household Consumption: The non-vulnerable farmers consumed by 19% higher than vulnerable farmers, which was significant (p<0.005), indicating a substantial difference in consumption levels between the two groups. Higher consumption levels among non-vulnerable farmers suggest better food security, improved nutritional status, and greater overall well-being. This in turn signifies lower sensitivity to economic and food system disruptions.

Household Production: Non-vulnerable farmers recorded a mean household production was by 47% higher than vulnerable farmers with significant variation (p<0.001). The marked differences show

Table 4: Perceived responses of farmers on climate hazards (Exposure) in the Gedeo Zone, Southeastern Rift Valley escarpments of Ethiopia

Exposure Indicators	**Vulnerable (n-279)**		**Non-vulnerable (105)**		**Statistical value**	
	Mean	Std. Dev.	Mean	Std. Dev.	Chi^2	p-value
Drought frequency	3.83	0.79	2.51	0.64	19	0.415
Flood incidence	3.07	0.63	2.82	0.59	4	0.133
Rainfall variability	4.24	0.86	3.75	0.72	23	0.076
Temperature changes	3.90	0.75	3.53	0.611	18	0.0952
Soil erosion	3.3	0.73	2.94	0.78	2.7	0.393

Table 5: Mean annual income (Ethiopian Birr), consumption (kg) and production (kg) of the studied vulnerable and non-vulnerable farmers in Gedeo zone, Southeastern Rift Valley escarpments of Ethiopia

Sensitivity Indicators	**Farmers' vulnerability** vulnerable (n-279)		Non-vulnerable (105)		**Statistical value**	
	Mean	Std. Dev.	Mean	Std. Dev.	Chi^2	p-value
Households' income	2699.77	0.67	4485.48	0.84	20	0.000
Households' consumption	2539.75	0.88	3128.29	0.83	21	0.000
Households' production	527	0.82	986	0.95	14	0.000

non-vulnerable farmers are substantially more productive, translating into greater self-sufficiency, higher market surplus, and reduced sensitivity to market and climate-induced production shortfalls.

3.4 Characterization of farmers ability to adjust climate related hazards (Adaptive Capacity) among vulnerable and non-vulnerable farmers

Results of the adaptive capacity indicators of vulnerable and non-vulnerable farmers in relation to their ability to adjust to climate-related hazards are shown in Table 6.

Access to Information: Both vulnerable and non-farmers perceived they received medium level of access to information, no significant differences were observed (P>0.05). suggests that access to relevant agricultural, climate, and market information remains a general challenge across the farming community, affecting both vulnerable and non-vulnerable farmers similarly in terms of perceived availability. The lack of significant difference implies that systemic issues in information dissemination or reception play, rather than a specific discriminatory barrier for the vulnerable.

Access to Credit Services: Non-vulnerable farmers perceived significantly high credit access compared to the non-vulnerable farmers (p<0.001). This significantly better access to credit for non-vulnerable farmers provides them with crucial financial flexibility to invest in adaptation measures, purchase inputs, or recover from shocks, thereby enhancing their adaptive capacity.

Financial Resources: Vulnerable farmers perceived their financial resources significantly lower compared to non-vulnerable farmers (p<0.001), showing that non-vulnerable farmers possess significantly greater financial capital. This stark difference directly impacts their ability to respond to climate shocks, invest in long-term adaptation measures, or cope with unexpected expenses.

Social Networks: Non-vulnerable farmers had significantly higher social networks compared to vulnerable farmers (p<0.001). While social networks are important for both groups, non-vulnerable farmers might more benefit from more extensive, diverse, or influential networks that provide enhanced access to information, labor, or collective action.

Training and Education: Both vulnerable and non-vulnerable farmers perceived their access to training and education as medium, no significance differences were reported. Similarity to access to training and education suggests more accessible agricultural and climate-related training and education for all farmers, irrespective of their current vulnerability status

Access to Technology: As expected, non-vulnerable farmers perceived significantly more access to technology than vulnerable farmers (p<0.001). However, the fact that both groups recorded low to medium scores, showing that technological access remains a general constraint, but is particularly acute for the vulnerable.

Institutional Support: Vulnerable farmers perceived their access to institutional support as medium (Mean = 3.11, Std. Dev. = 0.72), while non-vulnerable farmers reported slightly lower, also medium, access (Mean = 2.96, Std. Dev. = 0.67), but the difference was significant (p>0.001). This counter-intuitive finding suggests that vulnerable farmers, being the primary target of many government and non-governmental aid programs (e.g. Productive Safety Net Programme in Ethiopia), might be more aware of or actively engaging with these support systems, leading to a higher perceived access. It doesn't necessarily imply that the support received is sufficient to lift them out of vulnerability, but rather that they are more connected to existing institutional mechanisms.

Community Engagement: Vulnerable farmers perceived their community engagement significantly higher compared to non-vulnerable farmers ($p<0.001$), implying that vulnerable farmers have higher community engagement than non-vulnerable farmers. Similar to institutional support, this suggests that vulnerable farmers might rely more heavily on community networks for support, mutual aid, and collective action, leading to a higher perception of engagement. This often reflects their necessity to pool resources and rely on social capital in the face of limited individual resources. Table 6: Perceived responses of farmers for adaptive capacity indicators in Gedeo zone, Southeastern Rift Valley escarpments of Ethiopia

4 Discussions

Drought remains the most pervasive climatic stressor for smallholder farmers, particularly those reliant on rain-fed agriculture with limited livelihood diversification (Gebremariam et al., 2021; Gebreyesus et al., 2023). Evidence consistently shows that drought disproportionately affects vulnerable households, intensifying food insecurity and undermining rural livelihoods Bryan et al., 2013; Kabir et al., 2019). Socio-economically disadvantaged groups experience greater impacts due to weak financial buffers and inadequate infrastructure (Habib et al., 2020; Ray et al., 2021). Increasing drought frequency and severity across Sub-Saharan Africa further compounds these risks, destabilizing agricultural systems and deepening poverty traps (Niang et al., 2014; Zampaligré et al., 2019. Although statistical differences between vulnerable and non-vulnerable groups were not significant, variations in exposure likely reflect microclimatic differences and unequal adaptive capacities, shaping subjective experiences of drought impacts (Deressa et al., 2009).

The high drought burden underscores the urgency of resilience-focused interventions. Key strategies include adoption of drought-tolerant crop varieties, expansion of irrigation infrastructure, improved water harvesting, and accessible early warning systems (Adger, 2018; Bedru et al., 2023). While drought is a communal challenge, policy frameworks should prioritize vulnerable groups in resource allocation to strengthen adaptive capacity (Food and Agriculture Organization (FAO), 2018).

Flooding, though less frequent, remains a significant hazard in lowland and river basin areas, often exacerbated by deforestation and poor land management (Abera et al., 2021; Masika et al., 2017; Mwakapalila, 2017; Nigussie et al., 2020). Communities near major river systems and coastal zones frequently report moderate to high flood exposure (Nguyen et al., 2016; Phompila et al., 2020). Despite its localized nature, floods cause severe damage to crops, infrastructure, and livelihoods (Awoke et al., 2018). Interestingly, this study found no significant difference between vulnerable and non-vulnerable groups, contrasting with literature that highlights disproportionate impacts on poorer households due to weaker housing and farm infrastructure (Deressa et al., 2009; Zampaligré et al., 2019). Effective interventions include improved drainage, flood-resistant farming practices, community-based disaster risk reduction, and robust early warning systems (Mengistu & Dadi, 2023; UNISDR, 2015). Policies should emphasize preparedness and rapid recovery, particularly as climate change is expected to intensify flood risks (Intergovernmental Panel on Climate Change (IPCC), 2021).

Rainfall variability emerged as a critical stressor, with vulnerable farmers reporting very high exposure. Empirical evidence confirms shifts in rainfall regimes, including delayed onset, early cessation, and increased intensity of short rains (Bewket & Conway, 2007; Conway et al., 2007; Mekonnen et al., 2018). Erratic rainfall patterns drive agricultural risk and food insecurity, particularly for staple crops (Antwi-Agyei et al., 2018; Olofintoye et al., 2020). Such variability necessitates adaptive strategies, as demonstrated in rice-growing regions where altered monsoon patterns compel farmers to adjust to unpredictable conditions (Aguilar et al., 2020; R. Khan et al., 2021; Perez et al., 2018; Sriplung & Sompong, 2022). Although statistical differences between vulnerable and non-vulnerable groups were not significant, the practical reality remains resource-constrained farmers are more susceptible to immediate consequences such as crop failure and yield reduction (Deressa et al., 2009.

Rainfall variability emerged as a critical stressor, particularly for vulnerable farmers, demanding targeted adaptation strategies (Müller et al., 2021). Climate-smart practices such as conservation agriculture, drought-resistant crop varieties, efficient water management through small-scale irrigation and rainwater harvesting, and improved seasonal forecasting are essential to reduce risks and guide planting decisions Altieri et al., 2015; Gebreyesus et al., 2023; Nkonya et al., 2016). Policy frameworks should prioritize investments in agro-meteorological services and extension programs that strengthen farmers' capacity to cope with increasing rainfall unpredictability (Food and Agriculture Organization (FAO), 2018).

Temperature increases observed in this study align with regional climate change trends, marked by significant warming, heightened heat stress, and altered crop phenology (Gebreyesus et al., 2023; Intergovernmental Panel on Climate Change (IPCC), 2021). Rising maximum temperatures and more frequent heatwaves have reduced crop yields, impaired livestock health, and strained water resources (M. Khan & Hanjra, 2009; Rahman et al., 2019; Sow et al., 2020; Traoré et al., 2017). These changes necessitate shifts in growing seasons and adoption of heat-tolerant crop varieties (Hughes, 2011; Lobell & Gourdji, 2012). Although statistical differences between groups were not significant, the slightly higher mean for vulnerable farmers reflects their limited ability to invest in adaptive measures such as irrigation or shade structures, amplifying their sensitivity to temperature stress (Deressa et al., 2009).

Adaptation strategies to mitigate heat stress should include promoting heat-tolerant crops, adjusting planting calendars, integrating agroforestry for shade, improving livestock management, and expanding irrigation to counter evapotranspiration losses (Asfaw et al., 2022; Mekonnen et al., 2018; Thornton et al., 2014). Policies must support research into climate-resilient crop and livestock breeds, ensure their dissemination, and build farmer capacity to implement thermal adaptation measures (Food and Agriculture

Table 6: Perceived responses of farmers for adaptive capacity indicators in Gedeo zone, Southeastern Rift Valley escarpments of Ethiopia

Adaptive capacity Indicators	vulnerable (n-279)		Non-vulnerable (105)		Statistical value	
	Mean	Std. Dev.	Mean	Std. Dev.	Chi^2	p-value
Access to Information	2.63	0.58	3.52	0.81	1.4	0.507
Access to credit service	3.42	0.79	4.05	0.73	18	0.000
Financial Resources	2.14	0.55	3.71	0.74	24	0.000
Social Networks	3.66	0.74	3.83	0.70	17	0.000
Training and Education	2.74	0.50	2.85	0.68	2	0.263
Access to Technology	2.47	0.43	2.62	0.65	5	0.030
Institutional Support	3.11	0.72	2.96	0.67	11	0.001
Community Engagement	3.47	0.66	3.28	0.69	16	0.000

Organization (FAO), 2018).

Income disparities identified in this study further reinforce vulnerability patterns. Low-income households consistently demonstrate reduced adaptive capacity, with limited ability to invest in resilience measures or recover from shocks (Abate et al., 2022; Bedru et al., 2023; Osman et al., 2022; Tadesse et al., 2021; Worku and Singh, 2021. Income poverty restricts access to credit and technologies, constraining livelihood diversification and heightening sensitivity to climate variability (Antwi-Agyei et al., 2018; Habib et al., 2020). Wealthier farmers, by contrast, are better positioned to adopt protective measures, underscoring income as a fundamental determinant of socio-economic sensitivity Intergovernmental Panel on Climate Change (IPCC), 2021; Nguyen et al., 2016; Niang et al., 2014; Ray et al., 2021).

Addressing income disparity requires policies that enhance vulnerable farmers' earning capacity. Key interventions include diversification into non-farm activities, improved market access, value-addition initiatives, and financial literacy and entrepreneurship training (Food and Agriculture Organization (FAO), 2018; Gebreyesus et al., 2023). Expanding microfinance and credit facilities, alongside risk transfer mechanisms such as crop insurance, can buffer households against shocks (Bryan et al., 2013). Social protection programs including conditional cash transfers and public works remain vital to provide safety nets for the most vulnerable (UNISDR, 2015).

Lower household consumption among vulnerable farmers observed in this study is a clear indicator of precarious food security, linking vulnerability to chronic food insecurity and poor dietary diversity (Dullo et al., 2022; Gebremariam et al., 2021; Haile et al., 2020; Molla et al., 2020; Nigussie et al., 2020. Consumption expenditure is widely recognized as a key metric for identifying food-insecure households, which are more sensitive to price shocks and climate impacts (Masika et al., 2017). Households with lower consumption are disproportionately affected by food price volatility and recurrent droughts, often resorting to coping strategies that erode long-term resilience (Zampaligré et al., 2019). Inadequate consumption reflects limited purchasing power and restricted access to essential goods and services (M. Khan and Hanjra, 2009; Ray et al., 2021). Thus, consumption patterns serve as a robust proxy for household welfare and socio-economic sensitivity (R. Khan et al., 2021).

Addressing this consumption gap requires multi-dimensional interventions. Strategies include improving access to affordable and nutritious food through local markets, promoting home gardens to enhance dietary diversity, and strengthening food assistance programs (Food and Agriculture Organization (FAO), 2018). Policies should also aim to increase purchasing power via direct income support or reduced costs of essential goods, while simultaneously boosting agricultural productivity to stabilize food supply (Müller et al., 2021). Investments in healthcare and education further contribute to improved consumption outcomes and reduced vulnerability (Intergovernmental Panel on Climate Change (IPCC), 2021).

Lower household production among vulnerable farmers is consistent with existing evidence, often attributed to smaller landholdings, limited access to inputs, poor soil fertility, and reliance on traditional farming methods (Gebreegziabher et al., 2011; Gebreyesus et al., 2023; Haile et al., 2020; Osman et al., 2022; Tadese et al., 2020. Low productivity undermines food availability and income, reinforcing vulnerability (Olofintoye et al., 2020; Traoré et al., 2017). Restricted access to modern technologies and extension services further heightens sensitivity to climate shocks (Aguilar et al., 2020; Perez et al., 2018). Disparities in land, capital, and technical knowledge directly correlate with household sensitivity to agricultural crises (Khang et al., 2021; Sriplung & Sompong, 2022).

To enhance resilience, policies should prioritize access to climate-resilient seeds and fertilizers, expand irrigation technologies, and promote sustainable land management practices such as soil conservation and agroforestry (Altieri et al., 2015; Nkonya et al., 2016) . Strengthened extension services offering practical training in climate-smart techniques are essential (Food and Agriculture Organization (FAO), 2018). Collective farming initiatives and cooperatives can improve resource pooling, market access, and technology adoption (Asfaw et al., 2022). Securing land tenure rights further incentivizes long-term investments in productivity (Intergovernmental Panel on Climate Change (IPCC), 2021).

Medium access to climate and agricultural information, with no significant difference between vulnerable and non-vulnerable groups, reflects systemic inadequacies in extension services and information dissemination in Ethiopia (Alemayehu and Bewket, 2017; Bedru et al., 2023; Deressa et al., 2009; Gebremariam et al., 2021; Tesfaye and Mebit, 2021. Farmers often rely on traditional knowledge or informal networks due to poor access to formal meteorological services, limiting adaptive decision-making (Antwi-Agyei et al., 2018; Olofintoye et al., 2020). Even when information is available, barriers of accessibility, relevance, and interpretability persist (Nguyen et al., 2016; Ojha et al., 2019) .

Improving adaptive capacity requires strengthening extension services, diversifying communication channels (radio, mobile platforms, community meetings), and translating scientific forecasts into actionable advice (Bryan et al., 2013; Food and Agriculture Organization (FAO), 2018). Policies should invest in agro-meteorological services and build extension agent capacity to deliver tailored, context-specific information.

Credit constraints remain a major barrier for vulnerable farmers, limiting adoption of improved technologies and coping strategies (Abate et al., 2022; Dullo et al., 2022; Gebreyesus et al., 2023; Osman et al., 2022; Worku and Singh, 2021. Reliance on informal, high-interest loans exacerbates financial precarity (Habib et al., 2020; Ray et al., 2021). Restricted access to capital hinders investment in climate-smart agriculture and livelihood diversification (Sow et al., 2020; Traoré et al., 2017) . The significant difference observed in this study confirms financial capital as a critical determinant of adaptive capacity.

Expanding affordable credit access through tailored microfinance schemes, cooperatives, government-backed loan guarantees, and simplified procedures is essential (Food and Agriculture Organization (FAO), 2018). Innovative financial products, including climate-smart insurance, can enhance creditworthiness and resilience (Bryan et al., 2013).

Building the financial resilience of vulnerable farmers is essential for reducing climate-related risks. Key measures include promoting savings groups, expanding access to micro-credit, and establishing climate insurance schemes (FAO, 2019). Beyond direct financial access, policies should encourage diversified income streams, improve market integration for agricultural products, and implement social protection programs to provide safety nets against shocks (Müller et al., 2021) .

Social networks and community cohesion also emerge as critical non-financial assets for adaptation. They facilitate knowledge sharing, labor exchange, and collective coping mechanisms (Abate et al., 2022; Berhanu et al., 2014; Gebreyesus et al., 2023; Simane et al., 2016; Tesfaye and Mebit, 2021. Strong social capital enhances resilience by enabling collective responses to climate challenges (Antwi-Agyei et al., 2018; Zampaligré et al., 2019) . Community-based networks are particularly vital for disaster preparedness and recovery among vulnerable groups lacking formal support (R. Khan et al., 2021; Saroar and Alam, 2022) . The modest difference observed between groups suggests that non-vulnerable farmers benefit from broader networks, including ties to market actors and decision-makers, which provide additional adaptive advantages Deressa et al., 2009. Policies should therefore strengthen community-based organizations, promote farmer-to-farmer learning, and integrate traditional social structures into formal adaptation programs (Bryan et al., 2013; Food and Agriculture Organization (FAO), 2018).

Medium access to training and education across both groups highlights a systemic gap in knowledge and skill development crucial for climate adaptation (Bedru et al., 2023; Gebremariam et al., 2021; Haile et al., 2020; Nigussie et al., 2020; Tadese et al., 2020). Limited training in climate-smart agricultural techniques constrains adoption of resilient practices (Masika et al., 2017; Mwakapalila, 2017) , while inadequate farmer education programs hinder innovation uptake (Aguilar et al., 2020; Perez et al., 2018) . The absence of significant differences between groups indicates that both are underserved, though vulnerable farmers remain less equipped to capitalize on existing opportunities. Investment in comprehensive, context-specific training on climate-smart agriculture, water management, soil health, and livelihood diversification is therefore critical (Altieri et al., 2015; Food and Agriculture Organization (FAO), 2018).

Limited access to appropriate agricultural technologies such as improved seeds, irrigation equipment, and modern tools remains a well-documented constraint on productivity and adaptive capacity (Alemayehu and Bewket, 2017; Berhanu et al., 2014; Gebreegziabher et al., 2011; Nigussie et al., 2020; Osman et al., 2022). Affordability, knowledge gaps, and weak supply chains hinder adoption (Nkonya et al., 2016; Ray et al., 2021; Saroar and Alam, 2022; Traoré et al., 2017). The modest difference observed suggests that non-vulnerable farmers marginally overcome these barriers due to stronger financial resources or social networks. Policies should therefore prioritize making climate-smart technologies accessible and affordable, through subsidies, credit schemes, and strengthened supply chains for critical inputs such as drought-resistant seeds and efficient irrigation tools (Food and Agriculture Organization (FAO), 2018).

Interestingly, higher institutional support among vulnerable farmers reflects the design of development and humanitarian programs that deliberately target these groups (Bryan et al., 2013; Deressa et al., 2009; Gebreyesus et al., 2023; Simane et al., 2016; Tadesse et al., 2021). Vulnerable farmers are more likely to benefit from government and aid interventions, while non-vulnerable farmers often rely on market-based solutions. Humanitarian aid and social programs are thus channeled toward vulnerable populations, explaining their higher reported engagement (Intergovernmental Panel on Climate Change (IPCC), 2021; R. Khan et al., 2021. However, while institutional support is reaching its intended beneficiaries, policies must critically assess its effectiveness in enhancing adaptive capacity and reducing long-term vulnerability. Strengthening institutional coordination, ensuring flexible and needs-based support, and integrating aid with market mechanisms are essential to shift from short-term assistance toward sustainable resilience (Food and Agriculture Organization (FAO), 2018; UNISDR, 2015).

The higher community engagement observed among vulnerable farmers underscores the critical role of local social capital and collective action in coping and adaptation strategies (Abate et al., 2022; Bedru et al., 2023; Gebremariam et al., 2021; Osman et al., 2022; Tesfaye and Mebit, 2021). Community-based disaster risk reduction initiatives and informal networks often serve as the first line of defense for vulnerable populations. Strong social ties facilitate collective management of common resources and coordinated responses to environmental stress (Sow et al., 2020; Zampaligré et al., 2019). The significant difference found in this study suggests that while community engagement benefits all farmers, it is particularly vital for those with fewer individual resources. Policies should therefore strengthen existing community structures and indigenous coping mechanisms (Food and Agriculture Organization (FAO), 2018), foster participatory planning, and empower local leaders to enhance resilience (Bryan et al., 2013).

The negative impact of vulnerability on household income is well-documented. Vulnerable households, characterized by limited assets, poor market access, and reliance on rain-fed agriculture, consistently report lower and unstable income streams (Abate et al., 2022; Bedru et al., 2023; Dullo et al., 2022; Osman et al., 2022; Worku and Singh, 2021. Climate variability exacerbates these deficits, deepening socio-economic inequalities (Antwi-Agyei et al., 2018) . Low and inconsistent income restricts investment in adaptive measures (Habib et al., 2020), directly correlating with food insecurity and reduced resilience (Ray et al., 2021; Sow et al., 2020; Traoré et al., 2017) . Income thus emerges as a fundamental driver of vulnerability. Addressing disparities requires targeted interventions to diversify livelihoods, expand non-farm opportunities, and strengthen market linkages (Food and Agriculture Organization (FAO), 2018). Access to affordable credit, microfinance, and financial literacy training can empower households to invest in resilience (Bryan et al., 2013), while climate-smart agriculture can stabilize and increase incomes (Gebreyesus et al., 2023).

Significantly lower household consumption among vulnerable farmers highlights chronic food and nutritional insecurity. Vulnerable households often face poor dietary diversity and reduced access to basic needs (Dullo et al., 2022; Gebremariam et al., 2021; Haile et al., 2020; Molla et al., 2020; Nigussie et al., 2020). Lower consumption expenditures reflect struggles to meet caloric and nutritional requirements, especially during climate shocks (Masika et al., 2017; Mwakapalila, 2017). Income instability and limited market access further constrain consumption (Khang et al., 2021). Global assessments confirm that climate change disproportionately affects consumption patterns in vulnerable populations (Intergovernmental Panel on Climate Change (IPCC), 2021). Addressing these gaps requires integrated food security interventions: increasing production, improving market access, reducing food prices, and promoting nutrition education (Food and Agriculture Organization (FAO), 2018). Social safety nets such as food assistance and cash transfers provide immediate relief (UNISDR, 2015) , while investments in health and sanitation indirectly strengthen food utilization.

Lower household production among vulnerable farmers is a consistent finding, linked to limited access to inputs, poor soil fertility, rudimentary technologies, and heightened climate exposure (Gebreegziabher et al., 2011; Gebreyesus et al., 2023; Haile et al., 2020; Osman et al., 2022; Tadese et al., 2020). Low productivity undermines food availability and income, reinforcing vulnerability (Olofintoye et al., 2020; Traoré et al., 2017) . Farmers with restricted access to modern agronomic knowledge and technologies consistently achieve lower yields (Aguilar et al., 2020; Perez et al., 2018) . Production disparities intensify sensitivity to market and climate shocks (Khang et al., 2021; Sriplung and Sompong, 2022). Enhancing productivity requires improved access to climate-resilient seeds, fertilizers, efficient water management, and sustainable soil practices (Altieri et al., 2015; Nkonya et al., 2016). Strengthened extension services and tailored training programs are vital (Food and Agriculture Organization (FAO), 2018), while farmer cooperatives can improve access to inputs, markets, and shared technologies, collectively enhancing production capacity.

5 Conclusions

This study demonstrates that a substantial majority (72.65%) of smallholder farmers in the Gedeo Zone are highly vulnerable to climate-related hazards, with droughts, floods, and erratic weather directly undermining their food security and economic stability. Among these stressors, rainfall variability emerges as the most acute and differentiating hazard, disproportionately affecting vulnerable households and amplifying their sensitivity to climate shocks.

Our study reveals statistically significant disparities between vulnerable and non-vulnerable farmers across key socio-economic indicators. Vulnerable households consistently exhibit lower income, consumption, and production, confirming their heightened sensitivity to both climatic and economic shocks. In contrast, non-vulnerable farmers benefit from stronger adaptive capacity, largely due to better access to credit, financial resources and slightly stronger social networks However, both groups face systemic challenges in accessing timely information and training, highlighting structural gaps in extension and education services. These findings confirm that vulnerability directly erodes financial well-being, food security, and productivity, perpetuating cycles of poverty and fragility.

To effectively reduce vulnerability and build resilience in the Gedeo Zone, a comprehensive, integrated strategy should be implemented that combines accessible financial services, climate-smart agriculture, strengthened institutional and social support, diversified livelihoods, and targeted social protection. By addressing these dimensions simultaneously, farmers can enhance adaptive capacity, stabilize income and food security, and foster sustainable, climate-resilient livelihoods

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Availability of Data and Materials

All data generated or analysed during this study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no competing interests in relation to this study.

Authors Contributions

Tigistu Gezahegn: contributed to the conceptualization, data collection, formal analysis, investigation, project administration, visualization, and overall original manuscript writing.
Mesele Negash: played a key role in designing the methodology, supervising, validating, and reviewing the manuscript with constructive comments.
Eshetu Yirsaw: made significant contributions by reviewing, supervising, validating, and providing comments on the manuscript.

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