

**GENDER DIMENSIONS OF VULNERABILITY AND ADAPTATION
STRATEGIES TO CLIMATE CHANGE AND VARIABILITY:
WELFARE IMPACTS ON MALE- AND FEMALE-HEADED
HOUSEHOLDS IN NORTH WOLLO ZONE, AMHARA REGION,
ETHIOPIA**

PH.D. DISSERTATION

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Gender Dimensions of Vulnerability and Adaptation Strategy to Climate Change and Variability: The Case of Smallholder Farmers in North Wollo Zone, Amhara Region, Ethiopia

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ABBREVIATIONS AND ACRONYMS

ATT	Average Treatment Effect on the Treated
ATU	Average Treatment Effect on the Untreated
CRGE	Climate Resilient Green Economy
CVC	Climate Variability and Change
CSA	Central Statistics Agency
EFCCC	Environment, Forest and Climate Change Commission
EPCC	Ethiopian Panel of Climate Change
FAO	Food Agricultural Organization
FDRE	Federal Democratic Republican of Ethiopia
FHH	Female-Headed Households
GAD	Gender and Development
GDP	Gross Domestic Product
GED	Gender, Environment, and Development
HDI	Human Development Index
IPCC	Intergovernmental Panel on Climate Change
LVI	Livelihood Vulnerability Index
MHH	Male-Headed Households
NAPA	National Adaptation Programme of Action
NMA	National Meteorological Agency, Ethiopia
NWZAO	North Wollo Zone Agriculture Office
SSA	Sub-Saharan Africa
TLU	Tropical Livestock Units
UNDP	United Nation Development Program
UNFCCC	United Nation Framework Convention on Climate Change
WID	Women in Development
WB	World Bank

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List of Articles/Manuscripts

This dissertation is based on the following three original papers, which are listed from 1–3.

1. Gender Dimensions of Determinants of Adaptation Strategies to Climate Change among Smallholder Farmers in Northeast Ethiopia. *Glob Soc Welf* (2024).
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2. Gendered Vulnerability to Climate Change among Smallholder Farmers in Northeast Ethiopia. **Status submitted under journal review**
3. Impact of Climate Change Adaptation Strategies on Household Welfare: A Gender Perspective from Smallholder Farmers in North Wollo Zone, Ethiopia. **Status Accepted**

Gender Dimensions of Vulnerability and Adaptation Strategies to Climate Change and Variability: Welfare Impacts on Male- and Female-Headed Households in North Wollo Zone, Amhara Region, Ethiopia

ABSTRACT

Climate change presents significant challenges for resource-limited communities, intensifying their vulnerability and diminishing their adaptive capacities. Male-headed and female-headed farm households experience varied impacts of climate change and variability due to their unique socioeconomic contexts, leading to the development of distinct adaptation strategies. Understanding these gender dimensions of climate change perceptions and responses is essential for providing tailored extension and advisory services. This study investigates the gender dimensions of vulnerability and adaptation strategies to climate change and variability among smallholder farmers in the North Wollo zone of Ethiopia. Data were collected from 396 randomly selected smallholder farmers, supplemented by qualitative insights from focus group discussions and key informant interviews. The analysis employed various statistical methods, including percentage, Chi-square tests, t-tests, and content analysis, alongside the Livelihood Vulnerability Index (LVI) and the Intergovernmental Panel on Climate Change Vulnerability Index, multivariate probit model, and endogenous switching regression model for impact analysis. Results indicate that female-headed households (LVI = 0.542) are more vulnerable to climate change than male-headed households (LVI = 0.446), reflecting greater sensitivity to climate-related stresses and limited adaptive capacity. Key factors contributing to this vulnerability include reliance on rain-fed agriculture, restricted access to irrigation, smaller landholdings, limited access to early warning information, and weaker social networks. In contrast, male-headed households exhibit greater adaptive capacity due to higher livestock and land ownership, better access to education, microfinance, and agricultural services, along with stronger social networks. Despite shared challenges such as land degradation and crop losses, adaptation strategies differ significantly between genders. While 92% of male-headed households have perceived recent climate changes, only 78% of female-headed households have done so. Moreover, a greater proportion of male-headed households (73.78%) have implemented adaptation strategies compared to only 58.91% of female-headed households. The study identifies critical determinants influencing adaptation choices, including age, education, landholding size, income, and access to climate information and credit. Notably, multivariate probit analysis reveals that land size significantly impact adaptation decisions for female-headed households, emphasizing the necessity to address gendered inequities in land rights. Furthermore, the study evaluates the welfare impacts of adaptation strategies, demonstrating that these strategies significantly improve both food consumption and household income for male- and female-headed households. Farmers who implement adaptation measures report higher levels of food consumption and income compared to those who do not. Specifically, female-headed households that did not implement adaptation strategies would see a decline of Birr 963.06 in food consumption expenditure, while male-headed households would face a considerably larger potential loss of Birr 3561.95. Additionally, households that engaged in adaptation strategies experienced income increases of 19.4% for female-headed households and 23.94% for male-headed households compared to their non-adapting counterparts. Targeted interventions are needed to enhance female farmers' adaptive capacity. These should include expanding small-scale irrigation, providing gender-sensitive microfinance, delivering tailored extension services, and improving access to climate information through women's farmer groups. Coordination by local agricultural offices, NGOs, and community organizations is essential to ensure effective implementation.

Keywords: - Adaptation Strategy; Climate change; Determinants; Vulnerability; Ethiopia; Gender

1. INTRODUCTION

1.1. Background of the Study

The world's environmental systems and oceans are being impacted by changes in climate variability (IPCC, 2014). The Intergovernmental Panel on Climate Change's (IPCC) sixth Assessment report unequivocally states that the global climate system is warming, as evidenced by temperatures on land (IPCC, 2023). Developing nations are already experiencing the effects through higher temperatures, more erratic rainfall, and increasing sea levels disrupting people's lives and livelihoods (Emediegwu et al., 2022; Pereira, 2017). Unless greenhouse gas emissions are sharply reduced, climate projections warn of more frequent and intense climate extremes such as droughts and floods endangering water resources, agricultural production, and food security (Adesete et al., 2022; Richardson et al., 2022).

Vulnerability to climate change in Africa has become a major global concern. The continent faces significant risks due to climate variability and change, more so than other regions. Many Africans rely on nature and agriculture for their livelihoods (Pereira, 2017). Since agriculture plays a vital role in rural communities across Africa, it is one of the most vulnerable sectors to climate impacts (Deressa and Hassan, 2010; Emediegwu et al., 2022). African smallholder farmers, in particular, have high exposure due to their dependence on rain-fed agriculture with limited irrigation options (Amare and Simane, 2017; Kogo et al., 2021). Changes in rainfall patterns pose serious threats to food production and security (Bai et al., 2022). Research has shown climate change is already disrupting agricultural seasons and yields in many African countries (Ahmed et al., 2022; Solomon et al., 2021). The lack of alternative livelihoods apart from climate-sensitive farming activities increases the vulnerability of local populations to droughts, floods and other climate-related hazards exacerbated by a warming planet (Araro et al., 2020; Emediegwu et al., 2022). Building resilience among small-scale farmers will be crucial to help address food insecurity facing many African nations in the face of ongoing climate risks.

While adaptation to climate change is important for all countries aiming to reduce current impacts and strengthen future resilience, it is especially relevant for developing nations whose societies already struggle with existing climate variability (Aryal et al., 2021; Belay et al.,

2017). For these vulnerable countries, adaptation has become a major challenge for achieving development goals and plays a key role in poverty alleviation (Fasina et al., 2021). The IPCC highlighted the need for deeper understanding of adaptation options and barriers, which remain understudied (IPCC, 2023). Other researchers recommend more in-depth analyses of farmers' on-the-ground coping strategies, noting that African adaptation studies often report generalized results without considering a range of practices (Aryal et al., 2021; Atube et al., 2021; Deressa and Hassan, 2010). Furthermore, the dominant top-down policy approach, starting at international levels and cascading down through negotiations and funding, often fails to reach the poor and vulnerable (Ahmed et al., 2022).

Ethiopia is among the countries most vulnerable to climate change, and is already experiencing severe impacts on livelihoods because of its limited adaptive capacity (Amare and Simane, 2017; Asfaw et al., 2021). The country's heavy reliance on rain-fed agriculture, which is directly influenced by climatic conditions, exacerbates the challenges faced by farmers (Bedeke et al., 2020; Deressa and Hassan, 2010; Simane et al., 2016). Any deviation from normal rainfall and temperature patterns can significantly disrupt agricultural production, leading to reduced yield and economic instability.

Agriculture remains central to the Ethiopian economy. As of 2023, the agricultural sector contributes approximately 35.8% of Ethiopia's GDP (Mulusew and Hong, 2023). Moreover, about 80% of the population is employed in agriculture, and agriculture constitutes a large share of export earnings (FAO, 2022). Smallholder farmers dominate the sector: more than 90% of cultivated land and most agricultural output come from smallholder farms (USAD, 2017; FAO, 2021).

Women play a very significant but often under-recognized role in Ethiopian agriculture. It is estimated that women perform up to 75% of farm labour in some areas and contribute to roughly 70% of household food production, though their productivity tends to lag behind men's due to unequal access to inputs and services (African Development Bank & UN Women, 2018). In terms of labor force participation, women account for about 47% of Ethiopia's agricultural labor force.

The consequences of climate change on Ethiopia's agricultural sector are profound and affect both food production and overall economic performance (Mekonnen et al., 2021). Rising

temperatures, shifting precipitation patterns, and an increase in extreme weather events such as droughts and floods have contributed to declining agricultural productivity and widespread food insecurity (Chidakwa et al., 2020; Rao et al., 2019). These challenges threaten the nutritional well-being of farming communities as food availability, accessibility, and dietary diversity have become increasingly constrained (Pereira, 2017). Given these pressing issues, climate change adaptation strategies have become essential for ensuring sustainable agricultural practices and enhancing the resilience of Ethiopian farmers (Belay et al., 2017; Echeverría and Terton, 2016). By implementing adaptive measures, such as improved irrigation systems, drought-resistant crop varieties, and climate-smart farming techniques, Ethiopia can safeguard its agricultural sector and secure the livelihoods of its rural population (Bedeke et al., 2020).

Gender plays an important role in determining vulnerability to climate change impacts (Mersha and van Laerhoven, 2019; Rao et al., 2019; Yiridomoh et al., 2022). Women often face greater risks due to inequalities in access to resources and assets needed to build resilience (Ampaire et al., 2020; Jost et al., 2016). The adverse effects of climate change are strongly tied to existing gender gaps. For instance, women typically have less economic independence and control over land and financial assets (Balikoowa et al., 2019; Bessah et al., 2021; Tanny et al., 2017). Prevailing social and cultural norms also limit their opportunities and equal participation. The domestic burdens of caregiving disproportionately fall on women and female-headed households (Goodrich et al., 2019). As a result, these groups face greater difficulties adapting to climate stresses like food and water insecurity exacerbated by droughts or flooding (Awiti, 2022; Rao et al., 2019). Limited autonomy and heavy workloads reduce women's capacity and options to cope with climate disasters when they occur (Alhassan et al., 2019; Maja et al., 2023). Moreover, patriarchal structures often prevent women from having a strong voice in climate decision-making. Achieving true gender equality, securing women's rights to assets and resources, and addressing gender stereotypes are important for justly distributing adaptation efforts and reducing vulnerability under a changing climate (Bryan et al., 2018).

Women's perceptions of climate risks may differ from men due to their different daily responsibilities and social positions within households and communities (Haque et al., 2023).

Perceptions of climate change impacts and available adaptation strategies diverge between male and female farmers based on their gender (Al-Amin et al., 2023; McKinley et al., 2016). Women often face greater challenges in deciding on and implementing adaptation measures. Their adaptive decision-making is thus more constrained than men's as a result of both differing perceptions and the effects of gender inequality in their communities (Bessah et al., 2021; Lawson et al., 2020).

This study was conducted at the household level in the Amhara region of Ethiopia, specifically in the North Wollo zone. Drought and flooding are the primary climate hazards in North Wollo, though their impacts vary across districts. Research shows communities and households in the area are highly vulnerable to observed climate impacts in recent years such as low agricultural productivity and degraded natural resources (Wassie et al., 2021). Many families are struggling with severe food insecurity following successive poor harvests. It is important to comprehensively understand how differing access to resources influences adaptive capacity and the selection of adaptation strategies for male-headed and female-headed households.

1.2. Statement of the Problem

Ethiopia has been heavily impacted by climate extremes such as floods and droughts in recent years (Asfaw et al., 2021; Zeleke et al., 2023). The country is particularly vulnerable to climate change given its reliance on rain-fed agriculture for food production (Pereira, 2017). Uneven rainfall and temperature distributions have resulted in poor crop yields during some growing seasons, leading to food shortages, increased farmer poverty, and differentiated vulnerabilities based on gender (Bessah et al., 2021; Chidakwa et al., 2020).

The IPCC has highlighted that vulnerabilities are shaped not just by climate factors but also by social inequalities (IPCC, 2023). Climate change impacts can disproportionately harm vulnerable groups who are marginalized. Intersecting social processes like gender cause vulnerabilities as well as greater exposure, exacerbating socioeconomic disparities and income inequalities (Awiti, 2022; Haque et al., 2023). Gender inequality significantly influences the vulnerabilities associated with climate change, particularly affecting female-headed households by limiting their access to resources and economic opportunities (IPCC, 2023). Differences in access to resources, information, social roles, and effects of disasters can impact

men and women differently (Rao et al., 2019; Ravera et al., 2016). Climate change is expected to worsen the gender dimension of vulnerability, especially among female-headed households, and threaten livelihoods by reducing economic opportunities, particularly for these households (Adzawla and Kane, 2019; Rao et al., 2019).

Capturing gender-specific vulnerabilities to climate change is important because its impacts may differ for men and women farmers based on varying abilities to adapt, physical assets owned, and social networks (Chidakwa et al., 2020; Goodrich et al., 2019). Currently, gender disparities render women more susceptible to climate change than men due to their limited access to key resources (Alhassan et al., 2019; Nong et al., 2020). This leads to greater vulnerability to climate impacts and constrained adaptive capacity (Balikoowa et al., 2019). Further, households in the same location facing similar climate exposures may experience different vulnerability levels. Vulnerability depends not just on a system's sensitivity and exposure but also on the adaptive capacities of its human components (Habib et al., 2022). Even within similar environments, factors like gender can create inequities that influence vulnerability. Understanding these societal influences on vulnerability is crucial for designing equitable and effective climate response strategies.

Adaptation to climate change is an appropriate response especially for smallholder farmers (Belay et al., 2017; Echeverría and Terton, 2016; Kabir et al., 2021). Adaptation refers to adjusting systems in response to climate changes to minimize harm or maximize benefits (Oppenheimer et al., 2014). Climate adaptation is critical for protecting households from localized and immediate effects of climatic shocks (Ahmed and Fatema, 2023; Khadka et al., 2022). At the farm level, possible adaptations include new crops/livestock, irrigation, crop diversification, mixed farming, and income diversification (Aryal et al., 2021; Megersa et al., 2022). Understanding adaptation measures, practices, and influential factors can improve policies and farmers' ability to cope with climate impacts. The adaptation process, like other aspects of climate change, is not gender-neutral (Adzawla et al., 2019; Cholo et al., 2020).

In Ethiopia, women often have less adaptive capacity than men due to limited resources, rights, mobility, and decision-making power (Mersha and Van Laerhoven, 2016). Women are more vulnerable to climate risks like floods and droughts; this can negatively impact communities as women steward resources and support households (Balikoowa et al., 2019;

Goodrich et al., 2019). Adaptation efforts should consider men's and women's different perspectives and strategies to plan community-based activities (Maja et al., 2023; Wrigley-Asante et al., 2019). Integrating gender issues at all levels is crucial for effective adaptation.

Women face barriers to effectively adapting to climate change. Traditional gender roles mean adaptation strategies are often designed and implemented without consideration for women's priorities, capacities, and constraints (Adzawla et al., 2019; Ahmed and Kiester, 2021). The UN Convention on Climate Change (UNFCCC) emphasizes the importance of designing adaptation strategies that take into account the unique challenges faced by women. This perspective is supported by various initiatives, including the United Nations Framework on Climate Change (2020) and the World Bank Gender Strategy 2016-2023: Endowments, as well as the work of the United Nations Development Programme (UNDP) 2020. Adaptation strategies also need to acknowledge that women have less time due to domestic duties like fetching water and firewood over greater distances as climate impacts intensify (Al-Amin et al., 2019; Haque et al., 2023). Community-based adaptation programs show promise but need to be designed and led with meaningful participation from women (Baloch et al., 2022). This ensures that strategies are tailored to their needs, skills are developed, and they have access to resources like land, credit, and technology. Without attention to such barriers, marginalized groups like rural women will continue to experience disproportionate vulnerability under climate change (Lawson et al., 2020).

The literature documents a range of climate change adaptation strategies employed by farmers worldwide and in Ethiopia. These strategies reflect a diverse array of approaches tailored to local conditions and challenges posed by climate change. These adaptation strategies include the use of drought-tolerant crop varieties, adjusting planting dates, practicing crop rotation, implementing intensive irrigation systems, adopting soil and water conservation techniques, and diversifying household income sources (Asrat and Simane, 2018; Atinkut and Mebrat, 2016; Deressa et al., 2009; Mihiretu et al., 2019; Ojo and Baiyegunhi, 2020).

However, gender inequality in Ethiopia manifests in unequal access to land, inputs, credit, and extension services, which constrains women's ability to implement capital-intensive adaptation strategies (Mersha & Van Laerhoven, 2016; FAO, 2021). Male-headed households often adopt resource-intensive measures such as irrigation and improved seed, while female-

headed households rely on low-cost strategies like crop diversification, income diversification, or migration due to their limited access to productive resources (Bessah et al., 2021; Wrigley-Asante et al., 2019). These differences highlight that adaptation is shaped not only by exposure to climate risks but also by structural inequalities that influence household welfare outcomes.

Promoting adaptation strategies for smallholder farmers has the potential to enhance farm income, improve household welfare, and improve agricultural yields, thereby reducing vulnerability to climate change (Adzawla et al., 2019). However, such strategies are underutilized in Ethiopia (Asmare et al., 2019). To develop effective and equitable policies that strengthen climate resilience, it is essential to understand the gender-specific barriers and enablers related to adaptation.

Research indicates that farmers' decisions to implement climate change adaptation strategies are crucial for minimizing the impact of climate change on household welfare (Asmare et al., 2019; Berhe et al., 2017; Oparinde, 2021). Studies by Afolami et al. (2015) and Oparinde (2021) suggest that these adaptation measures have a direct positive effect on household well-being by mitigating risks associated with climate change. Consequently, farm households that adopt such practices are more likely to achieve food security compared to those that do not (Ndiritu and Muricho, 2021; Zakari et al., 2022). Asmare et al. (2019) emphasize that the primary objective of climate change adaptation strategies is to enhance agricultural productivity in the face of changing climatic conditions, ultimately improving food security and reducing poverty. Hailu et al. (2021) further highlight that smallholder farmer who utilize a combination of improved technologies, rather than relying on a single method, experience significant gains in food security. Similarly, Amare and Simane (2018) found that farmers employing any form of adaptation strategy consumed more food calories per day per adult equivalent than those who did not, underscoring the vital role of adaptation in promoting household nutrition and resilience.

Previous empirical studies in Ethiopia have analyzed spatial differences in vulnerability and adaptation to climate change and variability across agro-ecological zones (e.g. Asfaw et al., 2021; Asrat and Simane, 2018; Belay et al., 2017; Deressa and Hassan, 2010; Megersa et al., 2022; Zeleke et al., 2023). These studies included the proportion of female-headed households as a key indicator in vulnerability assessments, revealing that higher proportions of

such households are associated with increased vulnerability to climate change. Notably, women's heightened discriminating vulnerability is often a result of gender-based socioeconomic constraints rather than inherent weakness. Additionally, the gender of the household head has been identified as a significant factor influencing the choices of adaptation strategies.

The analysis highlights the ambiguity in the factors that influence decision-making in male versus female-headed households, particularly in the context of climate change impacts on agriculture. It emphasizes that climate change affects male and female farmers differently, largely due to disparities in resource access that influence their coping strategies. While some Ethiopian researchers, such as Cholo et al. (2020) and Maja et al. (2023), have begun to investigate the gender dimensions of climate change focusing on perceptions and coping mechanisms there remains a significant gap in comparative studies. More research is needed to examine and contrast the adaptation strategies employed by male- and female-headed households across diverse regions. This additional research could improve the understanding of localized adaptation processes and promote the exchange of gender-disaggregated experiences, ultimately aiding in more equitable climate change responses.

Women often have different roles, responsibilities, and access to resources compared to men in agricultural settings (Wrigley-Asante et al., 2019). Therefore, recognizing these differences is vital for developing effective strategies. According to the United Nations Development Programme (UNDP), achieving gender equality is crucial for sustainable development and building resilience (UNDP, 2020). Therefore, policies must be designed with a gender-sensitive lens to ensure equitable access to resources and opportunities.

Disaggregated data on gender influences adaptation strategies and significantly enhances the effectiveness of policies. By collecting data that distinguishes between male- and female-headed households, researchers can analyze how resource access impacts decision-making processes differently across genders. Studies have shown that women have different priorities and preferences due to their roles as primary caregivers (FAO, 2021). Understanding these preferences allows for more targeted interventions that support women's specific needs while also enhancing overall community resilience. The relationship between resource access and strategy choices is critical in formulating effective responses to climate change impacts

(Alhassan et al., 2019). Male-headed households have more access to resources and ownership rights than female-headed households; thus, they may chose different adaptive strategies based on their resource availability.

The drought/flood-prone North Wollo Zone provides relevant context for understanding gender dimensions of climate vulnerability and responses. Male and female-headed households here experience different climate change/variability impacts and tend to choose diverse adaptation strategies due to socioeconomic factors. A better understanding of perceived climate risks and adaptations from a gender perspective in this local area could help tailor extension/advisory services to better support adaptation. Therefore, this study argues that vulnerability and adaptation to climate change need to be examined separately for male- and female-headed households to address knowledge gaps. Male and female household heads also have distinct priorities and needs for adaptation due to gender-differentiated climate change influences. Gender-disaggregated data and analysis can strengthen development of sensitive adaptation strategies. While adaptation strategies can potentially improve household welfare, there is still limited empirical evidence on how different approaches affect key welfare outcomes, such as income and food expenditures, for male- versus female-headed households.

1.3. Objectives of the Study

The general objective of this study is to investigate gender dimensions of vulnerability and adaptation strategy choices to climate change and its impact on the welfare of smallholder farmers in the North Wollo zone, Northeast Ethiopia.

The specific objectives of the study are:

- To assess the gender dimensions of vulnerability to climate change and variability.
- To examine perceptions of climate change and variability, along with the determinants of adaptation strategy choices for male-headed and female-headed households.
- To evaluate the impact of climate change adaptation strategies on the male and female households' welfare.

1.4. Research Questions

To address the above issues, therefore, this study attempted to answer the following research questions:

- ✓ How are female and male-headed households vulnerable to climate change?
- ✓ What are the adaptation strategies female- and male-headed households utilize?
- ✓ What are the factors determining the choice of adaptation strategies in male- and female-headed households to climate change and variability?
- ✓ What is the impact of climate change adaptation strategies on male and female households' welfare?

1.5. Significance of the Study

This study attempted to add to the empirical literature related to gender dimensions of vulnerability and adaptation strategy choices to climate change and variability. It presented scientific and gender-disaggregated knowledge to help expand gender-sensitive adaptation strategies and packages as well as design gender-specific interventions. The study offered insights into how gender differences can increase households' vulnerability to climate change, reduce adaptive capacities, and shape responses to climate impacts and variability. It also provided an understanding of gender-differentiated adaptation strategy choices and their impacts on welfare when climate shocks occur. The research served as a reference for students and researchers interested in further empirical studies of the links between vulnerability, adaptation, and climate change from a gender perspective in Ethiopia. The results benefited researchers and development policymakers. They highlighted how accounting for gender is critically important to the design and targeting of effective climate resilience programming. Overall, the study aimed to advance gender-equitable approaches to building smallholder livelihood security in the face of a changing climate.

1.6. Scope and Limitation of the Study

This study investigated the gender dimensions of vulnerability, adaptation strategies, and impacts on welfare in the context of smallholder farmers in North Wollo zone, Northeast Ethiopia. Specifically, it assessed and compared vulnerability levels, adaptation strategy choices, and changes in annual incomes and household consumption expenditures between male- and female-headed households. The research was conducted across three districts within North Wollo zone (Wadila, Lasta, Habru) due to resource constraints limiting a broader geographical scope. A cross-sectional survey design captured data at a single point in time to analyze vulnerability, adaptation, and welfare outcomes between male and female households.

This study has several limitations that should be considered when interpreting the findings. The cross-sectional design limits the ability to assess changes in vulnerability, adaptation strategies, or welfare outcomes over time. Data were collected from only three districts, so villages or households outside these areas may have exhibited a different characteristic, which restricts the generalizability of the results. While the focus was on gender differences, other unobserved factors may have influenced household vulnerability, adaptation decisions, and welfare outcomes. Due to the absence of recorded household-level data on annual farm income, counterfactual estimates were used for impact analysis, potentially introducing some uncertainty. Meteorological data on rainfall and temperature from the Ethiopian Meteorological Agency were incomplete, which may have affected the accuracy of climate exposure assessments. Moreover, the study focused solely on household heads (male and female), excluding other household members such as wives, and therefore could not fully capture intra-household decision-making and resource allocation dynamics. Despite these constraints of scope, design, and data availability, the study provides valuable insights into the gender dimensions of climate vulnerability, adaptation strategies, and their impacts on welfare among smallholder farmers.

1.7. Organization of the Dissertation

This dissertation is organized into five chapters. Chapter one provides an introduction to the background, problem statement, objectives, significance and limitations of the study. Chapter Two presents a review of the relevant literature, exploring materials related to the current study and highlighting what approach this research provides. Chapter Three details the research materials and methods, outlining and justifying the statistical and econometric methods used to undertake the investigations. Chapter Four presents the results and discussion of the study findings. It includes descriptive and econometric analysis results from the research. Finally, Chapter Five provides a summary, conclusions, and recommendations from the study. It synthesizes the key takeaways and implications emerging from the empirical analyses.

2. LITERATURE REVIEW

This chapter explores the conceptual framework, theories, analytical approaches, and empirical studies related to gender, vulnerability, and adaptation strategies for climate change and variability among smallholder farmers. The theoretical framework section provides background that supports the investigation and is used to construct the theories underlying this study. The analytical framework section outlines the specific methods and analytical techniques and procedures that will provide clarity in the study. The empirical literature review provides evidence from past research relevant to the topic. Key areas covered include conceptualizations of vulnerability and adaptation, theoretical perspectives on the gender dimensions of climate impacts and responses, analytical methods employed in prior works, and findings regarding how gender shapes vulnerability and adaptive capacity in smallholder agricultural systems.

2.1. Concepts and Definitions

2.1.1. Concepts of Gender

Gender refers to the social and cultural expectations that societies assign to behaviors, characteristics and values associated with men and women. It is shaped by norms, laws, institutions and perceptions (Manfred and Sebstad, 2010). Gender is used to understand social relationships and power dynamics between men and women, as well as how concepts of masculinity and femininity are constructed (Laven et al., 2009). These attributes are learned rather than innate, and evolve with greater awareness and development over time (Alston, 2013).

Gender relations refer to the interactions between men and women in a society. While often seen as natural and linked to sex and reproduction, gender relations are conceptually distinct and influence all areas of social life, including economic, social, political and religious spheres (Moser, 2012). Men and women typically take on different household tasks and roles, though the definition of “women’s work” and “men’s work” varies between cultures in practice (Habtezion, 2013).

Gender relations frequently involve an unequal distribution of power, where men exercise more authority in some relational aspects and women in others. In this context, gender describes the societal connotations that impact all social domains, as well as its ties to natural differences in sex and reproduction. An empowerment approach aims to realize gender equality through equitable resource allocation and women's greater participation in self-reliance, decision-making and development opportunities. This promotes sustainable development through more balanced social relationships and power dynamics between men and women.

2.1.2. Climate Change and Variability

Climate change refers to statistically significant variations in climate patterns that persist over extended periods, typically decades or longer (IPCC, 2007). It involves changes in temperatures, rainfall levels, and extreme weather events such as droughts and floods that impact livelihoods.

Climate variability consists of natural, short-term fluctuations in weather that occurs without human interference. Isolating natural variability from anthropogenic climate change induced by human activities is challenging, as the former can influence the frequency and intensity of the latter, and vice versa (Khan and Akhtar, 2015).

Climate change can arise from internal natural processes or external radiated forcing, either directly or indirectly due to human activity (IPCC, 2007). However, the broader public commonly refers to anthropogenic global warming driven primarily by man-made greenhouse gases like carbon dioxide, which scientific evidence indicates are the dominant cause of warming trends over the past 50 years. This study defines climate change as variations in climate patterns over time that result from both natural causes and human influences. It considers shifts in critical climate elements and extreme climatic phenomena arising from both naturally-occurring variability as well as anthropogenic emissions associated with human systems that alter atmospheric composition at a global scale.

2.1.3. Climate Change Vulnerability

The IPCC defines vulnerability as the propensity or predisposition of a system to be adversely affected by climate change (IPCC, 2007). This incorporates susceptibility to harm and limited

adaptive capacity. This study uses the IPCC's definition, which considers a system's exposure, sensitivity and adaptive capacity. Exposure refers to the degree and nature of climate variations a system experiences (Oppenheimer et al., 2014). Sensitivity is the degree to which a system is affected, beneficially or adversely, by climate changes (Fellmann, 2012). Impacts may be direct, such as on agricultural production from temperature changes, or indirect, as with flooding from sea level rise (IPCC, 2007).

Adaptive capacity is a system's ability to adjust to climate impacts and cope with consequences (Gallopín, 2006). This comprises adaptation measures like using improved crop varieties, stronger agricultural services, and income diversification (Fellmann, 2012). Adaptive capacity relies on reducing stresses from social/economic factors like poverty and weak policies, as well as biophysical stresses including land degradation and drought affecting livelihoods (Gentle et al., 2013).

Vulnerability analyses employ socioeconomic and biophysical methods. Socioeconomic assessments examine interactions between climate, land use and livelihoods, considering factors like education, food/income access, health, social networks and access to services (Cutter et al., 2009). However, they may overlook biophysical stresses. Biophysical approaches assess environmental stresses on biological/physical systems from climate variables (Smit and Wandel, 2006). But focusing only on biophysical factors can misrepresent complex social contexts shaping climate risks and adaptation.

Both socioeconomic and biophysical perspectives are relevant - socioeconomic analyses understand vulnerability contexts (Rottenburg et al., 2011), while biophysical assessments inform coping strategies (Smit and Wandel, 2006). Therefore, this study integrates both in assessing the gender dimensions of vulnerability. A holistic view recognizes vulnerabilities arise from dynamic social and environmental interactions.

2.1.4. Adaptation to Climate Change and Variability

The IPCC defines adaptation as adjustments in ecological, social, or economic systems in response to actual or anticipated climate impacts (Oppenheimer et al., 2014). Its goal is to decrease vulnerability to climate change over time. This study conceptualizes adaptation to climate change as processes by which smallholder farmers' moderate potential damages from

climate impacts on their livelihoods. This involves transformations in livelihoods, behaviors and economic structures with the anticipated outcome of increasing resilience to climate change over the long run.

Smit and Wandel identify two types of adaptation based on timing of response. Reactive adaptation constitutes immediate responses to changes in climate conditions, often aimed at recovering resilience. Proactive adaptation more broadly seeks to preemptively reduce future climate hazards and vulnerabilities through forward-looking decision making (Smit and Wandel, 2006). This includes long-term planning to bolster adaptive capacities and better manage climate change impacts.

In summary, adaptation entails adjustments at ecological, social and economic levels to moderate damages from climate stimuli. For smallholders, it takes the form of livelihood, behavioral and economic adjustments to build resilience to climate change impacts. Adaptation can be reactive and aim to recover resilience during climate fluctuations, or proactive through anticipatory decision making to strengthen long-term adaptive capacities. The overarching goal is to decrease vulnerability and increase sustainability over time.

2.1.5. Impact Evaluation

Impact evaluation aims to determine the causal effect of an intervention on outcomes of interest (Gertler et al., 2016). It poses the question: what would outcomes have been in the absence of an intervention? Through comparison, impact evaluation seeks to isolate the net changes in outcomes directly attributable to a given intervention. The goal is to assess the impact or effect of the intervention on households that is exclusively due to the intervention.

Welfare encompasses non-monetary dimensions like freedom, health, education linked to income, but which cannot be captured by simple monetary measures (Deaton and Zaidi, 2002). However, given the multidimensional nature of welfare and how adaptation strategies can impact household well-being in various ways, this study focuses the discussion on monetary indicators. Specifically, it will evaluate the impact of adaptation strategies on income and consumption expenditures per adult equivalent (Okwi et al, 2006).

This provides a quantified approach to determine the counterfactual - what household welfare levels would be without the adaptation strategies. The study aims to isolate the attributable net

impacts in order to evaluate the causal effect of different adaptation options on targeted economic outcomes that influence welfare. In doing so, it will seek to answer questions about how adaptation strategies change welfare levels for beneficiaries.

2.2. Gender in Ethiopian Climate Change Policies

Ethiopia has demonstrated commitment to integrating gender in climate change and environmental policies by signing major international agreements on these issues and through domestic actions. One of the first key policies was Ethiopia's 1997 Environmental Policy. This represents the country's principled approach to pursuing sustainable socioeconomic development through sound management and use of natural, cultural and built resources, and protecting the overall environment (FDRE, 1997).

The policy ensured social and gender concerns were mainstreamed as cross-cutting issues. It identified four objectives in this regard: Ensure formal and informal training in environmental and resource management incorporate methods for assessing and addressing inequalities. Develop environmental awareness and public education programs that engage both men and women across all segments of society. Require all policies, programs and projects to undergo impact evaluations maximizing equitable outcomes for marginalized groups. Facilitate women's participation in all aspects of environmental governance and resource management across society. By emphasizing sustainability, social inclusiveness and gender equality, this seminal policy demonstrated Ethiopia's early commitment to addressing climate challenges and environmental degradation in a manner respectful of socioeconomic vulnerabilities and attentive to empowering women. It set out a progressive vision and implementation framework.

Ethiopia has established a nationwide climate change coordination mechanism and community network to address climate change impacts. It submitted both a National Adaptation Programme of Action (NAPA) and mitigation plan to the UNFCCC (Gebreegziabher et al., 2011). The NAPA prioritized urgent actions to adapt to adverse climate impacts, with the goal of building resilience. The 11 priority projects focused on enhancing adaptive capacities, strengthening natural resources management through community participation, expanding irrigation agriculture and rainwater harvesting, improving early warning systems and awareness raising (NMA, 2007). However, the NAPA document submitted to UNFCCC did

not explicitly consider integrating gender into priority projects, merely mentioning it as integral to all development activities (Ababa, 2007).

In 2009, Ethiopia's Environment, Forest and Climate Change Commission undertook a gender study to inform gender-sensitive adaptation decision-making. It identified three key issues: differences in adaptive needs, opportunities and capacities between women and men; ensuring equal participation and power in adaptation planning processes; and equal access to economic resources and benefits from adaptation programs. This signaled Ethiopia's growing recognition that climate adaptation strategies must consider social differentiation and power dynamics to effectively build resilience for all vulnerable groups, including addressing the differentiated gendered impacts of climate change and empowering women's agencies in adaptation governance (EFCCC, 2018).

Ethiopia developed the Climate Resilient Green Economy (CRGE) strategy in 2011 to reduce GHG emissions, unsustainable resource use and achieve middle-income status by 2025 through green development. The sector-based strategy has four pillars: agriculture, forestry, power and transport. Gender is considered in only one pillar (power), with minimal focus on integrating women. Initiative two promotes efficient stoves to reduce biomass usage, rural energy's primary source and the second largest GHG contributor. Efficient stoves increase rural household income 10%, create a \$15 million industry, cut 50Mt CO₂ by 2030, and improve health and gender equality by reducing indoor air pollution harming mainly women and girls (Duflo et al., 2008).

Natural resource use and management differ between sexes, with depletion affecting women differently (FAO, 2014). This reinforces involving women in climate adaptation policies to reduce vulnerabilities and build capacity to respond to current and future climate impacts through sustainable development (Roehr, 2007). Adaptation requires expanding human capabilities, strengthening institutions, and sound economic and natural resource management (Adger et al., 2005). Integrating climate issues into national policies ensures coherence between adaptation and poverty reduction needs. While policies recognize gender impacts, greater focus is needed on women as agents of response. Gender equality is key to effective strategy design, implementation, monitoring and evaluation. The framework established in

Ethiopia's policies provides an opportunity to strengthen consideration of women in climate action from impacts to empowerment.

In summary, Ethiopia's national climate change and environmental policies lay an important foundation for mainstreaming gender considerations. While earlier efforts centered on assessing different climate impacts on women and men, policy frameworks now recognize the critical role of women as agents of response. By establishing principles of social inclusiveness, participation and empowerment, laws and strategies create opportunities to strengthen focus on women in climate action - from understanding differentiated vulnerabilities to fostering women's leadership in adaptation. One can thus conclude that promoting gender equality is key to the effective design, rollout, oversight and assessment of climate strategies, programs and initiatives. National commitments demonstrate growth in conceptualizing gender as a cross-cutting issue in building resilience, rather than a separate concern. Continued progress requires maintaining this integrated approach and fully harnessing women's voices, priorities and capacities across all phases of climate governance and action. The foundation laid emphasizes that attaining inclusive, sustainable climate outcomes demands recognizing women not just as beneficiaries but importantly as leaders and decision-makers.

2.3. Theoretical Frameworks

The Gender, Environment, and Development (GED) approach emphasizes enabling equitable participation to address environmental changes' disproportionate impacts across gender identities. This perspective emerged from feminist movements advocating more balanced power relationships (Tong, 2009). Feminism encompasses diverse theories seeking social, economic, and political empowerment regardless of gender. Three prominent theories conceptualize gender and climate change. Ecofeminism links domination across gender identities and nature. Feminist political ecology examines how social roles shape vulnerability to environmental shifts. Feminist intersectionality considers gender intersecting with other identities like socioeconomic class or ethnicity in structuring power. These theories provide a framework to analyze factors influencing vulnerability to climate stressors, capacity to respond to impacts from a gender-inclusive lens. They aid understanding root causes of inequitable outcomes and crafting solutions respecting diversity. Theories frame how social constructions of roles relate to the environment and adaptation. This study draws on their

perspectives to characterize experiences across gender identities within Ethiopia's agricultural system and options promoting inclusive participation and rights. Overall, the GED and feminist theories emphasize a holistic understanding of gender as a spectrum, to comprehensively address disproportionate environmental impacts experienced across different identities.

2.3.1. Eco-feminism

Early feminist theories of development emerged in the 20th century, informed by scholars like Ester Boserup examining women's economic roles. The Women in Development (WID) approach aimed to improve development outcomes through women-specific projects within existing structures. Its key idea was enhancing women's economic participation strengthens equity (Flanagan, 2013). In the 1980s, perspectives shifted to a more inclusive Gender and Development (GAD) framework. GAD recognized women's productive and reproductive contributions while critically examining power imbalances underlying oppression (Sturgeon, 2016). It sought equitable development by addressing unequal gender relations structuring women's marginalization. Both women and men were framed as agents of change.

Concurrently, more holistic theories linked gender, environment and development. Known as ecofeminism or GED, these perspectives notably drew connections between women's oppression and environmental domination (Manion, 2002). A significant development was conceptualizing gender not just as an individual trait but as a system organizing control dynamics. This framed an essential shift in feminist environmental activism - from assessing climate impacts on women to critically interrogating power relations influencing vulnerability and adaptation across societies (Manion, 2002; Gaard, 2015). Together, these evolving theories progressively centered issues of inequity, power and social relations within development and environmental change - offering analytical lenses still critical to gender-just climate policy and action today.

In the 1980s-early 1990s, ecofeminism predominantly framed the relationship between women's oppression and environmental degradation stemming from patriarchal social systems (Tong, 2009). A core ecofeminist argument stressed that women experience disproportionate impacts as primary caregivers and managers of household sustainability (Arora-Jonsson, 2011). Mellor (1997) and Manion (2002) argued that as resources diminish under ecological

stresses like climate change, marginalized groups suffer most acutely. Manion (2002) particularly noted oppressed peoples bear heavier burdens, facing further disadvantage relative to their oppressors. Ecofeminists maintained certain ecological issues, including climate change, differentially harm women more severely than men. This is because women devote more time to unpaid household and care work essential for family welfare and food security. During these duties, climate disruptions like unreliable water sources, depleted food storage, vanishing forests and less productive farmland due to weather shifts undermine household sustainability - consequently impacting women's responsibilities and livelihood security to a greater degree than men (Rocheleau et al., 2016).

In the context of this study, ecofeminism provides a critical lens for understanding why male- and female-headed households in North Wollo Zone experience climate change differently and adopt distinct adaptation strategies. The theory highlights how entrenched gender roles, unequal access to land, credit, information, and decision-making power shape differential vulnerability and adaptive capacity. In rural Ethiopia, especially in North Wollo where rain-fed agriculture dominates, women often bear the responsibility for food provision, water collection, and household care. Climate-induced resource scarcity therefore places heavier labor and emotional burdens on female-headed households, constraining their ability to diversify livelihoods or invest in technological solutions. At the same time, structural barriers such as limited institutional support, cultural norms, and exclusion from extension services reduce women's participation in formal adaptation programs. Thus, ecofeminism helps explain not only why female-headed households may face higher vulnerability, but also how unequal power relations influence adaptation choices and ultimately affect household welfare outcomes. By applying ecofeminist insights, this study situates gender as a central analytical category in examining the welfare impacts of climate adaptation strategies and underscores the need for gender-responsive policies that address both environmental challenges and social inequalities.

2.3.2. Feminist Political Ecology

Feminist Political Ecology (FPE) emerged in the mid-1990s as a feminist lens applied to political ecology (Rocheleau et al., 2013). Political ecology initially developed in human geography during the 1980s to critically examine power dynamics shaping unequal access to

and control over resources across scales (Castree and Braun, 2001). FPE brings feminist theory, goals and analyses into political ecology. It advocates for gender equity and social justice in environmental change. Sundberg (2017) conceptualizes FPE as locating gender alongside other factors like class and race that political ecology considers important in constructing resource access, control and knowledge, as well as environmental relations. FPE draws from women's grassroots involvement in local environmental struggles and movements. It maintains disasters lay bare gender and other forms of social differentiation. Current gender, climate and disaster discourses often center poor rural women in the global South severely impacted by climate variability and change. Bankoff and others argue FPE illuminates how heterogeneous social groups differentially experience and shape environmental issues based on their positions and identities (Bankoff et al., 2013). It provides a framework for systematic gender critiques of political ecological questions like vulnerability, resilience and adaptation to climate change from the perspectives of marginalized populations.

FPE scholars argue that recognizing women's roles as environmental managers is critical to effective adaptation and resilience programs. They maintain women and gender specialists must be meaningfully included in all climate-related decision making (Röhr et al., 2008). Enarson and Morrow (1998), contested that gendered vulnerability stems not from singular attributes but from socially differentiated patterns of practices, norms and power dynamics that disadvantage some groups more than others. FPE emphasizes the need to acknowledge diverse vulnerable positions beyond generalized 'disaster victim' categories (Arora-Jonsson, 2011; Resurrección, 2017). In their seminal work, Rocheleau, Thomas-Slayter and Wangari explored three core FPE concerns regarding climate change: (1) gendered environmental knowledge and practices in adaptation; (2) unequal resource access and vulnerability linked to gender; and (3) women's roles in climate policies and programs across scales (Sundberg, 2017).

In the context of this study, Feminist Political Ecology (FPE) is highly relevant for analyzing how gendered power relations shape access to resources, adaptation choices, and welfare outcomes among male- and female-headed households in the North Wollo Zone. The region is characterized by land scarcity, reliance on rain-fed agriculture, and institutional structures that often privilege male farmers in terms of access to land rights, credit, extension services, and climate information. FPE helps to explain why female-headed households, despite possessing rich indigenous environmental knowledge, are frequently marginalized in decision-making

spaces and excluded from adaptation programs. This framework also highlights how cultural norms and local governance systems influence who controls productive assets and who bears the burden of climate-related shocks. By recognizing that vulnerability and adaptation are socially constructed rather than gender-neutral, FPE enables this study to move beyond describing differences between men and women to uncovering the underlying political, economic, and institutional factors that produce those differences. Therefore, applying FPE allows this research to critically assess not only the gender-differentiated impacts of climate change but also how adaptation strategies themselves may reproduce inequality or enhance household welfare depending on how power and resources are distributed.

2.3.3. Feminist Intersectional Theory

Feminist intersectional theory, introduced by Crenshaw in 1991, builds upon diverse feminist perspectives examining gender's interplay with other factors shaping oppression. Where radical feminism centered patriarchy, Marxist feminism highlighted class, and black feminism prioritized race, intersectionality emerged as a framework acknowledging multiple, interlocking aspects of identity and power relations (Tong, 2009). It is grounded in feminist understandings of how power and knowledge are constructed (Kaijser and Kronsell, 2014). Davis (2008) characterizes intersectionality as examining gender's interaction with other identity categories in peoples' lives, social practices, policies, cultures and ideologies - and how these intersections perpetuate or dismantle power imbalances. Further, as Chaplin et al. (2019) notes, intersectionality provides an approach for considering intra-group differences and how myriad identity axes together influence individuals' and collectivities' relationships to power and marginalization. Rather than treating gender as a singular or primary variable, intersectional theory recognizes the complexity of social locations and advocates comprehensive analysis of how gender intersects with and amplifies other forms of domination and privilege across differing social contexts.

Intersectional theory emphasizes that power relations are constantly renegotiated and how individuals and groups can experience both power and domination simultaneously (Chaplin et al., 2019). Social groups are neither homogeneous nor passive. Intersectional approaches recognize this complexity by considering historical, cultural, social and political contexts. This framework offers a means to understand and respond to diverse lived experiences. It fosters

awareness of peoples' needs, identities, capabilities and realities - informing more targeted and equitable policies and programming. Taking a systemic view of power structures underpinning social categorizations, intersectional analysis also examines how these are reinforced or challenged in the context of climate change (Kaijser and Kronsell, 2014). By acknowledging intragroup differences and multiple fluid aspects of identity, intersectional thinking supports nuanced, context-specific climate governance, attentive to heterogeneous vulnerabilities and capacities. It encourages policymaking inclusive of all members of society to build resilience for present and future generations.

Overall, intersectionality moves beyond simplistic analyses to recognize dynamic, interlinked social constructions of disadvantage and privilege shaping climate impacts and adaptive processes differently across diverse populations. Responsibility and decision-making related to climate change can reflect social structures based on characteristics like gender, socioeconomic status, ethnicity, nationality, ability, sexual orientation, age and location. Moreover, climate impacts and adaptation practices are shaped by these social structures as climate issues are contextualized through a social and gendered lens (Kaijser and Kronsell, 2014). From an intersectional view, how individuals relate to climate change depends on their positioning within context-specific power arrangements tied to social categorizations.

Intersectional approaches aid understanding differentiated root causes of vulnerability and resilience, and determining salient factors in a given setting. Hankivsky (2014) noted vulnerability to climate change or encounters with adaptation results from multiple intersecting variables including decision-making power, responsibilities and roles. Chaplin et al. (2019) observed climate hazards exacerbate pre-existing inequities, threatening groups facing highest risks and needing greatest flexibility - often marginalized populations confronting barriers to rights like women, disabled people, children, elders, minorities and others. Elmhirst (2015) added marginalized individuals are less able to relocate from climate impacts and have poorer prospects if displaced due to weather extremes. Overall, intersectional framings recognize climate issues amplify social differentiation, demanding gender-inclusive and equitable solutions attentive to diverse local lived experiences.

In the context of this study, feminist intersectional theory offers a crucial framework for understanding why male- and female-headed households in North Wollo do not experience

climate change impacts or adaptation opportunities uniformly. In this region, climate vulnerability is not determined by gender alone, but by the intersections of gender with other structural factors such as access to land, wealth status, education, marital status, household labor responsibilities, institutional support, and social norms. For example, some female-headed households may be widowed, land-poor, elderly, or excluded from community decision-making, making them more vulnerable than other women who have better social networks or resource access. Likewise, not all male-headed households have equal adaptive capacity young, landless, or resource-poor men may also face constraints. Intersectional theory helps this study move beyond a simple “men vs. women” comparison to reveal how multiple layers of privilege and marginalization shape who is most exposed to climate risks, who can implement adaptation strategies, and who ultimately achieves better welfare outcomes. By applying an intersectional lens, this research identifies the specific social, economic, institutional, and cultural configurations that determine differentiated vulnerability and adaptive capacity in North Wollo, thereby informing more targeted, equitable, and gender-responsive climate adaptation policies.

2.4. Analytical Frameworks

2.4.1. Approaches of Measuring Vulnerability to CVC

Measuring vulnerability to climate variability and change (CVC) requires integrating interactions between human and natural systems within societal contexts. It involves characterizing exposure, sensitivity and adaptive capacity across socio-economic and biophysical systems. There are two main approaches: indicator and econometric methods (Deressa and Hassan, 2010). Indicators are commonly used since vulnerability is multidimensional and not directly observable (Hinkel, 2011). This involves selecting relevant metrics to assess risk. Hoddinott and Quisumbing (2003) outline econometric approaches including: expected poverty modeling; expected utility analysis; and uninsured exposure modeling. These evaluate vulnerability levels across social groups using household survey data.

However, limitations exist. Cross-sectional data in expected poverty modeling assumes temporal variance is captured. Expected utility is difficult to calculate. And uninsured exposure modeling is ex-post rather than anticipatory, requiring panel data for robust analysis

(Hoddinott and Quisumbing, 2003). Both approaches provide insights if applied cognizant of their constraints. A holistic understanding of vulnerability integrates biophysical, economic and social factors shaping differential risk experiences across populations over time under CVC.

The indicator approach involves selecting components an analyst deems representative of vulnerability and then computing scores for these indicators (Hinkel, 2011). Indicators are straightforward to apply and meaningful for integrating myriad physical and social factors contributing to climate vulnerability into a composite index (Cutter et al., 2009). A composite score provides advantage in capturing phenomena not represented by any singular metric. However, indicators rely on subjective selection and weighting of components (Hinkel, 2011). While useful for comparing relative vulnerability of systems to climate changes within particular places and times, performance can vary depending on indicator choice and score methodologies.

To minimize subjectivity, robust indicator frameworks apply transparent, replicable selection criteria and scoring anchored in vulnerability theory (IPCC, 2014). Sensitivity testing of component inclusion further bolsters credibility. When combined with qualitative methods to contextualize lived experiences, indicator approaches remain valuable for monitoring systems' evolving exposure, sensitivity and adaptive capacity over time under climate pressures (Niang et al., 2014).

Several studies have effectively applied indicator approaches to measure local-scale vulnerability to climate change (Alhassan et al., 2019; Bedeke et al., 2020; Simane et al., 2016). In Ghana, Alhassan et al. (2019) used indicators of land size, access to credit, education and weather information to explore factors impacting smallholder farmers' vulnerability. The study suggested identifying underlying causes and drivers of vulnerability through indicators can inform efforts to reduce climate impacts. Panthi et al. (2016) connected indicators to survey vulnerability differences among mixed crop-livestock producers across agroecological zones in Nepal. The research concluded indicators effectively compare climate vulnerability variations to mobilize resources building farmer resilience.

This study adopted an indicator-based method to measure and compare vulnerability of male- and female-headed households to climate variability and change. Vulnerability drivers are

location-specific and community-dependent (Panthi et al., 2016). Indicators help recognize highly vulnerable places, as Hinkel (2011) noted. Importantly, Smit and Wandel (2006) and Gallopín (2006) observed the indicator approach aims not just to rank vulnerability but depict underlying sources and causes to inform targeted adaptation planning.

Overall, when combined with qualitative data, indicator methods provide useful insights into differential exposures, sensitivities and adaptive capacities evolving over time and space under a changing climate. Indicators are suitable for local-scale vulnerability assessment where social and biophysical variables can be manageably operationalized (Rottenburg et al., 2011). Comparing components and results from different composite indices is crucial for capturing key vulnerability drivers, as multiple frameworks emerge for quantifying climate vulnerability (Baptista, 2014).

For example, social vulnerability indices tend to focus on hazard-loss appraisals using economic metrics, lacking exposure indicators (Ge et al., 2013). Meanwhile, climate vulnerability indices are applied to evaluate spatial-temporal differences but often exclude socioeconomic data (Pandey and Jha, 2012). Conversely, livelihood vulnerability indices incorporate diverse social, economic, physical and climatic factors considered influential for vulnerability (Hahn et al., 2009). This comprehensive approach is easily understood and applied for understanding male and female farmers' context-specific risk experiences. Selecting or developing an indicator framework requires evaluating which components and methodologies most meaningfully reflect local vulnerability dynamics to inform context-appropriate, gender-inclusive responses. A mixed methods approach combining qualitative data strengthens indicator-based assessments.

Selection of vulnerability indicators

The selection of "indicators" to be used in the vulnerability index construction is an important component in vulnerability estimates. Any incorporated indicator should represent a household's adaptive capacity, sensitivity, or exposure to climate change.

Adaptive capacity denotes a system's ability to successfully adjust to climate change impacts while coping with consequences (Gallopín, 2006). Generally, lower adaptive capacity equates to increased vulnerability. Hahn et al. (2009) measured adaptive capacity using socio-demographic characteristics, livelihoods, and social networks. Zeleke et al. (2023) also

outlined indicators like socio-demographic conditions, wealth, income, technology, infrastructure, and institutional/social networks. Additional indicators have been employed elsewhere as well (Alhassan et al., 2019; Amare and Simane, 2017; Asfaw et al., 2021; Bedeke et al., 2020).

Sensitivity refers to the degree to which a system is adversely or positively impacted by climate change or variability (Fellmann, 2012; Gallopín, 2006). It is largely dictated by a system's ecological and socioeconomic conditions, as effects may be immediate or lagged. Highly sensitive systems are more prone to high vulnerability given the strong correlation between sensitivity and vulnerability (Hahn et al., 2009). To construct household sensitivity in the current study, indicators focused on water, food and health were included, aligning with factors used in other research (Amare and Simane, 2017; Bedeke et al., 2020; Hahn et al., 2009). Systems that are very reliant on climate-influenced resources for basic needs like water, food and health are more sensitive to climate impacts. Incorporating such sector-specific indicators provides a way to quantitatively represent households' predispositions based on their contextual circumstances.

Climate change exposure refers to the degree and character of a system's exposure to meaningful climate fluctuations (Oppenheimer et al., 2014). It depicts the connection between a system and climatic drivers. Variables such as precipitation, minimum and maximum temperatures, floods, droughts, land degradation, and crop losses were used in this study to assess a system's exposure to climate change. Similarly, farmers with limited ability to take preventative actions due to a lack of knowledge about trends in climatic factors like temperature and rainfall are more prone to impacts. Relationships between these exposure components and climate vulnerability are anticipated to be positive. Systems facing greater changes in climate drivers with which they must contend are theoretically more exposed, incorporated through measurable indicators that capture fluctuations in relevant local climatic and environmental conditions.

In this study, indicators were captured through both household survey data and secondary sources to represent the three components of vulnerability: exposure, sensitivity, and adaptive capacity. Exposure indicators, such as the frequency of droughts, floods, and crop failures, were obtained from household reports and complemented with climate records from the

National Meteorological Agency. Sensitivity indicators, including household size, dependency ratio, proportion of income from rain-fed agriculture, and landholding size, were gathered from household survey responses. Adaptive capacity indicators, such as education level of the household head, access to extension services, membership in farmer cooperatives, credit use, and ownership of productive assets, were also captured through survey data. To ensure gender relevance, the indicators reflected structural differences faced by male- and female-headed households, particularly in access to land, credit, extension, and decision-making power. These indicators were then standardized and aggregated to construct composite vulnerability indices that allow for comparison between male- and female-headed households.

Livelihood Vulnerability Index (LVI)

The Livelihood Vulnerability Index (LVI) applies the Sustainable Livelihood Approach, which examines five types of household assets - natural, physical, human, social and financial capital. It incorporates additional dimensions of climate variability into vulnerability assessment (Rottenburg et al., 2011; Fellmann, 2012). The LVI comprises eight main components: socio-demographic profile, livelihood strategy, social networks, natural capital, health, nutrition, water, and natural hazards/climate variability (Hahn et al., 2009). Each component contains various sub-indicators.

Indicators are normalized using a min-max method for calculation simplicity. This enhances replicability across contexts by adjusting factors relevant to local conditions (Hahn et al., 2009). The index is robust and adaptable, capturing multidimensional household vulnerability driven by intersecting socioeconomic and biophysical factors shaping risk exposure and resilience over time. When combined with qualitative methods, the LVI provides an effective means to compare relative vulnerability, identify key determinants, and develop targeted, tailored adaptation strategies attentive to heterogeneous community needs.

Indicators in the LVI can be equally weighted, which has practical advantages for assessment (Hahn et al., 2009). Beyond incorporating secondary data on hazards like drought, flooding, temperature and precipitation patterns, the LVI integrates primary household-level data collected via surveys (Shah et al., 2013). This comparative, mixed methods approach has proven valuable across diverse settings and farming household types in resource-constrained areas (Simane et al., 2016; Bedeke et al., 2020).

As a result, the replicable yet adaptable LVI provides meaningful insights for comparing relative climate vulnerability between distinct communities (Antwi-Agyei et al., 2013). When combined with participatory methods, it fosters understanding of locally-specific drivers and differentiated risks to craft inclusive adaptation strategies addressing heterogeneous vulnerability. Weighting indicators based on community priorities further bolsters the index's policy relevance and utility. Overall, the LVI remains an effective tool for vulnerability monitoring and gender-sensitive climate resilience planning.

Vulnerability Index of IPCC (VI-IPCC)

The VI-IPCC provides an alternative framework to combine indicators into a single score based on IPCC's vulnerability conceptualization (IPCC, 2007). Initially applied at the local level by Hahn et al. (2009), the VI-IPCC assesses household vulnerability in terms of exposure, sensitivity and adaptive capacity. This incorporates an additional dimension of adaptive capacity into livelihood vulnerability analysis. Within VI-IPCC, exposure comprises natural threats and climate variability, while sensitivity includes food, water and health stresses. Adaptive capacity reflects social networks and livelihood diversification relative to exposure and sensitivity levels.

The VI-IPCC has a simple aggregation method, differing from LVI in how adaptive capacity influences the overall index. Higher adaptive capacity denotes lower vulnerability. This approach streamlines understanding how climate-exposed communities simultaneously cope with changing conditions. Several studies have applied VI-IPCC (Alhassan et al., 2019; Bedeke et al., 2020) to evaluate how climate factors like rising temperatures and rainfall variability reduce adaptive capacity and increase vulnerability across agro ecological zones and amongst smallholders.

Ultimately, the VI-IPCC provides meaningful insights by integrating exposure, sensitivity and adaptive capacity dimensions of household-level climate risk.

While the IPCC vulnerability index conceptualizes vulnerability as a function of exposure, sensitivity, and adaptive capacity, the Livelihood Vulnerability Index (LVI) extends this framework to the household level by incorporating a wider range of livelihood dimensions such as health, food, water, and social networks. The LVI can therefore be seen as a practical

operationalization of the IPCC framework, offering more detailed insights into household-level vulnerabilities, which can later be reorganized into the IPCC's three-component structure for comparability.

2.4.2. Methods to Identify Determinants of Choice of CVC Adaptation Strategies

Econometric models can identify determinants of adaptation choice. Univariate probit/logit regression models estimate choice of discrete adaptation options as functions of independent variables. However, farmers may adapt portfolios of complementary practices. Univariate models overlook potential relationships between unobserved disturbance factors influencing different strategies, risking statistical bias and inefficiency (Temesgen et al., 2009).

When assessing multiple adaptation options, multivariate choice models like multinomial logit (MNL) or multivariate probit (MVP) are most appropriate. Both MNL and MVP are commonly used to analyze distributions with multiple, unordered response categories and interdependent adaptation portfolios (Belay et al., 2017).

However, MNL assumes independence of irrelevant alternatives, limiting its ability to assess adaptation choice determinants and error term relationships (Cheng and Long, 2007). Therefore, this study was using MVP. MVP accounts for correlation between error terms, overcoming limitations of univariate and MNL approaches (Yirga, 2020; Mihretu et al, 2021). MVP models the influence of independent variables on each adaptation option while allowing error terms to be fully correlated (Cappellari and Jenkins, 2003). It generalizes probit to jointly analyze multiple binary outcomes. The MVP dependent variable was indicating user/non-user of specific adaptation strategies by male- and female-headed households. By identifying key determinants of adaptation choices across social groups, MVP enhances understanding of differentiated vulnerabilities and supports design of inclusive, tailored climate resilience interventions.

The Multivariate Probit (MVP) model was employed instead of the Multinomial Logit (MNL) model because adaptation strategies among smallholder farmers are not mutually exclusive. Farmers in the study area often adopt multiple strategies simultaneously, such as combining crop diversification with soil and water conservation. Unlike the MNL model, which assumes a single choice among alternatives and imposes the restrictive independence of irrelevant

alternatives (IIA) property, the MVP model allows for simultaneous decisions and explicitly accounts for correlations between the error terms of different adaptation equations. This feature makes MVP more appropriate for capturing complementarities or trade-offs among adaptation strategies and for reflecting the real-world decision-making context of farm households.

2.4.3. Methods to Measuring the Impact of CVC Adaptation Strategies on Welfare

Measuring the impact of adaptation strategies on household welfare using non-experimental data is challenging due to self-selection bias and the lack of suitable counterfactual scenarios. Estimating the effect of an adaptation practice on welfare outcomes is difficult without observing what would have happened to users had they not adapted (Manda, 2016). In other words, we cannot observe the counterfactual welfare outcomes for users under non-use conditions. Experimental studies address this by randomly assigning treatment and control status to households, ensuring the outcomes observed for controls without adaptation are statistically comparable to potential outcomes with adaptation. However, in reality, adaptation choices are not randomly distributed between users and non-users. Households self-select into use based on their own information and characteristics, so users and non-users may inherently differ systematically (Asmare et al., 2019).

Econometric techniques address self-selection bias and lack of proper counterfactuals in assessing adaptation strategy impacts on household welfare. Common approaches include propensity score matching (PSM) and endogenous switching regression models. While PSM controls for observable differences between treated and untreated groups, its limitation is neglecting unobserved heterogeneity (Abdulai & Huffman, 2014). Endogenous switching regression reduces selection bias by controlling for both observed and unobserved differences between treatment groups, despite distributional and exclusion restrictions (Asmare et al., 2019; Ndiritu & Muricho, 2021).

PSM relies on the conditional independence and common support assumptions, meaning that after controlling for observed characteristics, treatment assignment is as good as random. However, it cannot correct for bias arising from unobserved heterogeneity. By contrast, the ESR model accounts for both observed and unobserved heterogeneity by jointly estimating the selection and outcome equations, under the assumptions of joint normality of error terms and

the availability of at least one valid instrumental variable. Thus, while PSM provides a non-parametric check on observed differences, ESR is more robust where self-selection on unobservable is likely.

In this study, climate adaptation techniques for smallholders are not randomly assigned. Instead, households self-select into using or not using strategies. This self-selection implies potential systematic differences between user and non-user groups. Therefore, to account for observable and unobserved sources of heterogeneity, this study was employed an endogenous switching regression model to estimate the impact of adaptation techniques on household welfare.

2.5. Empirical Review

2.5.1. Gender Dimensions of Vulnerability to Climate Change and Variability

Vulnerability to climate change and variability differs across households with different gender heads, such as male-headed and female-headed households. It also varies depending on the type and severity of extreme climate events experienced. A study by Suhiyini et al. (2019) took a gender perspective in measuring vulnerability of smallholder farmers in Ghana using the livelihood vulnerability framework. They found differences in vulnerability levels between female-headed and male-headed households. Specifically, they discovered that female-headed households were highly vulnerable in terms of livelihood activities, social systems, water, and nutrition. However, male-headed households were found to be more vulnerable to health impacts. The researchers argued that although both gender groups experienced the same climate conditions, female-headed households were more sensitive to climate change and variability impacts due to having the lowest adaptive capacity. This made them extremely vulnerable in terms of the contributing factors of vulnerability, despite exposure to common climate risks.

Similarly, a study by Balikoowa et al. (2019) analyzed gender-differentiated vulnerability to climate change information collected from 735 household units across four areas in Eastern Uganda. They used a cross-sectional survey design to develop a gender vulnerability framework for comparing vulnerability between male-headed and female-headed households. The findings showed that female-headed households were more vulnerable than male-headed

households. The researchers argued that differences in adaptive capacity were a greater cause of disparities in vulnerability between female and male-headed households, more so than either sensitivity or exposure.

Tanny et al. (2017) examined climate-induced vulnerabilities by gender in northwestern Bangladesh based on a gender vulnerability index to measure vulnerability levels. They found that 72.2% of households were highly vulnerable, with females being nearly twice as vulnerable as males. The researchers proposed that the transition of female-headed households from low to medium or high vulnerability was influenced by levels of farmland ownership and less access to credit. Similarly, a study by Garutsa et al. (2018) in Zimbabwe found that most females had no or less access to assets like land, credit, markets, and smaller decision-making control, which created distinct vulnerabilities between female and male-headed households.

A 2019 qualitative study examined gender dimensions of vulnerability to climate change in semi-arid districts of East Africa. The researchers employed a gender-oriented measurement approach to assess vulnerability. The findings showed that low-income women were the most vulnerable to climate change impacts (Rao et al., 2019). Key areas of gender disparity identified in adaptation processes included women's inadequate access to and control over natural resources, higher family work burdens such as responsibilities for water and firewood collection, high engagement in agricultural activities, and lower literacy rates. These were determined as major vulnerability-enhancing factors. Additionally, gender inequalities in wages and business opportunities were cited as other important drivers of vulnerability to climate change impacts.

A case study on gender differentiated vulnerability to climate change in East Asian countries by Paris and Rola-Rubzen (2018) found that female-headed households were more vulnerable as they faced greater constraints. These included a lack of land ownership, limited access to formal credit services, weak agricultural extension services, and heavier workloads. The most significant gender disparity identified was female-headed households' lack of access to innovative technologies through rural training programs. Both gender groups also had low access to weather-related data and were impacted by extreme flooding events. Although both were vulnerable, female-headed families faced profoundly higher vulnerability due to unequal access to and control over assets that could help mitigate climate change impacts. Another

study by Abebe and Bekele (2017) examining vulnerability of smallholder farmers to climate change in Ethiopia's central rift valley, using the vulnerability as expected poverty (VEP) approach, found that vulnerability levels differed between men and women in relation to diverse socio-economic characteristics affecting their ability to cope with climate change risks.

In conclusion, the empirical studies reviewed provide compelling evidence that vulnerability to climate change impacts varies significantly according to gender. Across multiple geographic contexts, including Africa, Asia and parts of Ethiopia, research consistently found that female-headed households faced higher levels of vulnerability compared to their male counterparts. Key factors contributing to increased vulnerability of women included unequal access to and control over productive resources like land, lower literacy rates, greater workload burdens, as well as less access to services such as agricultural extension, credit, markets and early warning weather information. The disparities in adaptive capacity between female- and male-headed households, arising from underlying socioeconomic constraints experienced disproportionately by women, emerged as a major cause of differentiation in vulnerability levels between gender groups. The findings highlight the need for gender-sensitive climate change adaptation and vulnerability reduction measures that directly address barriers limiting women's empowerment and resilience building potential. Here are some potential gaps in research on gender dimensions of climate vulnerability that could be explored in the Ethiopian context. More localized/community-level studies are needed. Most existing research focuses on national or regional levels. Understanding intra-community differences would help target interventions. Quantitative vulnerability assessments that measure and compare vulnerability indices between female- and male-headed households are limited. More empirical data is needed.

2.5.2. Gender Dimensions of Adaptation Choices to Climate Change and Variability

Several empirical studies conducted across various developing countries have shown that the adaptive capacities and adaptation measures of male-headed versus female-headed households may differ within a given socio-cultural setting. The findings of some of these studies are reviewed here.

A study in Ghana by Adzawla et al. (2019) found that common adaptation practices employed by both men and women included modifying planting dates, shifting to earlier planting,

planting early maturing and drought-tolerant seed varieties, mixed cropping, and intercropping. However, a study by McKinley et al. (2016) on gender differences in climate change perceptions and adaptation in Vietnam observed little variation overall. While there was no strong gender gap in climate change perceptions, access to climate information, or choice of adaptation practices between genders. However, small differences arose from individual adaptive capacities and specific adaptation practices adopted. This shows that while basic adaptation may involve similar practices across genders, the ability to successfully employ adaptations and tailor solutions to local needs and roles can differ due to variance in access to resources and socio-cultural influences between male and female groups in specific contexts.

For instance, a study by Aryal et al. (2014) in India found the likelihood of adopting climate change adaptation strategies significantly differed between male-headed and female-headed households in Bihar. Male farmers had better access to credit, hiring, or purchasing agricultural inputs and extension services. Similarly, Ahmed and Kifle's (2021) study in South Western Ethiopia indicated productivity factors like labor force, farm size, experience, capital levels, access to weather information, appropriate credit access, and extension contacts influenced women's choice of adaptation techniques.

Jost et al. (2016) in a study across Uganda, Ghana, and Bangladesh noted women appeared less adaptive due to financial or asset limitations, male control over information and extension facilities, and available adaptation practices increasing female labor burdens. A study by Elaine et al. (2019) in semi-arid Ghana used intra-household gender analysis and found choice of adaptation methods was influenced by socio-demographics like age, marital and employment status, further impacting decision-making and control within households.

Assan et al. (2018) found female-headed households primarily depended on loans from village savings funds and groups as an adapting strategy, versus male-headed households relying more on livestock sales. Shifting planting/harvesting dates, crop diversification, and improved varieties were also major smallholder adaptations. Comparable findings in East Africa and South Asia confirmed significant differences in choice of adaptation techniques between male-headed versus female-headed households, as well as across countries (Jeetendra et al., 2021).

Yirga (2020) evaluated gender differences in climate change adaptation strategies based on a survey of 2065 households practicing maize-legume agriculture across four regions in Ethiopia. Adaptation techniques employed differed between male-headed and female-headed households, potentially due to varying access to assets, skills, and information. The study found male-headed households were more likely to use stubble and soil water conservation practices compared to female-headed households. Gender roles and obligations influenced the differing adaptation options as availability of male and female labor impacted choices. Maintaining social norms, values, and farmers' capabilities and connections were also deemed important for promoting specialized and sustainable adaptation practices. Another study by Azeb and Frank (2016) in rural Ethiopia found that gender-based discrepancies in choice of adaptation strategies at the household level were driven by socio-cultural, economic, and institutional constraints.

In conclusion, the empirical evidence demonstrates that adaptation choices can differ between male-headed and female-headed households depending on the local social-ecological context. Gender roles, norms, access to assets and resources, labor availability, and networks all influence the adaptive capacities and options available to each group. While basic adaptation practices may overlap, tailored solutions are needed to empower equitable resilience. A key gap in research from the Ethiopian context is a lack of localized quantitative or qualitative studies examining how socio-cultural dynamics impact adaptation decision-making processes within households and communities. Future research could employ mixed methods to better understand adaptation barriers and potentials facing women, while identifying entry points for gender-transformative climate initiatives. Intervention design and evaluation should also consider gender dimensions of adaptation to strengthen equitable resilience building in Ethiopia's diverse agro-ecological zones and cultural settings. Addressing this research gap would provide critical insights for strengthening Ethiopia's climate policy and planning from a gender perspective.

2.5.3. Impact of Climate Change Adaptation Strategies on Household Welfare

Various studies have examined the impacts of climate change adaptation strategies on household income, production, and food security across developing countries. A review of some key studies follows.

Adzawla and Alhassan (2021) studied the impacts of climate adaptation on the technical efficiency of maize production in Northern Ghana using a frontier model analysis. Their findings showed that while climate adaptation techniques generally led to higher maize yields, crop rotation and row planting specifically improved the technical efficiency of maize production. Additionally, Ojo and Baiyegunhi (2020) evaluated the impact of climate adaptation on the net farm income of rice farmers in south-west Nigeria using an endogenous switching method. They found that the average net income per rice farm from those employing adaptation practices was significantly higher than from those not adapting.

Another study by (Ndiritu and Muricho, 2021) in Kenya examined the effect of climate change adaptation on food security among pastoralists using an endogenous switching regression model. The findings showed pastoralists who had not adapted were seven times more likely to be food insecure, while users of adaptation strategies were 27% more likely to be food secure compared to non-users. Additionally, Berhe et al. (2017) assessed the impacts of adaptation to climate change on income levels of pastoralist households in rural Ethiopia. Adaptation strategies were found to have increased household incomes, with forage production, access to water sources, livestock improvement, and relocation being the most influential adaptation practices.

A study by Rahman et al. (2021) in Indonesia evaluated the effect of climate change adaptation strategies on fishers' household income and food security using propensity score matching. The results demonstrated adaptation techniques had a positive and significant impact on both income and food security. Households employing adaptations exhibited improved income and food security status over non-adapters. Similarly, Ali and Erenstein (2017) found a positive and significant relationship between climate change adaptation use and food security, as well as a negative association with poverty levels, according to propensity score matching model outcomes.

A study by Ogunpaimo et al. (2021) in Nigeria using a difference-in-difference approach found the need for climate change adaptation among farming households increased with farm size, extension contact, marital status, land ownership, family size, education level, assets, and location - though these factors had mixed effects on choice of adaptation techniques. The findings showed climate adaptations helped farming households improve food security amid

challenging climatic conditions. A similar study by Diallo et al. (2020) in southern Mali evaluated the effect of adaptation strategies on household food security. The use of organic fertilizers and short-duration maize varieties was found to promote household food security.

Additionally, a 2015 study in the Nile basin of Ethiopia used an endogenous switching model to estimate impacts. The findings approved crop diversification had a positive and significant effect on farm income while decreasing on-farm labor demand (Asmare et al., 2019). The selection of crop diversification was recommended to enhance household welfare and create a resilient agricultural system.

Meanwhile, a study by Di Falco et al. (2011) utilized cross-sectional data from 1,000 households in the Ethiopian Nile basin to examine adaptation impacts on food security. By generating household-specific precipitation and temperature data with an endogenous switching model, they found a significant and non-negligible difference in food productivity between smallholders adopted versus non-adopted to climate change adaptation strategies.

In conclusion, the empirical evidence presented shows that climate change adaptation strategies can play an important role in boosting household welfare indicators like agricultural productivity, income levels, and food security status. Well-designed adaptations tailored to local context have demonstrated positive impacts on livelihood resilience for vulnerable communities. However, more research is still needed, especially within the Ethiopian context, to better understand the multi-dimensional welfare impacts of adaptation over the long-term, under dynamic social and environmental conditions. Some key gaps include a lack of household analyses disaggregated by gender; limited mixed-methods qualitative data on complex livelihood impacts; and insufficient monitoring and evaluation of existing adaptation programs and policies in Ethiopia from a welfare perspective. Addressing these knowledge gaps through localized, empirical, mixed-methods impact assessments would help strengthen evidence-based climate adaptation planning and implementation in Ethiopia. This could in turn maximize welfare co-benefits for communities facing increasing climate vulnerability.

2.6. Conceptual Framework

The conceptual framework shows the relationship between climate change vulnerability, the factors that influence household adaptation approaches, and how adaptation ultimately affects

welfare. Gender is a cross-cutting issue that impacts vulnerability levels and ability to adapt. The conceptual framework (Figure 1) guides this research based on a review of relevant literature. The IPCC (2007) defines vulnerability as a function of exposure, sensitivity and adaptive capacity. As shown in the framework, exposure pertains to risks from current and future climate variability and extremes like droughts and floods. Higher exposure influences sensitivity, as greater frequencies and intensities of climate hazards affect outcomes such as agricultural productivity and income.

Exposure also determines adaptive capacity. Better ability to implement adaptation actions can reduce damages from climate variability, building resilience to climatic risks. Adaptive capacity depends on access to resources, assets, technologies, knowledge and information. Limited adaptive capacity elevates sensitivity to climate stresses. Vulnerability is influenced by exposure to changes in rainfall and temperature patterns. This exposure can increase sensitivity and decrease adaptive capacity due to biophysical and socioeconomic factors. Gender inequality also impacts the vulnerability level.

Smallholder households' ability to adapt to climate change is influenced by various factors: Demographic Factors: Age, family size, and similar characteristics. Socioeconomic factors: Elements like income, education, and ownership of assets. Institutional factors: Access to information, credit, and agricultural extension services. Physical factors: Availability of infrastructure and technology. Additionally, gender inequality plays a significant role in shaping these adaptation factors. The strategies and measures that smallholder households adopt in response to climate change ultimately affect their welfare and livelihood outcome.

In terms of vulnerability, gender inequality serves to increase vulnerability levels through its influence on exposure and adaptive capacity. Women often have less control over resources and decision making which shapes their ability to cope with or recover from climate impacts. As primary caregivers and managers of natural resources, women's workload may increase disproportionately under climate stress with flow-on effects for livelihood security.

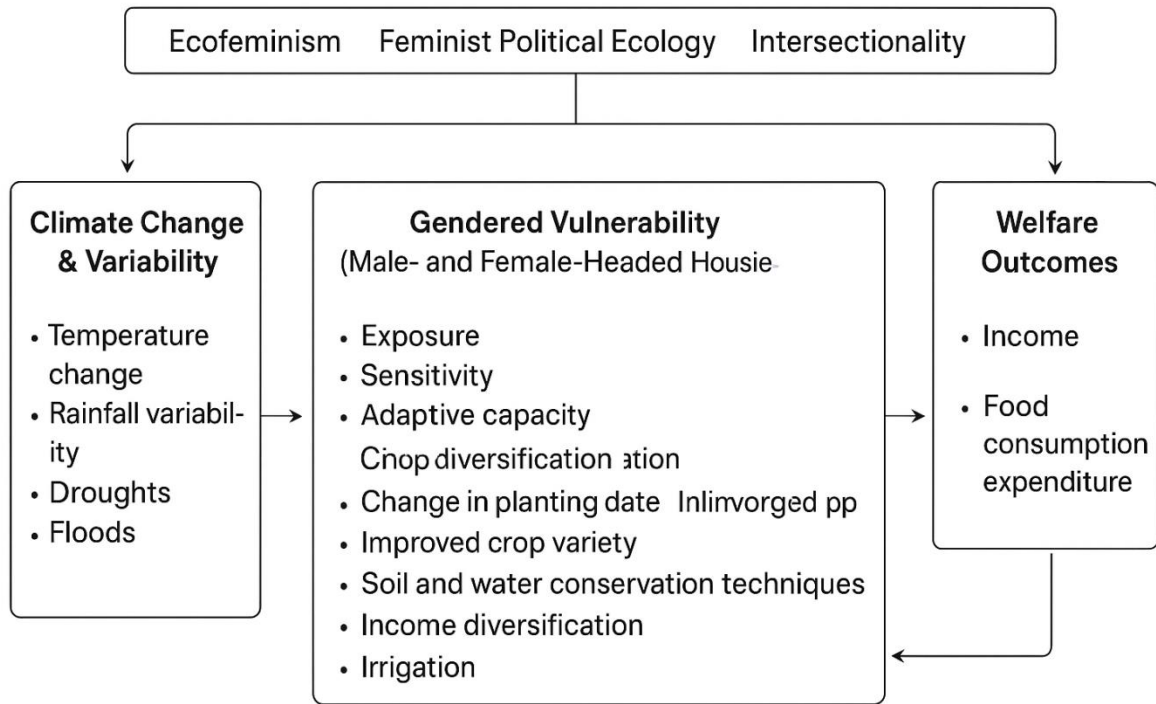
Regarding adaptation, gender inequality introduces barriers that make it more difficult for women to employ effective strategies to build resilience. Women typically have less access to information on climate threats and response options due to socio-cultural constraints. They

also tend to have limited access to financial services, technology and supporting institutions compared to men. This constrains their agency to plan and implement adaptive measures.

Physical factors like time poverty due to unbalanced domestic responsibilities and mobility restrictions imposed on women further impede their capacity to adapt. For example, women may find it challenging to diversify crops/livelihoods or access new farming areas, technologies and markets as responses to climate change impacts. At the household level, gender norms can influence decision making over adaptation choices and control of adaptation benefits. Without consideration of women's roles, the strategies selected may not address the most pressing climate risks women face or enhance their ability to cope. This can undermine intended positive outcomes for welfare.

Overall, the conceptual framework suggests gender inequality serves to exacerbate vulnerability and hamper effective adaptation through its influence on multiple social, economic and institutional domains, unless addressed in policy and program design. Recognizing women's differentiated experiences of climate impacts and responses is important.

Figure 1 Conceptual framework



Source: Related literature reviews own construct

3. RESEARCH METHODOLOGY

This chapter first describes North Wollo zone agroecology and the climate system to understand how physical systems work and affect people's livelihood. It then provides an overview of the zone demographic profiles and farming systems that shape its adaptive capacity to uncertain events. It further describes methods used to select sample households from the study population, data collection, and data analysis methods.

3.1. Description of the Study Area

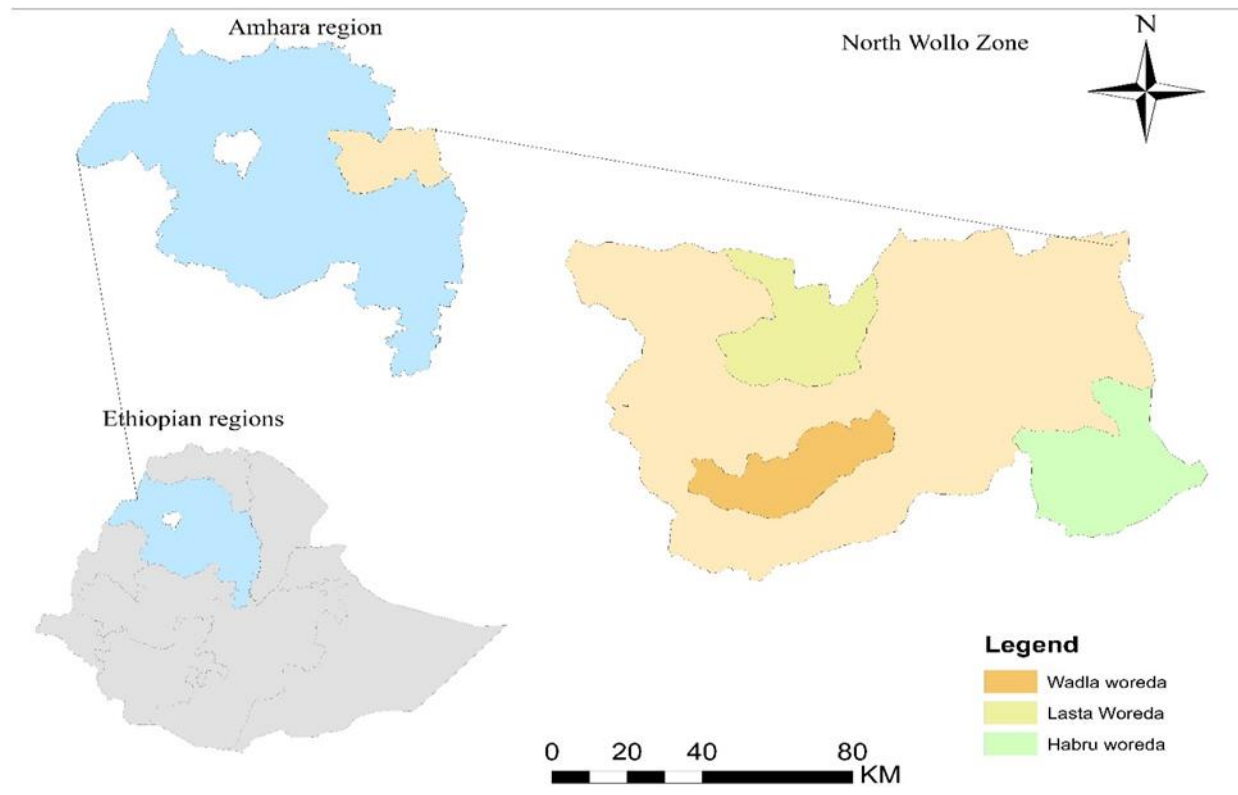
The research was conducted in North Wollo Zone, located within Amhara Regional State in northern Ethiopia. North Wollo is one of 12 administrative zones comprising Amhara Region. Geographically, it sits at 11.9°N latitude and 39.1°E longitude. North Wollo shares borders with multiple zones - South Wollo to the south, South Gondar to the west, Wag Hemera to the north, Tigray Region to the northeast, and Afar Region to the east (Fig. 2). The capital and largest city of North Wollo Zone is Woldia.

3.1.1. Biophysical Context

Agro-ecological zone

North Wollo Zone contains three main agro-ecological zones based on elevation, soil type, climate patterns and farming systems (Ferede et al., 2013). The Kolla (29% of land area) located in low lying hot to semi-arid areas faces recurrent droughts and erratic rainfall, challenging agricultural productivity. The Weina Dega (33%) consists of agricultural lands predominantly growing staples and vegetables. While climate and soils suit rainfed farming, rainfall during growing seasons is often insufficient. The highland Dega zone (38%) has lower production potential due to rapid degradation from population pressures (Wassie et al., 2021). Pulses, barley and wheat can be rainfed here. Each zone experiences distinct environmental conditions influencing crop choices and vulnerability to climate hazards like drought. The Kolla faces greatest climatic risks, while the Dega struggles with degraded soils.

Figure 2 The geographical location of the study area



Source: ARC GIS

Climate

Climate profoundly impacts land use and livelihoods in the area. Ethiopia's climate pattern varies according to topography, influencing key agricultural factors like temperature and precipitation (McSweeney et al., 2010). Analysis of data from 1992-2019 shows average annual maximum temperatures in North Wollo range from 20.6°C in highland areas to 30.4°C in lowlands (Wassie et al., 2021). Minimum temperatures vary between 7.1°C in cool highlands and 15.4°C in warmer lowlands. Precipitation totals reach a maximum of 1061.2 mm in midland zones, compared to 624.8mm in drier lowland agro-ecologies (Wassie et al., 2021). The highlands rely principally on the Belg rains for crops, while midlands and lowlands depend on the Meher season rains (Aragie and Genanu, 2017).

Seasonal rainfall distribution and amounts fluctuate considerably between years and within the Zone. This introduces uncertainty, impacting crop choices and productivity across agro-climatic areas with distinct climatic risk profiles. Understanding such climate variations is essential for analyzing vulnerability and adaptation dynamics in the region.

There are three main seasons in North Wollo zone as in most parts of Ethiopia - two wet seasons and one dry season. The main rainy season (Meher/Kiremt) occurs from mid-June to mid-September, accounting for 60-80% of annual rainfall needed for agriculture (Wassie et al., 2021). Mean annual Kiremt precipitation varies spatially from 800-1400mm. Failure of these rains can lead to food shortages until the next harvest season. A short rainy season (Belg) happens between March to May, yielding around 150mm of rain on average - though it is less dependable than Kiremt (Wassie et al., 2021). Both wet seasons are critical for crop growth and pastoral resources. The dry season (Bega) extends from December to February when temperatures rise to their maximum and rainfall decreases below 10mm on average.

Smallholders in the zone face several agricultural challenges from climate change and variability, such as diminished or erratic precipitation, warming temperatures, crop pests, livestock diseases, flooding, drought, soil erosion and degradation (Wassie et al., 2021). Current climate impacts contribute to reduced agricultural productivity. The long-term sustainability of farming in the area depends on effective adaptation strategies employed by communities.

Table 1 Major agro ecological zones in the North Wollo zone

Agro-ecological zone	Elevation (m)	Rainfall (mm/year)	Average annual Temperature (°C)
Kola (lowlands)	700-1500	201-700	28-18
Weina Dega(midlands)	1501-2300	801-1100	21-16
Dega (highlands)	2301-3200	900-1200	17-12

Source; Wassie et al. (2021)

3.1.2. Socio-Economic Context

Demographic feature

Administratively, North Wollo Zone is composed of 10 rural districts and 4 town administrations. According to the 2007 population and housing census, the total population of North Wollo Zone was 1,500,303 people (CSA, 2008). The vast majority (85.2%) reside in rural areas, while 14.8% live in urban centers. Women make up approximately 50.5% of the total population. From the total population, women account 50.5% and 49.5% lived in urban and rural area, respectively. Rural livelihoods overwhelmingly rely on subsistence agriculture and related activities. The population primarily comprises smallholder farmers cultivating

plots of less than 1 hectare. The lack of alternative income source means that households are highly sensitive to climate impacts on food and income security.

Farming systems

North Wollo zone practices mixed farming systems where livelihoods depend heavily on rain-fed agriculture. Crop production is widespread across agro-ecological zones, though some varieties are only grown at lower elevations. Main annual crops include teff, sorghum, barley, wheat, maize, beans and linseed (Bantider et al., 2011). Land remains a core family asset for combined crop farming and livestock rearing. Common animals include cattle, sheep, goats, donkeys, camels and poultry raised for food, income and as agricultural inputs. Livestock provide manure for soil fertility and fuel, while oxen are critical plowing agents. Donkeys, horses and camels facilitate transportation of people, water and produce (Bantider et al., 2011).

Strong inter-linkages exist between crops and livestock through organic fertilizer, traction, animal feed and income. Altering one component affects others. Other income sources involve local casual labor, handicrafts like weaving and construction, petty trade, selling drinks and small ruminant/cattle trading (Aragie and Genanu, 2017). Given crop-livestock integration and rain-fed nature, these climate-sensitive systems render livelihoods highly vulnerable to climatic disruptions like drought.

North Wollo Zone faces high drought vulnerability, with all rural districts among the 48 most drought-prone and food insecure in Amhara (Hailu, 2013). Over recent decades, the area has frequently experienced drought-induced disasters along with floods, landslides and crop/livestock diseases. Such risks negatively impact sizable portions of the population through reduced crop and livestock production (Hailu, 2013). Furthermore, smallholder farms consist of fragmented parcels that have been cultivated for millennia with little improved techniques. Farmers often lack sufficient resources like land, oxen and inputs to boost productivity on these holdings.

Environmental degradation, including land degradation, has exacerbated a deteriorating climate trend of more frequent drought and crop failures, leading to periodic food shortages and famines in the study area. While land situated from Kobo to Girana presents a promising

potential for agricultural growth due to relative fertility, environmental constraints and lack of livelihood resilience challenges sustainable development across much of North Wollo Zone.

3.2. Sampling and Sample Size Determination

Sampling methods were chosen to select a representative sample from the target population in a randomized, unbiased manner. A multi-stage stratified random sampling technique was used. In the first stage, North Wollo Zone's 10 districts were stratified into three strata based on agroecology - five highlands, two midlands, and three lowlands. Three districts were randomly selected representing each stratum - Wadla (highland), Lasta (midland), Habru (lowland). From each stratum, one district was randomly selected to avoid purposive bias while still ensuring that all agro-ecological zones were represented in the sample. In the second stage, lists of all rural kebeles within each district were obtained. Two kebeles were randomly selected from Wadla (25 total kebeles), Lasta (26 total), and Habru (30 total), for a total sample of six kebeles.

The third stage determined the sample size using Kothari's formula, which calculates the minimum needed to estimate a population proportion with 95% confidence and 5% precision. This yielded a required sample of 396 households.

$$n = \frac{Z^2 pqN}{e^2(N-1) + Z^2 pq} \qquad n = \frac{(1.96)^2(0.5)(0.5)106,095}{(0.05)^2(106,094) + (1.96)^2(0.5)(0.5)} = 396$$

Where n is the desired sample size; N is the total target population; Z is the standard cumulative distribution that corresponds to the level of confidence with the value of 1.96; e is the desired level of precision; p is the estimated proportion of an attribute present in the population with the value of 0.5 to get the desired minimum sample size of the households at 95% confidence level and $\pm 5\%$; q=1-p

In the fourth stage, stratify a total household in the selected districts by using a stratified sampling technique based on the gender of household heads (Table 2). Finally, a total of 396 households were randomly selected for the study using probability sampling proportionate to size. The allocation of male- versus female-headed households in the sample was determined based on their population proportions. However, the actual sample sizes of male- and female-headed households were not equal, despite being proportionately selected. This unequal

representation occurred because the average household sizes differed between male- and female-headed homes at the population level.

Table 2 Total household heads and sample size

Districts	Total HHs			Sample HHs		
	Male HHs	Female HHs	Total	Male HHs	Female HHs	Total
Wadla	25,539	6,878	32,417	86	36	122
Lasta	26,425	8,539	34,964	87	40	127
Habru	27,910	10,808	38,718	94	53	147
Total	79,874	26,225	106,095	267	129	396

Source: NWZAO (2022)

3.3. Data Sources and Collection Methods

This study utilized both primary and secondary data sources to address the research objectives. Primary data was collected through several methods. A semi-structured questionnaire was used to collect quantitative data from households. Focus group discussions were conducted separately with males and females to gain qualitative insights into perceptions, knowledge, and gender-specific experiences. Discussion guides were used to elicit participants' views. Key informant interviews were undertaken with elders, kebele leaders, and subject experts using interview schedules. These specialized informants provided context beyond household perspectives.

Secondary data provided important climate and disaster indicators to contextualize the primary data collected. Records of past drought and flood events that impacted the study area were gathered from reports unpublished by the North Wollo Zone Agriculture Office (NWZAO) in 2022. Monthly temperature and rainfall data spanning 1992 to 2020 were obtained from the National Meteorological Agency of Ethiopia for the nearest weather station in each study district. Daily maximum and minimum temperature readings, as well as total monthly rainfall, were compiled for each station over the nearly 29-year period. The meteorological data obtained from the National Meteorological Agency contained some missing monthly observations within certain years. To address this, missing values were imputed using the annual mean of the respective year, which ensured continuity of the time series without distorting long-term climate variability trends.

Survey questionnaires

A semi-structured questionnaire was used to collect quantitative data from households. The questionnaire aimed to gather information on several topics. Demographic and socioeconomic factors included questions on household characteristics like household size, education levels, occupations, income sources, and assets. This provided context on the households. Questions on adaptive capacity focused on households' skills, resources, and ability to adapt to changes. This helped assess their vulnerability and resilience. Issues around climate change exposure and sensitivity examined households' experiences with climate hazards as well as dependence on climate-sensitive livelihoods like agriculture and access to services. Adaptation strategies addressed what measures households have implemented to cope with or benefit from climate impacts. Determinant factors investigated what internal or external conditions influenced households' adaptive actions.

The first draft questionnaire was developed based on the study objectives and an extensive literature review on similar research tools. A pre-test was administered to 2% of the sampling frame who did not participate in the main survey. This pilot testing identified any unclear, poorly worded, or complex questions. Their input was used to refine the wording and response options before finalizing the standardized questionnaire for wider distribution to sampled households. This rigorous development and validation process aimed to collect accurate and useful quantitative data.

Qualitative data is necessary to collect and analyze as it provides the researchers with insight into the trends of thoughts, attitudes, and perceptions respondents hold. The aim is to explore, on a broader scale, major issues under investigation. Both FGD and Key informant interview methods were used to collect qualitative data.

Focus group discussions (FGD)

Focus group discussions (FGDs) are a qualitative data collection technique that involves facilitating in-depth guided discussions among a small group of participants. For this study, FGDs were utilized to collect additional qualitative data from households to supplement information gathered through other instruments.

Twelve FGDs were held with male and female farmers selected from six kebeles across the districts. The FGDs followed a purposive sampling approach based on participants' knowledge

of research topics, as identified through consultations with extension agents. Each FGD was comprised of 6-8 heads of households. Willingness to participate and ability to communicate experiences reflectively were also determining factors in selection. Six of the FGDs only included women participants, as they were deemed to have specialized knowledge of different adaptation strategies employed. Separating the female groups allowed women to feel more comfortable openly sharing their perspectives without intimidation from men.

The discussions were facilitated by a researcher and followed a guide with open-ended questions exploring participants' perceptions, experiences, and choices regarding adaptation options. Data from the FGDs served to provide deeper qualitative insight that supplemented the quantitative household survey information. This aided a more comprehensive understanding of the research issues.

Key Informant Interview

Key informant interviews were conducted to obtain specialized perspectives and information not captured through other methods. Key informants included elderly farmers (male and female), and academics with expertise in agriculture. Informants were purposively selected based on their in-depth knowledge of issues under investigation, as identified through consultation with extension workers. A total of 21 key informants were interviewed, with 6 male and 6 female elders, along with nine representatives from district agricultural offices chosen for their extensive experience and expertise.

Interviews were undertaken with each informant to allow for flexibility in the discussion. Interview guides were developed specifically for this study, with questions tailored according to the informant's background and role. Questions aimed to elicit the informant's unique perspective on topics such as community characteristics and vulnerabilities, existing agricultural and environmental practices, impacts of climate hazards experienced, adaptation approaches used, and barriers and opportunities for building resilience

The use of both key informant interviews and focus group discussions, in addition to the household survey, allowed for the triangulation of qualitative data. This strengthened the validity and reliability of findings by cross-checking information across multiple sources and

methods. Overall, this multifaceted approach aided a comprehensive examination of the research problem from various angles.

To effectively collect data from the field, 15 enumerators were recruited to assist with administering questionnaires and facilitating focus group discussions. Both male and female enumerators were selected from district agricultural offices, all holding at least an advanced diploma level of education.

Data Collection

The questionnaires were first developed in English, and then translated to Amharic with the help of translators to ensure comprehensible, culturally appropriate terminology. Once finalized, the Amharic questionnaires were administered by trained enumerators to randomly sampled households across the study area over three months. Enumerators directly entered responses into digital forms using smartphone under the researcher's supervision to minimize errors or missing responses.

For focus group discussions and key informant interviews, prior consent was obtained from all participants regarding audio recording and note taking. Recorded discussions were transcribed verbatim and translated to English. Where recording was not permitted, detailed notes were taken in Amharic then translated.

Completed questionnaires were reviewed daily by enumerators and the researcher to identify any inconsistencies or gaps requiring clarification. Data was uploaded securely to a central database to facilitate analysis upon completion of fieldwork.

3.4. Data Analysis

Quantitative data from the household survey was entered into Stata 16 for statistical analysis. Descriptive statistics such as frequencies, means, and percentages were generated to summarize and categorize sample household characteristics. Chi-square tests examined potential associations between attributes of households stratified by the head of household's gender. Independent sample t-tests analyzed differences in characteristics between male-headed and female-headed households. Climate data from 1992-2020 was subjected to trend

analysis to describe temperature and rainfall patterns over time in the study area. This helped triangulate survey respondents' perceptions of climate trends.

The vulnerability of female-headed and male-headed households to climate change was analyzed using the Livelihood Vulnerability Index and VI-IPCC frameworks per IPCC principles. A multivariate probit regression model estimated the determinants of adaptation strategy choices among surveyed households. Explanatory variables considered socio-demographic and climatic factors. An endogeneity switching regression was also employed to analyze the impact of adaptation strategies on household welfare like food consumption expenditure and income.

Qualitative data from focus group discussion and key informant interviews underwent content analysis. Transcripts and notes were carefully reviewed to identify common themes in perceptions and experiences related to climate change vulnerability and adaptation between male and female respondents.

By integrating qualitative insights with quantitative household and biophysical data, the study captures both the contextual drivers of adaptation decisions and their measurable outcomes. Socioeconomic data provide information on household sensitivity and adaptive capacity, while biophysical data capture exposure to climate risks; together, they form a comprehensive framework for assessing gender-differentiated vulnerability.

3.4.1. Measuring Gender Dimension of Vulnerability to Climate Change and Variability

The vulnerability level of female-headed and male-headed households to climate change and variability was analyzed by applying the following indices; the livelihood vulnerability index (LVI) and VI-IPCC based on the IPCC vulnerability framework.

Livelihood vulnerability index calculation

The calculation of the livelihood vulnerability index first involved normalizing the raw data collected using differing measurement scales into standard units such as percentages, ratios, and indices (Shah et al., 2013). Normalization was the process by which subcomponent units of an indicator were brought into the same standards (Nardo et al., 2014). Given that each subcomponent was measured in different scales, it had to be transformed into a standard unit

which allowed for comparability in the assessment. Each transformed score was then standardized through equation 1 following Hahn et al. (2009).

$$IndexS_G = \frac{S_G - S_{min}}{S_{max} - S_{min}} \quad (1)$$

Where, S_G is the sub-component score for a specific gender G and S_{min} and S_{max} are the minimum and the maximum values, respectively for each sub – components from the data.

The next step dealt with weighting the indices based on their relative importance to the overall climate change vulnerability index score. In this step, following the approach of Hahn et al. (2009), the study applied an equal weighting method. The main advantage of using equal weighting was that it was simple to use and hence could be easily applied by local development workers during index-based vulnerability assessments (Hahn et al., 2009).

The next step involved aggregating the subcomponent scores into an overall composite index. Aggregation is the process of combining multiple social and biophysical factors that contribute to climate change vulnerability into composite indices (Hinkel, 2011). In this step, following the approach of Panthi et al. (2015), the study aggregated several sets of climate change vulnerability indicators into composite indices. The average score of a major component was calculated using Equation 2:

$$M_G = \frac{\sum_{i=1}^{11} S_G}{n} \quad (2)$$

Where, M_G is the major component index, which consists of several subcomponents for the gender G; S_G denotes one of the sub-components, which is indexed by i, that make up each major component and n is the number of sub-components within the major component.

Later, the major component indices were calculated, which could then be averaged to calculate the livelihood vulnerability index for each gender using Equation 3:

$$LVI_G = \frac{\sum_{i=1}^{11} w_{Mi} M_G}{\sum_{i=1}^{11} w_{Mi}} \quad (3)$$

Where LVI is the Livelihood Vulnerability Index for the gender G, equals the weighted average of the eleven major components, w_{Mi} - the weights of each major component, i which

were a function of the number of subcomponents that each major component was composed of. These were compiled to confirm that all sub-components contributed equally to the overall livelihood vulnerability index. The LVI score ranged from 0 (least vulnerable) to 1 (most vulnerable).

The study then applied the Vulnerability Index (VI) defined by the IPCC to measure households' adaptive capacity, sensitivity, and exposure to climate change. Adaptive capacity was measured in terms of demographic profile, knowledge and skill, livelihood strategy, asset, technology, and social network related factors. Sensitivity was evaluated through food, natural capital, water, and health components. Exposure incorporated natural disaster and climate variability.

Following the approach of Hahn et al. (2009), each of the IPCC-defined factors contributing to climate change vulnerability (exposure, sensitivity and adaptive capacity) was calculated using Equation 4:

$$CF_G = \frac{\sum_{i=1}^n w_{Mi} M_{Gi}}{\sum_{i=1}^n w_{Mi}} \quad (4)$$

Where, CF_G is results of exposure index, sensitivity index or adaptive capacity index for the gender G, M_{Gi} is the major components index by i, w_{Mi} is a weighting factor, determined by the number of major components in each IPCC factor; and n is n is the number of major components associated with each contributing factor for the gender G.

Finally, the LVI-IPCC consisting of sensitivity, adaptive capacity and exposure scores is calculated using equation (5):

$$VI_{IPCCs} = (E_G - A_G) * S_G \quad (5)$$

Where, VI_{IPCCs} is the total vulnerability index of the IPCC for the gender G, E_G is the exposure index, A_G is the adaptive capacity index and S_G is the sensitivity index. The VI_{IPCCs} the index ranges from -1 (least vulnerable) to 1 (most vulnerable) (Hahn et al., 2009).

3.4.2. Modeling Determinants of Households' Choice of CVC Adaptation Strategies

To analyze the determining factors of climate change adaptation strategy choices by male-headed and female-headed smallholders, a multivariate probit model was employed. The

model indicated the relationships between the likelihoods of choosing adaptation strategies and sets of independent variables. It permitted the investigation of choices across more than two categories of dependent variables. This allowed for determining the probabilities of choices for distinct categories, as described by Wooldridge (2006).

The multivariate probit model was used to analyze how various determining factors influenced the adaptation strategy choices of male-headed and female-headed smallholders. By examining relationships between the likelihoods of choosing strategies and independent variables across multiple dependent variable categories, the model provided probabilities of choices for different adaptation options. This approach permitted a detailed investigation of the determinants, as outlined in Wooldridge's 2006 discussion of multivariate probit models.

Model specification

The multivariate probit model undertakes that given a set of explanatory variables, the multivariate response is an indicator of the event that some unobserved latent variable (Z), expected to arise from a multivariate normal distribution, falls within a certain interval (Wooldridge, 2006). The MVP model demonstrates that each subject has J distinct binary responses and a matrix of covariates that can be any mixture of distinct and continuous variables.

Specifically, let $J_i = J_{i1}, \dots, J_{iN}$, represent the J dimensional vector of observed adapting strategies 0/1 responses on the i^{th} subject, $i = 1, \dots, n$ let Y_i be $N \times P$ design matrix which is vector of independent factors, and $X_i = X_{i1}, \dots, X_{iN}$ denote N variate normal vector of latent variables such that

$$X_i = Y_i\beta + \varepsilon_i, i = 1, \dots, N \quad (1)$$

The relationship between X_{ij} and Z_{ij} in the multivariate probit model is given by

$$Z_{ij} = 1 \text{ if } X_{ij} > 0, 0 \text{ otherwise} \quad (2)$$

where $j = 1, 2, \dots, N$ represents availability of climate adaptation strategies and Y_i is a vector of explanatory variable, β represents the vector of a parameter to be estimated, and ε_i is vector of residual error distributed or random error terms distributed as a multivariate normal distribution with zero mean and unitary variance. It is supposed that a rational i^{th} farmer has a

latent variable, X_{ij} which captures the unobserved preferences or demand related with the j^{th} choice of adaptation strategy. This latent variable is expected to be a linear combination of observed household and other characteristics that affect the choices of adaptation strategy, as well as unobserved characteristics captured by the stochastic error term (Wooldridge, 2006).

The MVP model identified factors that influenced the likelihood of MHHs and FHHs independently choosing different adaptation strategies. This allowed comparisons of how adaptation choices may differ between MHHs and FHHs based on gender, addressing the key dimension of how household head gender intersects with adaptation decision-making.

3.4.3. ESR Model Specification

Households self-select into adaptation or non-adaptation, which introduces endogeneity due to both observed and unobserved heterogeneity. To address this, the Endogenous Switching Regression (ESR) model was employed. ESR corrects for sample selection bias by jointly estimating the selection equation (adaptation decision) and the outcome equations (household welfare).

1. Selection Equation (Adaptation decision):

The decision to adopt adaptation strategies is modeled as a binary choice:

$$A_i^* = Z_i\gamma + u_i$$

Where A_i^* = latent variable representing household i's propensity to adapt, A is a binary 0 or 1 dummy variable for the use of the adaptation strategies; $A_i = 1$ if a farmer practice at least one of the given adaptation strategies; $A_i = 0$ otherwise; γ is a vector of parameters to be estimated; Z_i is vector of household and institutional characteristics (e.g., education, land size, access to credit, extension contact); and u_i is the error term.

2. Outcome Equations (Household welfare):

Conditional on adaptation status, household welfare (Y) is specified as:

$$Y_{1i} = X_{1i}\beta_1 + \epsilon_{1i} \text{ if } A_i = 1$$

$$Y_{0i} = X_{0i}\beta_0 + \epsilon_{0i} \text{ if } A_i = 0$$

Where, Y_{1i} , Y_{0i} are household welfare indicators (household food consumption expenditure and income); X_{1i} , X_{0i} are vectors of explanatory variables; $\beta_1\gamma$ and β_0 are vectors of parameters and ϵ_{1i} and ϵ_{0i} error terms, correlated with selection error term u .

3. Estimation Procedures

The ESR model is estimated in two stages:

Stage 1 – Probit Selection Model: Estimate the probability of adaptation using the selection equation.

Stage 2 – Full Information Maximum Likelihood (FIML): Jointly estimate outcome equations for adopters and non-adopters, correcting for endogeneity and unobserved heterogeneity.

From the estimates, counterfactual outcomes are constructed: what would be the welfare of adopters if they had not adapted, and vice versa. This allows robust estimation of average treatment effects (ATE) and gender-differentiated welfare impacts.

4. Justification of Instrumental Variables

Two instruments were included in the selection equation but excluded from the outcome equations: Access to climate information (radio, extension, or early warning systems). This variable strongly influences the likelihood of adopting adaptation strategies (relevance), but it does not directly affect household income or food expenditure except through adaptation (exogeneity). Access to agricultural extension facilitates adoption by increasing access to advice and inputs (relevance). It does not directly affect household welfare outcomes beyond influencing adoption choices (exogeneity). The instruments meet the relevance criterion (correlated with adaptation) and the exogeneity criterion (uncorrelated with error terms in the welfare equations).

5 Treatment Effects in the ESR Framework

Let $A_i \in \{0, 1\}$ denote household i 's adaptation decision (1 = adopter). The ESR comprises:

- Selection (first stage, Probit):

$$A_i^* = Z_i\gamma + u_i \quad A_i = 1(A_i^* > 0) \quad \text{With } u_i \sim N(0, 1)$$

- Regime-specific outcomes (second stage):

$$Y_{1i} = X_{1i}\beta_1 + \epsilon_{1i} \text{ if } A_i = 1$$

$$Y_{0i} = X_{0i}\beta_0 + \epsilon_{0i} \text{ if } A_i = 0$$

Where $(u_i, \epsilon_{1i}, \epsilon_{0i})$ are trivariate normal with $E(\epsilon_{1i}) = E(\epsilon_{0i}) = 0$,

$$\text{Var}(\epsilon_{1i}) = \sigma_1^2$$

$$\text{Var}(\epsilon_{0i}) = \sigma_0^2$$

$$\text{Cov}(u_i, \epsilon_{1i}) = \rho_1\sigma_1$$

$$\text{Cov}(u_i, \epsilon_{0i}) = \rho_0\sigma_0$$

Correlations $\rho_1, \rho_0 \neq 0$ capture self-selection on unobservables.

Define $u_i = Z_i\gamma$ the inverse Mills ratios (IMR):

$$\lambda_{1i} = \frac{\phi(u_i)}{\phi(u_i)} \text{ for } A_i = 1 \text{ and } \lambda_{0i} = \frac{\phi(u_i)}{1 - \phi(u_i)} \text{ for } A_i = 0$$

Where ϕ (.) is the standard normal probability density function, Φ (.) the standard normal cumulative function.

Conditional expectations and counterfactuals

Because the conditioning event is $A_i = 1$ or $A_i = 0$ the same IMR enters both counterfactuals for a given group:

- Among adopters $A_i = 1$

$$E[Y_{1i}|A_i = 1] = X_{1i}\beta_1 + \rho_1\sigma_1\lambda_{1i},$$

$$E[Y_{0i}|A_i = 1] = X_{0i}\beta_0 + \rho_0\sigma_0\lambda_{1i},$$

- Among non-adopters $A_i = 0$

$$E[Y_{0i}|A_i = 0] = X_{0i}\beta_0 + \rho_0\sigma_0\lambda_{0i},$$

$$E[Y_{1i}|A_i = 0] = X_{1i}\beta_1 + \rho_1\sigma_1\lambda_{0i},$$

Here Y is the welfare metric (we use income and food consumption expenditure)

Average treatment effects

Let n_1 and n_0 be the numbers of adopters and non-adopters.

- ATT (effect on the treated/adopters):

$$ATT = \frac{1}{n_1} \sum_{i=A_i=1} \left\{ \frac{X_{1i}\beta_1 + \rho_1\sigma_1\lambda_{1i}}{E[Y_{1i}|A_i=1]} - \frac{X_{0i}\beta_0 + \rho_0\sigma_0\lambda_{1i}}{E[Y_{0i}|A_i=1]} \right\}$$

- ATU (effect on the untreated/non-adopters):

$$ATU = \frac{1}{n_0} \sum_{i=A_i=0} \left\{ \frac{X_{1i}\beta_1 + \rho_1\sigma_1\lambda_{0i}}{E[Y_{1i}|A_i=0]} - \frac{X_{0i}\beta_0 + \rho_0\sigma_0\lambda_{0i}}{E[Y_{0i}|A_i=0]} \right\}$$

- ATE (population average effect):

$$ATE = p \text{ ATT} + (1-p) \text{ ATU} \quad p = \frac{n_1}{n_0 + n_1}$$

Gender-disaggregated effects

Compute ATT/ATU/ATE separately for MHHs and FHHs by:

- Estimating two ESR models (split sample by headship),
- Report ATT^{MHH} , ATT^{FHH} (and similarly ATU/ATE). A Wald test on interaction terms provides a formal test of gender differences.

3.5. Definition of Variables and Hypotheses

After the analytical procedures are explained, it is required to classify the potential explanatory variables that influenced the gender dimension of vulnerability indicators, adaptation choices, and impact on welfare.

3.5.1. Definition of Variables for Vulnerability Analysis

Adaptive capacity indicator variables

Demographic profile: Within the household, productive age and healthy family members have the capacity to participate in different livelihood strategies and be involved in labor-intensive adaptation strategies like soil conservation practices and irrigation (Shah et al., 2013). A younger household head age and larger working-age family helped bolster adaptive capacity through the provision of human capital for diverse livelihood activities and climatic adaptations demanding physical labor. Dependency ratios and household demographics were important influencers of smallholders' resilience. Therefore, age and family size influenced the adaptive capacity to climate change and variability.

Knowledge/skill: Particularly, personal factors such as education were important influencers on household heads' decision-making abilities. For instance, literate households were more likely to participate in income diversification activities and utilize agricultural technologies, whereas illiterate household heads may have been constrained in their capacity to obtain weather-related data and utilize adaptation and coping strategies (Alhassan et al., 2019). Education levels and access to technical guidance influenced adaptive capacity by empowering smallholders with knowledge and skills to make informed choices regarding diverse livelihoods and climate-smart practices. Limited education and extension constrained this adaptive function.

Assets: Animal resources were important due to the role livestock play in expanding vulnerable people's resilience capacity against varying risks (Adimassu et al., 2014). Greater livestock holdings and farmland area provide both on-farm resources and income buffers during stress periods. Land tenure security, versus renting/sharing, also impacts the ability to

make long-term investments and decisions in the land. These asset indicators reflected a household's means to diversify and its ability to withstand climate shocks.

Livelihood strategies: Income was important for households to manage climate change and variability, derived from either agricultural income or off-farm activities. A household with diversified income sources had increased opportunities to access resources needed to utilize adjustment strategies (Adu et al., 2018). Additionally, diversifying livelihoods through non-farm activities helped decrease vulnerability levels. Diversified incomes and access to credit supported greater adaptive capacity through flexibility in livelihood strategies and resource access. Therefore, livelihood strategies influenced adaptive capacity.

Technology: Technology is important for adaptive capacity and reducing vulnerability to climate change. The following indicators were used to assess use of agricultural technologies: The percent of household heads that did not use insecticides, pesticides, or herbicides. The percentage of household heads who did not utilize organic or inorganic fertilizers, and the percent of household heads who stated they did not have access to drought-resistant and short-season crop varieties. The percent of households that did not have access to irrigated land. Utilizing technologies like agricultural chemicals, improved seeds, fertilizers, and irrigation can increase productivity under changing climatic conditions (Asfaw et al., 2021; Bedeke et al., 2020; Zeleke et al., 2023). Limited adoption of such technologies reflects weaker adaptive capacities as households have fewer means to counter climate impacts on crop and livestock production. Overall, greater employment of climate-smart agricultural practices enhances resilience to climate hazards.

Social networks: Membership in farmers and informal associations can serve as channels of information on adapting new technologies and practices. It can also provide a source of soft financial support during climate shocks (Shiferaw et al., 2014). Therefore, membership in social groups was used as an indicator of adaptive capacity. Strong social networks, as reflected in group membership and support received, enhances adaptive capacity through sharing of information and resources that assist smallholders facing climate impacts. Limited integration in social networks can constrain this supportive function.

Sensitivity indicators

Food: Households that previously stored portions of food grains from prior years' production would be less sensitive to crop failures during certain growing periods, according to Balikoowa et al. (2019). Households reliant solely on farm income and unable to store food grains for drought periods would have higher vulnerability to climate changes, as described by Hahn et al. (2009). Therefore, a household's ability to store food serves as an indicator of its sensitivity. Households with food reserves are better able to cope with climate stressors like crop failure caused by drought, compared to those without storage options. The availability of stored food bolsters resilience.

Water: Acute water scarcity, poor water management, and frequent water conflicts contribute significantly to farmers' vulnerability to climate change and variability (Bedeke et al., 2020; Zeleke et al., 2023). Access to clean, reliable water sources near the home reduces sensitivity to climate impacts like drought. Limited access increases vulnerability, reflecting water as a key sensitivity indicator. Smallholder farmers who rely on sufficient water supply are particularly vulnerable to climatic variability and change due to scarcity, distance to sources, and water conflict.

Health: Inadequate access to health services may increase households' sensitivity to extreme climate events by exacerbating health-related climate risks, according to Adu et al. (2017). Limited accessibility to healthcare, as well as preexisting chronic illnesses or recent sicknesses missing work/school, can magnify vulnerability to climate hazards such as heat waves or infectious disease outbreaks. Farther distances, illnesses, and missed work/school are indicators of higher health-based sensitivity for smallholder households.

Exposure indicators

Natural disaster and climate variability: Generally, exposure was measured by the occurrence and intensity of climate change through quantifying the causes of climatic stress, preferably using real climatic information (Hahn et al., 2009). Drought and flood risk indices from the past ten years of records were obtained from the North Wollo zone agriculture office. These indices quantify and combine both the frequency of floods and droughts as well as the underlying yield loss and crop damage per hectare. Monthly temperature and rainfall data from 1992 to 2020 were obtained from the Ethiopian National Meteorological Agency to analyze trends and variability. Indicators of exposure included: The percent of households reporting

land degradation from climate extremes in the past ten years. The percentage of households that lost crops due to floods and drought, and the percentage of households that did not receive warnings about upcoming disasters. Drought and flood risk values averaged over ten years during rainy seasons. Temperature and rainfall variability based on monthly means and standard deviations. Real climatic data, risk indices, and farmer-reported impacts captured exposure to climate hazards like erratic precipitation and recurrent droughts and floods. This assessed vulnerability to current and projected climate conditions.

Table 3 Major and subcomponents contributing to climate change vulnerability in the study area

Component	Sub-component	Indicators	Hypothesis Sign	Sources
Adaptive Capacity	Demographic	Age dependency ratio	(-) higher dependency = ↑ vulnerability	Hahn et al. (2009)
		Average age of household head	(-) older HH heads = less adaptive	
		Total family size (adult equivalent)	(±) larger family can ↑ labor (+) or ↑ pressure (-)	
	Knowledge & Skills	% without formal education	(-) no education = ↑ vulnerability	Alhassan et al. (2019); Asfaw et al. (2021); Bedeke et al. (2020)
		% without access to weather info	(-) less info = ↑ vulnerability	
		% without climate training	(-) less skill = ↑ vulnerability	
		% without extension services	(-) no access = ↑ vulnerability	
	Livelihood Strategies	% without access to microfinance	(-) no finance = ↑ vulnerability	Amare & Simane (2017); Zeleke et al. (2023)
		% dependent mainly on agriculture	(-) mono-dependence ↑ vulnerability	
		Livelihood diversification index	(+) diversification ↓ vulnerability	
	Assets	Livestock ownership (TLU index)	(+) more assets ↓ vulnerability	Zeleke et al. (2023)
		Farmland size (ha)	(+) larger land ↓ vulnerability	
		% renting/sharecropping land	(-) loss of land control ↑ vulnerability	
	Technology	% not using pesticides/herbicides	(-) low technology ↑ vulnerability	Asfaw et al. (2021); Bedeke et al. (2020); Zeleke et al. (2023)
		% not using fertilizer	(-) low input use ↑ vulnerability	
		% without drought-resistant varieties	(-) no access ↑ vulnerability	
% without irrigated land		(-) no irrigation ↑ vulnerability		
Social Capital	% borrowing from relatives/groups	(+) strong social ties ↓ vulnerability	Alhassan et al. (2019); Asfaw et al. (2021); Bedeke et al. (2020)	
	% receiving NGO food aid	(+) safety net ↓ vulnerability		

		% not members of farmer/women groups	(-) exclusion ↑ vulnerability	
Sensitivity	Food	Crop diversity index	(+) more diversity ↓ sensitivity	Adu et al. (2018); Amare & Simane (2017)
		Months without enough food	(-) more food shortage ↑ sensitivity	
		% without grain reserves	(-) no reserves ↑ sensitivity	
	Water	% without daily clean water	(-) poor access ↑ sensitivity	Bedeke et al. (2020); Zelege et al. (2023)
		Distance to water source (minutes)	(-) longer distance ↑ sensitivity	
		% facing water conflicts	(-) conflict ↑ sensitivity	
	Health	Distance to health center (minutes)	(-) longer distance ↑ sensitivity	Alhassan et al. (2019); Hahn et al. (2009)
		% with chronic illness in family	(-) illness ↑ sensitivity	
		% missing work/school due to illness	(-) illness ↑ sensitivity	
Exposure	Natural Disasters	% reporting land degradation (10 yrs)	(-) degradation ↑ exposure	Asrat & Simane (2017); Hahn et al. (2009); Zelege et al. (2023)
		% losing crops to floods/drought	(-) crop loss ↑ exposure	
		% without disaster early warning	(-) no info ↑ exposure	
		Avg. drought risk values (10 yrs)	(-) higher risk ↑ exposure	
		Avg. flood risk values (10 yrs)	(-) higher risk ↑ exposure	
	Climate Variability & Change	Std. dev. of max daily temp.	(-) high variability ↑ exposure	
		Std. dev. of min daily temp.	(-) high variability ↑ exposure	
		Std. dev. of monthly rainfall	(-) high variability ↑ exposure	

3.5.2. Definition of Variables for CVC Adaptation Strategy Analysis

Dependent variables

The dependent variables in the analysis were the primary adaptation strategies employed by male-headed and female-headed households across the different agro-ecological zones in the study area. The adaptation options included:

- **Improved crop varieties:** Adoption of new, climate-resilient seed varieties.
- **Crop diversification:** Introduction of additional crops to mitigate risk.
- **Shifting planting dates:** Adjusting the timing of planting activities in response to changing climatic cues.
- **Soil and water conservation practices:** Implementing technologies such as terracing, mulching, and water harvesting to manage soil and moisture.
- **Non-farm income diversification:** Engaging in alternative income-generating activities beyond agriculture.
- **Irrigation:** Utilizing irrigation infrastructure and systems for crop production during dry periods.

Independent variables

Age of household head: Age was measured as a continuous variable indicating the number of years. Some previous studies found that older farmers may have accumulated more knowledge than younger ones over their lifetime due to extended experience, which affected their awareness of temperature changes. Atinkut and Mebrat (2016) noted in their study that older farmers were more likely to practice adaptation options like crop diversification compared to younger farmers. However, a separate study by Marie et al. (2020) found evidence that the age of the household head was negatively associated with farmers' decisions regarding choice of adaptation strategies. Considering these mixed findings, this study approached the age of the male and female household heads as variables that could potentially have both positive and negative influences on adaptation practices. Older age may correlate with greater adaptive knowledge but reduce openness to new practices, while younger farmers face learning curves but remain more flexible.

Education level: Education was measured as a dichotomous dummy variable, indicating whether the household head had attended any formal education or not. Previous research suggested that farmers who obtained a formal education may be more likely to choose adaptation strategies. A study by (Hirpha et al., 2020) found education to be an important determinant, with educated households found to be more responsive to agricultural practices and technologies as they had better understanding and access to weather-related information. Similarly, Zewdu (2020) noted that education increased the probability of the household head adapting to climate change through strategies like increased crop diversification, soil and water conservation methods, and adjusting planting dates. Considering these findings, this study hypothesized that education level would have a positive relationship with the adaptation choice decisions of both male and female farmers. Educated household heads may be more open to new practices and better equipped to make informed production choices under changing climatic conditions.

Family size: Family size was measured as a continuous variable indicating the total number of family members living in a household, expressed in adult equivalents to account for age differences. Household members represent potential sources of labor that can be mobilized for agricultural activities. Previous research found that household size influences adaptation choices. Atinkut and Mebrat (2016) indicated it had an impact on options like crop diversification and soil/water conservation practices. Getahun et al. (2021) also found larger households were more likely to utilize adaptation strategies, potentially due to having more family labor available. When faced with climate stresses, households with greater labor capabilities may find it easier to employ labor-intensive adaptation options. Considering these studies, this research hypothesized that household size would share a positive relationship with the adaptation choice decisions of both male-headed and female-headed farm households. Larger families were expected to opt for strategies requiring higher labor inputs more readily.

Farming experience: Farming experience was measured as a continuous variable indicating the total number of years the household head had spent engaged in agricultural activities. Previous research found that experience level influences adaptation choices. Experienced farmers were found to have expanded likelihoods of choosing adjustment strategies. With more years cultivating the land, experienced smallholders had better access to information and data on changes in climatic patterns and conditions over time due to their observation and participation

in agricultural practices for an extended period (Atube et al., 2021). Additionally, a study by Belay et al. (2017) showed heads' farming experience increased the likelihood of undertaking adaptation strategies, as older farmers had accumulated knowledge regarding when and how climate change had impacted the local area previously. They understood which adaptation methods worked best in specific locations based on their lengthy engagement in agriculture. Considering these findings, this study hypothesized farming experience would share a positive relationship with the adaptation choice decisions of male-headed and female-headed farm households. More experienced farmers were expected to select strategies based on refined experiential learning over many years of crop production.

Farmland size: Farmland size was measured as a continuous variable in hectares, indicating the total area of land cultivated by the household. Previous studies found that farmland size influences adaptation choices. Households with larger land areas were found to produce different crop mixes than those with smaller plots. Atinkut and Mebrat (2016) found a positive relationship between the size of cultivated land and the selection of adaptation practices in their analysis. Specifically, Belay et al. (2017) noted that larger farm sizes positively influenced choices around soil and water conservation methods, increased crop diversification through the integrated production of more varieties, and greater utilization of improved seed varieties. Considering these findings, this research hypothesized that farmland size would positively influence the adaptation choices of both male-headed and female-headed households. Those cultivating more extensive tracts of land were expected to more readily opt for strategies requiring wider land areas, such as integrated soil management or diversified crop rotation schemes.

Livestock ownership in TLU: Livestock ownership was measured as a continuous variable in tropical livestock units (TLU), a standard unit that allows for the comparison of different livestock species. Previous studies found that livestock levels influence adaptation choices. Keeping livestock provides opportunities for income generation, supplements agricultural operations through manure fertilizer and draught power, and serves as a savings mechanism. Menghistu et al. (2021) noted that higher livestock holdings improved the adoption of adaptation practices. Additionally, Belay et al. (2017) indicated livestock production exhibited a positive association with adaptation strategy selection, such as integrated crop-livestock systems and

soil/water conservation methods. Considering these findings, this research hypothesized that a positive relationship between livestock holdings, as measured in TLU, and the adaptation choices of male-headed and female-headed farm households.

Annual income: Annual income was measured as a continuous variable reported in Ethiopian Birr (ETB). Previous research found that levels of income influence adaptation choices. Atube et al. (2021) found household heads with higher annual earnings from both farm and non-farm activities were more likely to select strategies like using improved seed varieties and irrigation systems to reduce vulnerabilities to climate change impacts. Higher income providers have greater financial resources and purchasing power to invest in new production techniques or equipment. It allows for the testing of improved inputs and technologies one may not otherwise afford. Considering these findings, this study hypothesized that annual income would share a positive relationship with the adaptation choice decisions of male-headed and female-headed smallholder farm households.

Climate information: Access to climate information was measured based on household ownership of resources that can aid in receiving data, such as, radio, television, and telephone. Access to timely and relevant climate data can be important for adapting strategies. Better information enables farmers to make more informed decisions when selecting among options to better manage climate variability and change impacts (Mihiretu et al., 2019; Getahun et al., 2021). Previous studies found that greater access positively influences adaptation choices. Amare and Simane (2017) found that better access to early warnings about drought and flooding, before events occurring, had a significant and positive impact on the likelihood of adopting agronomic practices and soil/water conservation methods. Considering these findings, this study hypothesized climate information access would share a positive relationship with the adaptation choice decisions of male-headed and female-headed smallholder farm households.

Access to agricultural extension service: Access was measured as a dichotomous dummy variable, taking a value of 1 if the household had contact with extension services or 0 if not. Previous studies found that extension access influences adaptation choices. Interacting with extension agents helps expand households' knowledge and skills regarding changing climatic conditions and the range of management practices that can be utilized to adjust to impacts (Saguye, 2016). Increasing extension outreach has potential to raise farmers' awareness of

adaptation measures through information provision (Saguye, 2016; Hirpha et al., 2020). Additionally, a study by Amare and Simane (2017) found farm households engaged with extension were more likely to adopt improved technologies and progress their production. Given these findings, this research hypothesized that access to extension services would positively correlate with the adaptation choices of male-headed and female-headed smallholders.

Training on adaptations: Training was measured as a dichotomous dummy variable, taking a value of 1 if the household head participated in training related to climate change adaptation or 0 if not. Previous research found that training influences adaptation choices. Receiving guidance on managing or coping with climate risk helps expand households' adaptive capacities compared to those without such training opportunities (Hirpha et al., 2020). Skill-building activities give participants hands-on knowledge of context-specific adaptation options and best-fit practices. This equips farmers to make an informed selection of strategies aligned with local conditions (Hirpha et al., 2020). In consideration of these findings, this study hypothesized that training participation would positively correlate with the adaptation choices of male-headed and female-headed smallholder households. Training was expected to better support the selection of suitable response techniques.

Access to credit: Access to credit was measured as a dichotomous dummy variable, taking a value of 1 if the household had obtained a loan or 0 if not. Previous research indicates that credit access influences adaptation choices. Being able to obtain loans expands farmers' financial resources and improves their capacity to meet costs associated with potential adaptation strategies (Saguye, 2016). Households with credit access are better able to invest in farm/non-farm activities and purchase production inputs like fertilizers, improved seed varieties, and irrigation equipment or services. Amare and Simane (2017) specifically found that the influence of accessing credit services on farmers' decisions to invest in small-scale irrigation was strongly positive. Given these findings, this study hypothesized that access to credit would positively correlate with the adaptation choices of male-headed and female-headed smallholder households.

Membership in Local Organizations: Membership was measured as a dichotomous dummy variable, taking a value of 1 if the household had at least one member participating in a cooperative/producer group or 0 if not. Previous research found that membership influences adaptation choices. Being involved in cooperatives allows farmers to share knowledge, discuss

challenges with peers, and engage in collective decision-making (Saguye, 2016). Additionally, a study by Yirga (2020) specifically observed that membership in women's groups positively affected soil and water conservation practices. Interactions built awareness, social capital, and knowledge sharing related to such practices among female members. Given these findings, this study hypothesized that membership in organizations would correlate positively with the adaptation choices of male-headed and female-headed smallholder households.

Table 4 Adaptation strategy analysis variables

Variables	Variable type	Expected effect
Dependent Adaptation options to adverse effects of climate change	Improved varieties, crop diversification, soil and water conservation, change in planting date, income diversification, and irrigation.	
Age of household head	Continuous	+/-
Educational level	Dummy	+
Farming experience	Continuous	+
Household size	Continuous	+
Farm size	Continuous	+
Access to extension services	Dummy	+
Access to credit services	Dummy	+
Livestock ownership	Continuous	+
Information on climate change	Dummy	+
Annual income	Continuous	+
Training on adaptation strategy	Dummy	+
Membership in local organizations	Dummy	+

3.5.3. Definition of Variables for Adaptation Strategy Impact Analysis

Outcome variable

In this study following Afolami et al. (2015), two proxies were used to measure household welfare outcome: annual income, and household consumption expenditure.

Annual income: measures the total amount of monetary value received by the household within one year from various sources. It is a continuous variable measured in Ethiopian Birr (ETB). Income includes earnings from wage labor, crop and livestock sales, proceeds from other agricultural or non-farm businesses, remittances, pensions, rents and any other sources of revenue. The household survey gathered data on incomes from all contributing activities to construct a single aggregate annual income figure for each household.

Consumption expenditure: It is calculated as the total value of food crops consumed from own production plus any market purchases of foods, plus the value of livestock and livestock products consumed from own sources or commercial acquisitions. This aggregate figure is then divided by the number of AEs in the household to control for differences in family size when making comparisons. Data is collected through the household survey on all food expenditures, production for home consumption and purchases to derive consumption expenditure per AE per year variable measured in ETB.

4. RESULT AND DISCUSSION

This chapter presents the results of the study and engages in a discussion that compares these findings with those of similar research. The analysis is organized into several key sections, including the socioeconomic characteristics of household heads, the gender dimensions of vulnerability to climate change, and the perceptions of smallholder farmers regarding climate change and variability. Furthermore, it explores the adaptation strategies employed to mitigate the adverse effects of climate change and variability, as well as the determinants influencing the choices of these adaptation strategies. Finally, the chapter examines the gendered impact of adaptation strategies on household welfare.

4.1. Descriptive Analysis

This section provides an overview of the demographic, socio-economic profiles and institutional characteristics of the surveyed households based on descriptive statistics. In total, 396 households were interviewed for the study. Of these, the majority (267 households or 67.42% of the sample) were male-headed households, while 129 households (32.57%) were female-headed. The mean age of respondents was 45 years old. Male-headed households (47 years old on average) tended to be older than female-headed households (whose average age was 42 years old). The mean household size across the sample was 2.84 people. However, female-headed households had a smaller typical family size (averaging 2.36 people) compared to male-headed households (who had a larger average of 3.1 people).

When comparing the level of education between female-headed and male-headed households in the sample, some differences were observed. Among the 129 female-headed households surveyed, the majority (61.24% or 79 households) had no formal education. The remaining 50 households (38.75%) could read and write and had primary or secondary education. Among the 267 male-headed households, slightly fewer (50.93% or 136 households) lacked any formal education. The other 131 households (49.06%) were literate and had some primary or secondary schooling. Overall, the data indicates that female-headed households in the sample generally had lower levels of education attained compared to their male-headed counterparts.

Table 5 Socioeconomic characteristics of household heads (n=396)

Variables	Male household heads (267)	Female household heads (129)	t-test
Age (mean)	47	42	-4.42***
Family size (AE)	3.1	2.36	-6***
Farmland size (ha)	0.68	0.38	-7.55***
Livestock (TLU)	2.67	2.11	-4.14***

Source: own survey data 2023

Land ownership and livestock holding are important factors for rural households engaged in agricultural activities, which form the main livelihood and source of income in the study areas. Since non-farm opportunities are limited, access to land largely determines a household's living standards and food security. The sample households owned various types of livestock including cattle, oxen, small ruminants, poultry, and pack animals. On average, male-headed households held 2.67 tropical livestock units (TLU) and owned 0.68 hectares of farmland. In comparison, female-headed households owned 2.11 TLU on average and 0.38 hectares of farmland. This suggests that male-headed households had higher asset levels than female-headed households. With fewer resources and adaptive capacities, female-headed households were likely more vulnerable to impacts of climate change and variability in these rural communities where land and livestock are critical for livelihoods and resilience.

Table 6 Institutional characteristics of household heads

Variables	Male HH (267)		Female HH (129)		Total (396)		Chi (X ²)
	Yes	No	Yes	No	Yes	No	
Education status	131	136	50	79	181	215	3.72*
Access to extension	181	86	70	59	251	145	6.85***
Access to info	178	89	52	77	230	166	24.81***
Access to training	130	137	60	69	190	206	0.16
Access to credit	163	104	49	80	212	184	18.6***
Member in LO	153	114	56	73	209	187	6.73***

Source: own survey data 2023

The results reveal significant gender disparities in institutional access, which have important implications for adaptive capacity and household welfare. Access to extension services was significantly higher among male-headed households (MHHs) compared to female-headed

households (FHHs), as shown by the chi-square value ($\chi^2 = 6.85$, $p < 0.01$). This suggests that men are more likely to receive timely agricultural advice, improved practices, and information on climate variability. Limited access for women is consistent with earlier findings in Ethiopia, where female farmers were often marginalized in extension outreach due to socio-cultural barriers and resource constraints (Ragasa et al., 2013; Asfaw et al., 2021). Since extension services are a critical channel for the diffusion of climate-smart practices, such exclusion can significantly heighten the vulnerability of FHHs.

Similarly, membership in local organizations (LOs) was significantly higher among MHHs than FHHs ($\chi^2 = 6.73$, $p < 0.01$). Local organizations not only serve as platforms for collective action and mutual assistance but also provide channels for accessing credit, information, and safety nets during climate shocks. Women's lower participation in these institutions reflects persistent gender gaps in social capital and decision-making power, which reduces their resilience to climate risks (Zelege et al., 2023; Amare & Simane, 2017). This finding underlines the importance of strengthening women's inclusion in farmer cooperatives, water user associations, and women's groups to enhance adaptive capacity.

In contrast, no significant gender difference was observed in access to training programs ($\chi^2 = 0.16$, n.s.). This may indicate that both men and women are equally likely to participate in formal training sessions when offered. However, the relatively low participation rate across both groups suggests that training opportunities remain inadequate overall. Training is often irregular, project-driven, or not tailored to the specific needs of women farmers, which may limit its transformative potential (Alhassan et al., 2019; Bedeke et al., 2020).

Overall, these findings confirm that gendered inequalities in institutional access particularly in extension services and organizational membership contribute to differential adaptive capacities between MHHs and FHHs. Policies aimed at strengthening female farmers' participation in extension programs and local institutions are therefore essential to reducing vulnerability and promoting equitable welfare outcomes in the context of climate change adaptation.

4.2. Gender Dimensions of Vulnerability to Climate Change

This section presents the findings of the study on the comparative vulnerability to climate change between male-headed and female-headed smallholder households. Two methods were used to

assess vulnerability: 1) a livelihood vulnerability index and 2) a gender vulnerability assessment based on the VI-IPCC (Vulnerability-Integrated Assessment) framework developed by the IPCC. The results from these two approaches provide insights into the relative vulnerabilities faced by different gendered household types in adapting to climate change in smallholder farming communities.

4.2.1. Livelihood Vulnerability Index Results

Adaptive capacity of smallholder farmers to climate change and variability

Demographic profile: This component includes three indicators: the age dependency ratio, the average age of household heads, and the adult equivalent ratio. The results indicate that male-headed households exhibit higher vulnerability (0.771) compared to female-headed households (0.711) based on their dependency ratio. This difference can be attributed to a larger proportion of dependents individuals under 15 and over 65 in male-headed households. In terms of labor resources, the average adult equivalent ratio in male-headed households is 3.1, whereas in female-headed households, it is 2.36. A higher adult equivalent ratio suggests more available labor resources for various agricultural tasks during the growing season, underscoring the significance of demographic factors in coping with climate change, as noted by Amare and Simane (2017) and Asrat and Simane (2017). Furthermore, labor endowment, which reflects a household's potential for labor exchange and participation in communal activities, serves as a vital source of social capital in rural economies. Research by Alhassan et al. (2019) and Tanny et al. (2017) also highlights that demographic profiles can influence farmers' decisions to adapt their agricultural practices in response to climate change. When considering the three indicators that comprise the demographic component, male-headed households show a lower adaptive ability index (0.558) compared to female-headed households (0.455).

Knowledge/Skill: This component consists of four indicators: education, access to climate information, training, and extension services. Education and training play a crucial role in influencing farmers' decision-making and their ability to adapt to climate change. In the study, over 48% of respondents from male-headed households reported having access to various training opportunities related to climate issues, compared to only 31% in female-headed households. Regarding literacy, 49% of male-headed respondents and 38.75% of female-headed respondents had received formal education. Despite female-headed households relying solely on

rain-fed agriculture, their access to weather forecast information is limited due to lower education levels. This lack of education can hinder their ability to analyze and interpret weather variability information, as well as diminish their motivation to respond to changing conditions (Rao et al., 2019), ultimately affecting their capacity to cope with climate change. Focus group discussions revealed that men generally have better access to weather information. They receive updates from sources such as radio, neighbors, agricultural experts, and traditional forecasters. In contrast, women farmers often lack access to extension agents because they have less time to meet with agricultural experts. Consequently, female-headed households scored significantly higher on the knowledge and skill profile index than male-headed households, with scores of 0.55 and 0.41, respectively. This aligns with findings by Alhassan et al. (2019), which highlighted that differences in respondents' adaptive capacities in relation to gender and educational backgrounds.

Asset: The asset profile consists of three key indicators: landholding, livestock ownership, and land rental or sharecropping arrangements. Among these, the asset component had a value of 0.703, indicating its significant impact on the vulnerability of female-headed households. This high value likely reflects the lower levels of livestock ownership and smaller landholdings among female-headed households compared to their male counterparts. The data reveal that female-headed households had an average landholding size of 0.38 hectares, whereas male-headed households averaged 0.68 hectares. The livelihoods of households led by women tend to be less stable, making them more vulnerable to the effects of climate change. Many female-headed households, often comprised of widowed women, have limited land ownership because access to land and other properties is typically obtained through marriage (Balikoowa et al., 2019). More than 45% of female-headed households reported relying on renting or sharecropping their land, which restricts their ability to diversify and enhance crop production.

Focus group discussions indicated that female-headed households are often forced to rent out their land or provide it to sharecroppers due to a lack of adult male laborers and oxen available for farming. As noted by Asrat and Simane (2017), the size, productivity, and utilization of cultivated land are closely linked to both vulnerability and adaptability, as these factors facilitate the implementation of soil conservation practices and allow for crop diversity. When considering the indicators that comprise the asset component, male-headed households demonstrated a lower

vulnerability index of 0.509 compared to 0.703 for female-headed households. This finding aligns with the observations of Maja et al. (2023) and Rao et al. (2019), who highlighted the increased vulnerability of female-headed households due to their limited access to and entitlement to resources, particularly land and labor, in a system where men traditionally dominate most roles.

Table 7 Livelihood vulnerability indexed scores across each gender group

Major components	Sub-components	An index score of sub-components		An index score of major components	
		Male HH	Female HH	Male HH	Female HH
Demographic profile	Age dependency ratio	0.771	0.711	0.5586	0.4555
	The average age of household heads	0.4871	0.3589		
	Total family size in the adult equivalent	0.4175	0.2964		
Knowledge and skill	percent of household heads that have never attended formal schools	0.5094	0.6124	0.4195	0.5504
	percent of household heads who reported not having access to weather variability information	0.3333	0.5969		
	percent of household heads did not attend training on climate change and variability	0.5131	0.5349		
	percent of household heads who stated that has not had access to extension service	0.3221	0.4574		
Livelihood strategy	percent of households that have no access to microfinance services	0.3895	0.6202	0.479	0.613
	percent of households solely dependent on on-farm income sources	0.65	0.7		
	Average livelihood diversification	0.4	0.52		
Asset	Index of average households having livestock in TLU	0.7797	0.8393	0.509	0.7037
	Index of average farmland size in hectares	0.6181	0.8145		
	percent of households rented out or sharecropped their land	0.129	0.4573		
Technology	percent of household heads who are not using insecticide, pesticide, and herbicide	0.415	0.5813	0.428	0.565
	percent of household heads who are not using organic/inorganic fertilizer	0.415	0.5736		
	percent of household heads who stated that they did not have access to drought-resistant and short-season varieties	0.454	0.5426		
	percent of households that do have not access to irrigated land	0.6966	0.8217		
Social capital	percent of households that have not membership in farmers association	0.427	0.5659	0.483	0.645
	percent of households' money borrowed from relatives and others	0.312	0.456		
	percent of households that receive aid from local organizations	0.712	0.914		

Food	Average crop diversity index	0.1675	0.375	0.3172	0.4794
	Average food insufficient months per year	0.175	0.25		
Water	percent of households that never store grains for drought periods	0.4723	0.75		
	percent of households that have no access to safe drinking water	0.476	0.484		
Health	percent of households that have faced water conflict(s)	0.356	0.345	0.3601	0.367
	Average walk time to travel to water sources (min)	0.2483	0.2736		
	Average walking time to get to primary health facilities (min)	0.4933	0.5066	0.4988	0.6134
	percent of households that have a family member in a chronic illness	0.5941	0.6667		
Natural disaster	percent of households that have a family member missing work or school due to illness	0.409	0.6667		
	percent of households reporting land degradation by climate-related extremes during the past ten years	0.2585	0.45	0.423	0.516
	percent of households who lost crops as a result of the floods and drought	0.638	0.666		
	percent of households that did not receive a warning about the pending natural disasters	0.2029	0.45		
	Drought risk values averaged over ten years during the rainy season.	0.5714	0.5714		
	Average flood risk values per year over ten years during the rainy season	0.4457	0.4457		
Climate variability and change	Mean SD of average maximum monthly temperature (oC)	0.5756	0.5756	0.465	0.465
	Mean SD of average minimum monthly temperature (oC)	0.4005	0.4005		
	Mean SD of average precipitation by month (mm)	0.4208	0.4208		
LVI			0.446	0.542	

Source own collected data (2023)

Table 8 livelihood vulnerability index scores of each agro ecologic

Major components	Sub-components	An index score of sub-components			An index score of major components		
		Highland	Mid-land	Lowland	Highland	Midland	Lowland
Demographic profile	Age dependency ratio	0.62	0.57	0.68	0.503	0.513	0.51
	The average age of household heads	0.48	0.52	0.47			
	Total family size in the adult equivalent	0.41	0.45	0.38			
Knowledge and skill	percent of household heads that have never attended formal schools	0.50	0.51	0.53	0.435	0.4525	0.5
	percent of household heads who reported not having access to weather variability information	0.41	0.42	0.49			
	percent of household heads did not attend training on climate change and variability	0.51	0.47	0.53			
	percent of household heads who stated that has not had access to extension service	0.32	0.41	0.45			
Livelihood strategy	percent of households that have no access to microfinance services	0.38	0.39	0.42	0.476	0.47	0.473
	percent of households solely dependent on on-farm income sources	0.65	0.61	0.7			
	Average livelihood diversification	0.4	0.41	0.3			
Asset	Index of average households having livestock in TLU	0.77	0.73	0.54	0.69	0.63	0.44
	Index of average farmland size in hectares	0.61	0.53	0.34			
Technology	percent of household heads who are not using insecticide, pesticide, and herbicide	0.41	0.45	0.58	0.48875	0.471	0.595
	percent of household heads who are not using organic/inorganic fertilizer	0.415	0.435	0.52			
	percent of household heads who stated that they did not have access to drought-resistant and short-season varieties	0.45	0.41	0.53			
	percent of households that do have not access to irrigated land	0.68	0.59	0.75			
Social capital	percent of households that have not membership in farmers association	0.42	0.39	0.48	0.49	0.46	0.58
	percent of households' money borrowed from	0.32	0.31	0.45			

	relatives and others						
Food	percent of households that receive aid from local organizations	0.73	0.68	0.82			
	Average crop diversity index	0.17	0.15	0.32			
	Average food insufficient months per year	0.16	0.12	0.20	0.263	0.213	0.28
Water	percent of households that never store grains for drought periods	0.46	0.37	0.32			
	percent of households that have no access to safe drinking water	0.46	0.41	0.52	0.346	0.336	0.49
	percent of households that have faced water conflict(s)	0.36	0.42	0.65			
Health	Average walk time to travel to water sources (min)	0.22	0.18	0.30			
	Average walking time to get to primary health facilities (min)	0.44	32	0.52			
	percent of households that have a family member in a chronic illness	0.52	0.41	0.67	0.456	0.443	0.52
Natural disaster	percent of households that have a family member missing work or school due to illness	0.41	0.37	0.62			
	percent of households reporting land degradation by climate-related extremes during the past ten years	0.27	0.21	0.3			
	percent of households who lost crops as a result of the floods and drought	0.61	0.41	0.68			
	percent of households that did not receive a warning about the pending natural disasters	0.25	0.20	0.31	0.414	0.304	0.458
	Drought risk values averaged over ten years during the rainy season.	0.45	0.39	0.58			
Climate variability and change	Average flood risk values per year over ten years during the rainy season	0.49	0.31	0.42			
	Mean SD of average maximum monthly temperature (oC)	0.40	0.46	0.58			
	Mean SD of average minimum monthly temperature (oC)	0.29	0.32	0.40			
	Mean SD of average precipitation by month (mm)	0.47	0.48	0.41	0.386	0.42	0.463
LVI				0.442	0.417	0.48	

Livelihood strategies: Female-headed households exhibit a higher vulnerability compared to male-headed households, with a livelihood strategies index value of 0.613. The dependence on agriculture increases household vulnerability, as crop failures can lead to significant income losses. Female-headed households typically exhibit less diverse livelihood strategies, resulting in fewer members engaged in non-farm activities and a smaller percentage participating in off-farm work. This lack of diversity suggests that expanding livelihood options could help reduce household vulnerability. In contrast, male-headed households benefit from a wider array of income sources, including non-farm jobs such as handcrafting, daily labor, and small-scale trading. This diversification provides these households with both primary and secondary income streams, making them less susceptible to the impacts of climate change and variability. Research by Chidakwa et al. (2020) highlights that limited income diversification and insufficient agribusiness development can lead to increased vulnerability to climate change. Access to microfinance services is crucial for expanding off-farm income opportunities; however, many female-headed households reported lacking timely access to such services, which hinders their ability to diversify their income sources. The limited availability of microfinance options, combined with low adoption of high-yield crop seeds and fertilizers, has resulted in lower agricultural productivity and yields among these households.

Technology: The disparities in technology usage between female-headed and male-headed households are primarily linked to differences in the application of chemical fertilizers, insecticides, improved seeds, and irrigation practices. With an index value of 0.63, technology significantly impacts the vulnerability of female-headed households more than that of male-headed households (see Table 6). In female-headed households, the use of insecticides and fertilizers is notably low, likely due to a lack of understanding regarding cultivation methods and limited access to these inputs. Discussions with women's focus groups revealed that women farmers often do not utilize technology because they lack training and do not have sufficient financial resources to purchase improved seeds and fertilizers. Consequently, this leads to lower yields and heightened vulnerability to climate change and variability.

The study indicate that nearly 30% of male-headed households engage in small-scale irrigation, while only 10% of female-headed households have access to such practices. A significantly higher percentage of female-headed households do not practice irrigation, which increases their

reliance on rain-fed agriculture an increasingly unreliable source of water due to climate change. Women face heightened agricultural production risks stemming from their limited access to high-yield crop varieties and insufficient availability of fertilizers, both of which contribute to their vulnerability to climate change. This aligns with previous research from semi-arid regions in Africa and Asia (Rao et al., 2019) and studies conducted in Ethiopia (Bedeke et al., 2020), which found that women have less access to information about and control over essential agricultural inputs like high-yielding crop varieties, further exposing them to greater vulnerability compared to men.

Social network: Social networks play a crucial role in determining the vulnerability of farmers in the study area. The findings indicate that female-headed households are more vulnerable in terms of social networks, with an index value of 0.645, compared to 0.483 for male-headed households. This increased vulnerability may stem from a higher proportion of female-headed households relying on social networks for borrowing money and receiving assistance from others. Conversely, male-headed households exhibit a lower index value for membership in various local social groups (0.427) compared to female-headed households. However, female farmers generally have low participation in social relations. Focus group discussions revealed that single women often lack time for socializing, as they prioritize meeting their family's food needs. Participation in social groups significantly influences the ability to adapt to climate change (Balikoowa et al., 2019). Over 90% of female-headed households reported seeking assistance from local organizations to cope with natural disasters, with emergency food aid being a primary form of support due to food scarcity and severe malnutrition resulting from frequent droughts. While male-headed households also sought assistance from local organizations, their access to food aid has helped enhance their resilience in facing extreme weather events.

Sensitivity of smallholder farmers to climate change and variability

Food: Food security is a significant factor contributing to vulnerability, particularly for female-headed households, which have an index value of 0.56. The findings indicate that female-headed households often struggle to provide adequate food for their families for approximately 3 months each year, compared to 2.1 months for male-headed households. Furthermore, a higher percentage of female-headed households 65% reported that they do not store any crops, while only 47% of male-headed households indicated the same. Interestingly, female-headed

households scored higher on the crop diversity index (0.375) compared to male-headed households (0.167). This may be attributed to the greater access that male-headed households have to land through various arrangements (leased, rented, or family land), which facilitates the production of a wider variety of crops and helps reduce their vulnerability to climate change. These findings suggest that adaptation strategies aimed at mitigating the adverse effects of climate change and variability on women farmers should prioritize enhancing food security. Consistent with the research by Balikoowa et al. (2019), female-headed households are reported to be food insecure, as many do not appear to have stored any of their previous season's harvest.

Water: The water component consists of three sub-components. Nearly 47% of both male-headed and female-headed households lack access to safe drinking water. Many households must walk for hours to obtain drinking water, and inadequate water delivery and storage services contribute to poor hygiene and sanitation practices. These water-related health issues can diminish household labor productivity and resilience, thereby increasing vulnerability to climate change. Research indicates that improving access to and the quality of rural drinking water can reduce vulnerability to climate change (Bedeke et al., 2020). Focus group discussions revealed that the responsibility for fetching water for household use falls solely on women. As a result, women are particularly sensitive to the onset of drought or water shortages, as they must ensure that both their families and livestock have enough water, especially in areas where resources are scarce.

Health: When considering all the sub-components, female-headed households demonstrate significantly higher vulnerability (0.613) compared to male-headed households (0.498). Specifically, female-headed households show greater vulnerability (0.506) regarding the typical travel time to health facilities, while male-headed households have an index of 0.493. The health status of smallholder farming households often deteriorates due to inadequate access to healthcare, increasing their susceptibility to extreme weather events. Additionally, female-headed households have a higher percentage of members who did not attend school or work in the past six months due to illness, underscoring how limited access to healthcare contributes to their vulnerability. The calculated vulnerability indices indicate that female-headed households (0.66) are more vulnerable to chronic illness than male-headed households (0.59). This finding aligns with Maja et al. (2023), which suggests that female-headed households generally have less

access to health services and experience higher rates of chronic illness compared to their male counterparts. This aligns with findings from Suhiyini et.al. (2019), household heads that cultivate only one type of food and have limited access to healthcare and safe water sources are particularly vulnerable to the impacts of climate change.

Exposure: In terms of natural disasters, analysis reveals that female-headed households are more vulnerable (0.516) compared to male-headed households (0.423). This heightened vulnerability among female-headed households can be attributed to three key factors. First, they reported higher percentages of crop losses and significant land degradation due to severe droughts and flooding, with figures of 45% and 25.84%, respectively. Additionally, a substantial number of farmers from both genders did not receive any warnings about impending natural disasters; however, this issue is particularly acute for female-headed households, with approximately 66% reporting a lack of information about upcoming disasters, which hampers their ability to prepare adequately. This suggests that early warning information is less accessible to female-headed households. Effective early warning systems and community awareness initiatives could help these communities better prepare for extreme weather events.

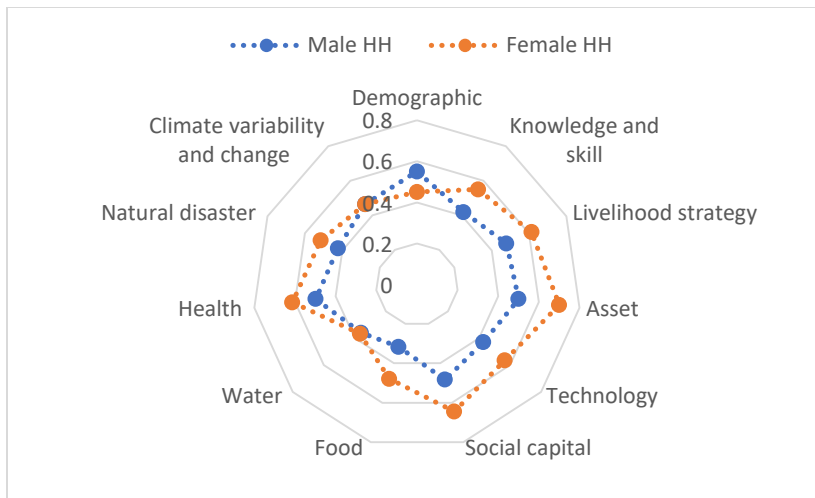
Seasonal weather forecasts provided by local farming associations can also assist farmers in adjusting planting schedules and managing water resources more effectively during adverse conditions. Focus group discussions indicated that women farmers are especially vulnerable to natural disasters, facing issues such as landslides from flooding. Unlike male farmers, who often employ soil and water conservation techniques to mitigate their vulnerability, women farmers lack access to early warning information due to poverty and limited access to radios, leaving them less informed about impending threats.

Furthermore, the dual responsibilities of women managing domestic duties while also were making food and firewood exacerbate their vulnerability to droughts, floods, and other climatic extremes. Traditional societal barriers, including restricted access to land, climate knowledge, credit services, and other resources, further heighten the vulnerability of disadvantaged groups to climate change and variability (Maja et al., 2023; Balikoowa et al., 2019).

Overall, female-headed households exhibit a higher Livelihood Vulnerability Index (LVI) than male-headed households (0.542 compared to 0.446), indicating greater vulnerability to the impacts of climate change and variability. Figure 3 illustrates a spider diagram of the 11 major

components, with the scale ranging from the center (least vulnerable) to 0.7 (most vulnerable). The diagram demonstrates that female-headed households are particularly vulnerable in terms of livelihood strategies, technology, knowledge and skills, social networks, assets, food security, health, and exposure to natural disasters. This aligns with findings from Alhassan et al. (2019), which showed that households headed by women in Ghana possess lower adaptive capacity, thereby increasing their vulnerability to climate change.

Figure 3 Gender vulnerability spider diagram



Source: own collected data 2023

4.2.2. The VI-IPCC Gender Vulnerability Assessment

The IPCC defines vulnerability as a system's adaptive capacity, sensitivity, and exposure to climatic stresses. In this assessment, the major components were categorized into three contributory factors: adaptive capacity (which includes the weighted averages of demographic profile, livelihood, assets, technology, knowledge/skills, and social networks), sensitivity (encompassing the weighted averages of health, food, and water), and exposure (corresponding to the natural disaster and climate change components). The calculated indices for these vulnerability contributory factors are presented in Table 7.

Table 9 Vulnerability index score based on the IPCC across each gender group

IPCCs defined components	Major indicators	Standardized index of each gender	
		Male HH	Female HH
Adaptive capacity		0.5124	0.4012
	Demographic profile	0.4414	0.5445
	Knowledge and skill	0.4906	0.3876
	Livelihood strategy	0.6667	0.4031
	Asset	0.4869	0.4651
	Technology	0.6779	0.5426
Sensitivity	Social capital	0.5805	0.4496
		0.392	0.4868
	Food	0.3867	0.5601
	Water	0.3263	0.3532
Exposure	Health	0.4988	0.6134
		0.4392	0.4975
	Natural disaster and climate variability	0.4392	0.4975
VI-IPCC		-0.0288	0.0468

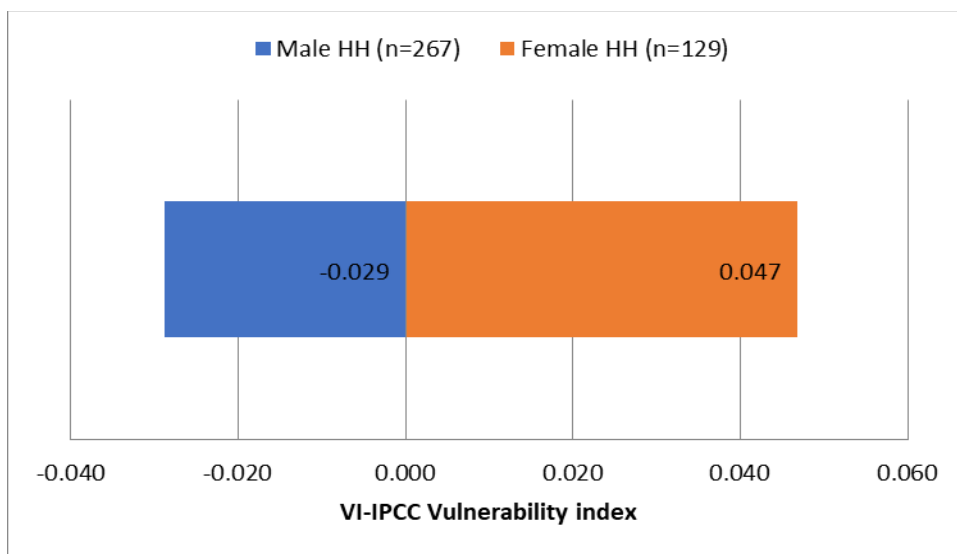
Source own collected data (2023)

The results indicate that female-headed households are more vulnerable in terms of adaptive capacity, with an index value of 0.58 compared to 0.47 for male-headed households. Additionally, female-headed households exhibit greater sensitivity to climate change and variability, scoring 0.486, while male-headed households score 0.392. In terms of exposure to climate change and variability, both groups are almost equally vulnerable, with scores of 0.439 for male-headed households and 0.497 for female-headed households.

The decomposition of vulnerability into exposure, sensitivity, and adaptive capacity provides a nuanced understanding of gender-differentiated climate impacts. The results indicate that female-headed households (FHHs) and male-headed households (MHHs) have similar exposure levels, reflecting the fact that both groups are subject to the same climatic hazards, such as droughts and floods, within the same districts and kebeles. However, FHHs exhibit higher sensitivity than MHHs, largely due to structural and socioeconomic constraints. Female-headed households typically have smaller landholdings, limited access to credit, lower ownership of productive assets, and reduced labor availability, which increases the impact of climate shocks on their livelihoods. Combined with relatively lower adaptive capacity in terms of access to extension services, social networks, and institutional support these factors contribute to greater overall

vulnerability among FHHs despite comparable exposure. This pattern underscores that vulnerability is multidimensional, and equal exposure does not guarantee equal risk: it is the interplay of exposure, sensitivity, and adaptive capacity that determines differential vulnerability across gender. These findings align with previous studies highlighting that gendered inequalities in resources and decision-making power amplify sensitivity and overall vulnerability for female-headed households (Mersha & Van Laerhoven, 2016; Balikoowa et al., 2019; Rao et al., 2019).

Figure 4 VI-IPCC Vulnerability indexes of male and female household heads



Source own data collected (2023)

The VI-IPCC index indicates that male household heads exhibit lower vulnerability, with a score of -0.029, while female household heads display greater vulnerability, reflected in a score of 0.047, within the context of the study area (see Fig. 4). This disparity in vulnerability is largely driven by differences in adaptive capacity and sensitivity. Female-headed households tend to have less adaptive capacity, making them more susceptible to the impacts of climate change. Although both groups experience similar levels of exposure to climate-related risks, the greater sensitivity of female-headed households contributes significantly to their overall vulnerability.

4.3. Agro-Ecological Zone-Based Analysis of Vulnerability

The results of the LVI analysis reveal substantial variations in vulnerability across agroecological zones. The overall LVI scores indicate that Lowland households (0.487) are the most vulnerable, followed by those in the Highlands (0.442), while Midland households (0.418) are relatively less vulnerable.

At the component level, Lowland households consistently score higher on vulnerability indices related to technology (0.595), social capital (0.583), water (0.490), health (0.527), and natural disasters (0.458). This suggests that weak institutional support, poor access to agricultural technology, recurrent water scarcity, and exposure to climate-related hazards amplify vulnerability in Lowland areas.

Highland households, despite relatively better asset ownership (0.690), remain vulnerable due to demographic pressure (0.503) and dependence on limited livelihood strategies (0.477). In contrast, Midland households show more balanced scores, with lower vulnerability in food security (0.213), natural disasters (0.304), and health (0.443), which contributes to their overall lower LVI.

Demographic Profile

All zones exhibit moderate demographic vulnerability, with Midland slightly higher (0.513). High dependency ratios reduce labor availability and savings, limiting households' ability to adopt adaptation strategies. This finding is consistent with evidence from the Upper Blue Nile basin, where households with high age-dependency ratios were more vulnerable to climate variability (Asmare et al., 2024).

Knowledge & Skill

Lowland households (0.500) face the highest vulnerability due to low education, limited extension service, and poor access to climate information. Similar patterns were reported in Arsi and East Shewa zones, where literacy and extension access significantly reduced vulnerability (Fufa et al., 2025).

Livelihood Strategy

Scores are relatively close across zones, but Lowland households remain slightly worse off (0.473), reflecting high dependence on on-farm income and weak access to microfinance. This aligns with findings in southern Ethiopia, where limited livelihood diversification and financial constraints exacerbated vulnerability (Molla et al., 2023).

Assets

Asset ownership is much stronger in Highland (0.690) and Midland (0.630) compared to Lowland (0.440). Asset poverty is a critical driver of vulnerability because livestock and land serve both as livelihood foundations and buffers during shocks. Similar conclusions were drawn

in northwestern Ethiopia, where asset endowment determined household resilience (Likinaw et al., 2024).

Technology

Lowland households (0.595) are most vulnerable due to limited access to drought-resistant crops, fertilizers, pesticides, and irrigation. Evidence from northwestern Ethiopia shows that households with access to agroforestry and improved inputs had lower vulnerability (Belay & Melese, 2024).

Social Capital

Social capital is weakest in Lowlands (0.583). Limited membership in farmer associations and reliance on informal borrowing increases exposure to shocks. Studies of Borana pastoralists confirm that weakening customary institutions and reciprocity networks undermine adaptation capacity (Beyene & Abdeta, 2023).

Food

Food security vulnerability is highest in Lowland areas (0.280), where households reported fewer months of adequate food and low grain storage. This is consistent with findings from southwestern Ethiopia, where food insecurity was closely linked to weak adaptation strategies (Kassa et al., 2024).

Water

Lowland households (0.490) are also more vulnerable in terms of water, facing limited access to safe drinking water, conflicts, and long travel times. National assessments emphasize that drought and rainfall variability have intensified rural water scarcity, particularly in semi-arid lowlands (Dessie et al., 2024; World Bank, 2025).

Health

Lowland households (0.527) are most affected by illness and long travel times to health facilities. Unsafe water and poor sanitation amplify vulnerability. Recent public health studies confirm that waterborne diseases remain widespread in Ethiopian rural areas, especially under climate stress (Haile et al., 2025).

Natural Disasters

Exposure to floods, droughts, and land degradation is highest in Lowland zones (0.458). Recent reviews confirm that drought is a chronic driver of vulnerability in lowland Ethiopia, while preparedness and warning systems remain inadequate (Tadesse, 2025).

Climate Variability & Change

Lowlands also face greater variability in rainfall and temperature (0.463). Climate projections for Ethiopia indicate that lowlands are disproportionately affected by temperature extremes and rainfall unpredictability (Dessie et al., 2024; Asmare et al., 2024).

4.4. Perception of Smallholder Farmers on Climate Change and Variability

Most farmers reported that over the past three decades, temperatures have risen, rainfall has decreased and water availability during the growing season has declined. Results showed that 92.13% of male household heads and 78.29% of female household heads perceived an increase in temperature, while 94% of male and 79.07% of female household heads perceived a decrease in rainfall (Table 8). This indicates that the perceptions of most male and female heads were consistent with meteorological records obtained from the NMA of Ethiopia (Figures 1 and 2, in the appendix section).

Previous research found that most respondents were aware of climate change and its impact on livelihoods (Asfaw et al., 2019; Mihiretu et al., 2021). However, there was a gender gap in perception levels, with a significantly lower proportion of women perceiving climate variable changes. Female household heads may be less aware of climate change than male heads for several reasons: Instead of having a more positive perception of an environmental factor affecting their livelihood, women lagged behind in perceiving the change (Wrigley-Asante et al., 2019). Female heads may be less aware due to lower educational status and limited access to information (Maja et al., 2023). While most farmers perceived changes in climate variables, a significantly lower proportion of female-headed households perceived these changes, likely due to socioeconomic and access-related factors.

Due to their dual responsibilities for farming and household duties, rural female farmers may lack sufficient time to obtain climate change information (Mersha and Van Laerhoven, 2016). The KII interviews and FGDs also showed that over the past three decades, temperature in the study area has increased while rainfall intensity and frequency has decreased. Previously, rainfall had a more predictable pattern but is now insufficient to support crop production during the growing season. Rainfall onset and cessation dates have become more erratic. Both male and female respondents agreed that irregular rainfall has negatively impacted total farm productivity, due to climate change and variability. They noted that inconsistent rainfall directly harms crop

and animal productivity, while excessive temperatures cause soil moisture evaporation and crop wilting. Early end to the rainy season and severe drought results in poor grain development and low crop yields.

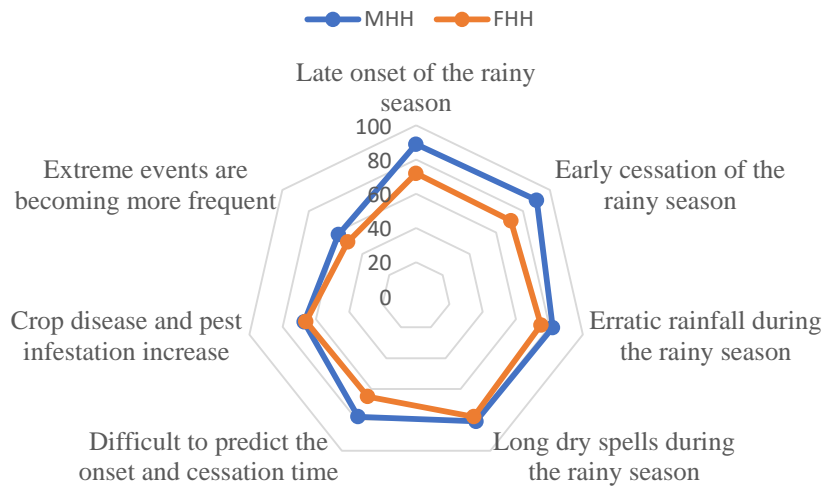
Table 10 Smallholder farmers' perception of climate change in the North Wollo zone (1992-2020)

Climate variables perceived change	Male household heads (n=267)		Female household heads (n=129)	
	Frequency	%	Frequency	%
Temperature				
Increase	246	92.13	101	78.29
Decrease	4	1.49	3	2.32
No change	17	6.36	25	19.37
Rainfall				
Increase	1	0.37	4	3.1
Decrease	251	94	102	79.07
No change	15	5.6	23	17.82

Source: own survey result 2023

Most farmers reported that the rains ended early and started later than usual: 90.2% of male and 71% of female household heads said the rains ended early; 89% of male and 72% of female heads said the rains started later (Figure 5). FGDs showed that during the rainy season, it is challenging to predict variability in rainfall patterns. They said agricultural production has been declining and they are facing food insecurity due to delayed rainfall onset and early cessation. According to other studies, most Ethiopian farmers are aware that temperatures are rising and rainfall is decreasing (Asfaw et al., 2019; Asrat and Simane, 2018). Findings also indicated 67% of male and 66% of female household heads perceived more crop diseases and pest infestations. This is consistent with reports that climate change in Ethiopia has resulted in lower crop yields and higher livestock deaths (Mihiretu et al., 2021).

Figure 5 Climate perceptions of household heads in the North Wollo zone a period of 1992-2020



Source: own survey data 2023

4.5. Adaptation Strategies to Adverse Effects of Climate Change and Variability

Respondents were asked to express the main adaptation strategies they have used to mitigate the negative effects of climate change and variability. The majority of respondents said they have implemented more than one adaptation measure on their farms to increase crop yields. The results of the chi-square test revealed a significant difference between the gender groups in terms of the adaptation strategies of changing planting date, irrigation, crop diversification, improved crop varieties, and soil and water conservation (Table 9). Nonetheless, there were gender differences in adaptation strategies due to gender inequalities in resource access and control, and different agricultural activities. These barriers limited land ownership, reduced access to credit, and lower participation in extension programs constrain women’s ability to translate knowledge and skills into effective climate adaptation measures. Overcoming these barriers requires gender-sensitive interventions, including securing land rights for women, providing targeted extension services and training, facilitating access to inputs and credit, and promoting participation in cooperatives and community decision-making. Strengthening these institutional supports would enable female-headed households to implement multiple adaptation strategies, thereby reducing their vulnerability and enhancing household welfare.

The findings indicate that changing the planting date for crops is the primary adaptation strategy for both gender groups in response to unpredictable rainfall, particularly late-onset rainfall. However, more male-headed households (73.78%) use this strategy compared to female-headed households (58.91%). This suggests that male-headed households were more likely than female-headed households to adjust planting dates because female-headed households experience more socioeconomic constraints. Males are more likely than females to work on farms, so they are more informed about climate change and the advantages of adaptation technologies and more likely to adopt them. Similar to this, Maja et al. (2023) revealed households with male heads change planting dates more frequently than households with female heads.

The second most common adaptation strategy among farmers with male heads was the practice of soil and water conservation techniques. Many of the male-headed farmers who were interviewed practiced soil and water conservation techniques in response to the perceived change in order to reduce the negative effects of climate change on their livelihood. (Belay et al., 2017) noted that soil and water conservation techniques are used for improving soil moisture and organic matter retention as well as reducing the risk of flooding. This was higher (70.03%) for male household heads and lower (52.71%) for female household heads as a choice of adaptation strategy. This suggests that the labor-intensive nature of soil and water conservation, it makes sense that male farmers would use the technique more likely than female ones. This is in line with other studies Atinkut and Mebrat (2016) and Deressa et al. (2009) argue that the adaptation of soil and water conservation measures may have been hindered by the presence of a female-headed household that may have less access to information, land, labor, and other resources.

Crop diversification was another preferred adaptation strategy, with more male household heads (66.67%) engaging in it than female household heads (55%). Farmers used this technique to protect themselves from crop failure and dry spells at crucial stages of crop development by planting different crops within the same cropping seasons. A key informant elder male farmer from the Lasta district noted that the majority of households practiced crop diversification as a result of agricultural extension officers' recommendations; however, since crop diversification requires a lot of land and women typically own less land than men, men typically perform better in this area than women. This is consistent with the finding by Wrigley-Asante et al. (2019) that

households headed by women implement crop diversification less frequently due to land constraints.

The result that 47.19% of male-headed households (MHHs) reported using drought-resistant, short-maturity, or improved crop varieties, compared to only 23.26% of female-headed households (FHHs) suggests that MHHs have better access to resources and information that facilitate adoption of improved technologies. One likely explanation is differential access to extension services, which provide farmers with information on improved seeds, planting practices, and climate-smart technologies. In many rural contexts, extension agents tend to interact more frequently with male household heads due to traditional gender roles, mobility constraints, and sociocultural norms that limit women's participation in training programs (Mersha & Van Laerhoven, 2016; Adzawla et al., 2019; Wrigley-Asante et al., 2019). This is supported by Wrigley-Asante et al. (2019) noted that male-headed households have more improved seeds such as short maturities and drought tolerance. This was a result of men being able to afford these inputs more easily than women. Similarly, to this, Deressa et al. (2009) revealed that male household heads were more likely than female household heads to use various crop varieties as a climate adaptation strategy. The FGDs revealed that men were more likely than women to have access to agricultural inputs because a male is the ability to purchase agricultural inputs rather than the female household head and they might be able to obtain credit to pay for these resources. This confirms other studies showing that women farmers do not have access to credit (Ngigi et al., 2017). Therefore, targeted interventions that enhance women's access to extension services, improved seeds, and credit could help reduce gender disparities in adaptation and improve overall household resilience to climate variability.

Income diversification was mentioned as a chosen adaptation strategy by slightly more male (29.21%) than female (28.68%) farmers. Women frequently turned to more varied occupations, especially petty trading, and making and selling traditional drinks in addition to other household activities. This was consistent with Tsegay et al. (2021) finding that FHH is more active than MHH in engaging in non-farm economic activities. The focus group discussion revealed that male and female household heads are engaged in off-farm and non-farm activities, but their incomes differ because men have access to credit and engage in high-income activities like the trade in small ruminant animals and cattle, while women lack such access due to collateral issues

and engage in low-income activities like petty trade, the sale of firewood and local drinks (known locally as “*Tella*”). This is consistent with Wrigley-Asante et al. (2019) revealed that in addition to on-farm agronomic approaches, women are more engaged in off-farm adaptation strategies, particularly petty trade.

Irrigation was a limited number of farmers' options for adaptation. Since irrigation requires both labor and capital, it is anticipated that a small number of households facing this issue to use irrigation as an adaptation strategy this is in line with (Belay et al., 2017). Due to the high sensitivity of rainfed agriculture to climate change, it is strongly advised to make every effort to intensify irrigation practices. There is a significant potential for irrigation in the district, as stated by an expert from the Habru district agricultural office, and some initiatives have been started to support rainfed agriculture, which has frequently been impacted by rainfall variability. Additionally, the current traditional irrigation methods used are not water efficient, necessitating a reconsideration of switching to technologies that would allow for the conservation of the limited water supply. An elder female farmer in the Wadla district stated that establishing irrigation by river diversion is impossible until supported by small-scale dams, although male households employed motor pumps to irrigate their plants during the dry season. However, women have technical challenges while operating pumps and women have limited access to irrigation due to a lack of capital, irrigated land, and labor. When irrigation facilities are available, perhaps through the building of small dams, they might be expensive, and it's likely that women won't have much access to them (Wrigley-Asante et al., 2019). This came up clearly in this study where 23.98% of farmers with the majority being males (30.34%) than females (10.85%) relied on irrigation.

The result showed that most adaptation strategies are motivated by the sudden change in the climate, where planned actions like irrigation and the diversification of non-farm livelihoods were not well developed, this is consistent with other studies (Asfaw et al., 2019; Belay et al., 2017).

Table 11 Distribution of adaptation strategies by the gender of respondents (n=396)

Adaptation strategies	Male HH (267)		Female HH (129)		Total (396)		Chi (X^2)
	frequency	%	frequency	%	frequency	%	
Crop diversification	168	62.92	71	55	239	60.35	5.03**
Change in planting date	197	73.78	76	58.91	267	68.93	16.45***
Improved crop variety	126	47.19	30	23.25	156	39.39	5.44**
Soil and water conservation techniques	187	70.03	68	52.71	255	64.39	21.89***
Income diversification	78	29.21	37	28.68	115	29.04	2.25
Irrigation	81	30.34	14	10.85	95	23.98	7.02**
Do nothing	70	26.21	53	41.08	123	31.06	7.34**

Source own collected data (2023) ** and *** at 5% and 1% significance level

4.6. Determinants of Choices of Adaptation Strategies to Climate Change and Variability

To estimate the determinants of farmers' selection of an adaptation option from a set of mutually exclusive adaptation strategies pursued in their context to mitigate the adverse effects of climate change. The multivariate probit (MVP) model was used separately for male- and female-headed households.

The variance inflation factor (VIF) and contingency coefficient for continuous and dummy explanatory variables, respectively were used to test for multicollinearity among the explanatory variables, and no problems were found across all household groups.

Age of the household head: The MVP model results indicate that the age of female household heads negatively and significantly correlates with soil and water conservation, crop diversification, changing planting dates, and the use of improved varieties, with significance levels of 5%, 10%, 1%, and 10%, respectively (see Table 10). In contrast, the age of male household heads negatively affects income diversification at a 10% significance level. As the age of female household heads increases, the likelihood of choosing soil and water conservation, crop diversification, changing planting dates, and improved crop varieties decreases. Focus group discussions revealed that older farmers tend to be less willing to use new technologies, such as improved varieties, while younger farmers are more eager to embrace adaptation strategies. The study found older household heads expressed less openness to new adaptation methods, preferring to rely on time-tested traditional knowledge. Younger heads open to

innovative measures had an advantage in responding strategically to changing climatic circumstances. Hence, age influenced adaptation choices, with older farmers demonstrating more reluctance towards new adaptive technologies and practices than their younger counterparts. This finding aligns with Atinkut and Mebrat (2016), whose research also noted older farmers were less inclined to choose soil and water conservation practices compared to younger farmers.

Farming experience: The MVP model results indicate that farming experience positively and significantly affected the choice of changing planting date and using an improved variety of female household heads and income diversification of male household heads. The household head has more experience and is expected to improve in his or her ability to predict the weather. This increases the likelihood that various climate change adaptation strategies to be used. This is in line with Mihiretu et al. (2019) found farmers' adaptation decisions are influenced by practical farming years rather than living longer.

Educational status: The educational status of male household heads is positively and significantly associated with using changes in planting date, using improved varieties, irrigation, and income diversification as an adaptation strategy to the unfavorable effects of climate change and variability (see Table 11). On the other hand, the female household head's educational status is positively and significantly influenced by irrigation at a 5% significance level. It is expected that knowledgeable and experienced farmers will know more about climate change and the agronomic techniques they can employ to adapt. Compared to illiterate farmers, literate farmers are more receptive to their farming technologies and have better access to scientific information. This also gives them the opportunity to learn about and practice climate change adaptation at the level of their farming. This is consistent with Maja et al. (2023) noted that education increases the ability of household heads to find and evaluate new information about climate change and the best adaptation strategies, which increases the likelihood of adapting to climate change.

Land size: Landholding size positively and significantly influenced the use of crop diversification and changing planting dates for female household heads at 5% and 1% significant levels. In order to mitigate the negative effects of climatic variability, households with larger farms were more likely to diversify their crop production during dry seasons and allocate their farm to different planting dates. Similarly, assertions have been made by female participants in focus group discussions regarding the limited crop diversification due to the small size of the

cultivated land. The findings showed that female-headed farming households tended to operate smaller-scale farms compared to their male-headed counterparts who were more commonly large-scale farmers. Farm size alone placed women at a disadvantage in terms of available adaptation options. Regarding specific gender differences, female farmers were more likely to modify their cropping patterns in response. Larger landholding size was assumed to facilitate the uptake of land-intensive technologies like irrigation infrastructure. An increased farm area would result in a higher probability of adapting through crop diversification, soil conservation practices, and tree planting. This aligns with research by Megersa et al. (2022) that found land size significantly increases the likelihood of using crop diversification and changing planting dates.

Access to extension service: Access to extension contact is one of the important institutional factors that influence farmers' adaptation choices. According to the multivariate probit model results, extension contact has a positive and significant correlation with the likelihood of selecting SWC, changing planting date, crop diversification and irrigation for male-headed households, and SWC, changing planting date and income diversification for female-headed households (see Tables 10 and 11). Farmers were more likely to be aware of climatic conditions if they regularly met and discussed issues with extension services. This suggests that farmers who have better access to information about the effects of climate change are more likely to implement adaptation strategies. The findings are also consistent with Maja et al. (2023) who noted that extension services increase the chance of changing planting dates in response to climate change. Megersa et al. (2022) also reported that increased access to extension services was positively related to the likelihood of using climate change adaptation options. According to Belay et al. (2017), agricultural extension agents are a key source of information about climate change.

Table 12 Multivariate probit model result of female-headed household's adaptation strategies choices

Explanatory variables	Soil and water conservation		Changing planting date		Crop diversification		Improved variety		Income diversification		Irrigation	
	Coef.	P-value	Coef.	P-value	Coef.	P-value	Coef.	P-value	Coef.	P-value	Coef.	P-value
Age	-0.052	0.022**	-0.043	0.094*	-0.101	0.000***	-0.069	0.062*	0.016	0.534	-0.045	0.365
Farming experience	0.045	0.120	0.078	0.014**	0.051	0.145	0.069	0.029**	-0.018	0.549	-0.010	0.825
Educational status	-0.211	0.659	0.294	0.491	0.447	0.305	0.325	0.519	-0.046	0.896	0.490	0.014**
Household size	-0.259	0.237	-0.232	0.330	-0.051	0.853	-0.009	0.981	0.036	0.879	-0.015	0.966
Land size	-0.012	0.233	0.291	0.007** *	0.645	0.043**	-0.369	0.746	-0.154	0.847	-0.812	0.428
Livestock in TLU	0.151	0.326	-0.050	0.771	-0.012	0.939	0.111	0.631	-0.139	0.400	-0.402	0.075*
Annual income	0.0003	0.319	0.0006	0.075*	-0.0001	0.799	0.0001	0.000***	0.008	0.012**	0.000 1	0.055*
Access to extension	0.962	0.044**	0.726	0.093*	0.488	0.267	-0.214	0.718	0.733	0.085*	-0.326	0.601
Access to credit	-0.203	0.593	0.083	0.837	-0.366	0.325	1.343	0.005***	0.720	0.025**	0.314	0.005** *
Access to information	0.116	0.753	-0.119	0.753	0.747	0.044**	0.116	0.802	-0.012	0.972	0.244	0.020**
Training access	0.924	0.013**	0.009	0.982	0.263	0.497	-0.648	0.179	0.380	0.289	-0.297	0.527
Member of local organization	0.422	0.234	-0.173	0.650	0.371	0.346	1.719	0.001***	-0.168	0.601	-0.735	0.109
Constant	0.802	0.512	-1.318	0.341	1.707	0.264	-5.74	0.001***	-3.02	0.012**	-3.96	0.034**

Source own collected data (2023) ***, **, * at 1%, 5%, and 10% significance levels respectively

Number of observations = (129) Log likelihood = -254.25845 Wald chi2(72) = 197.58 Prob > chi2 = 0.0000

Table 13 Multivariate probit model result of male-headed household's adaptation strategies choices

Explanatory variables	Soil and water conservation		Changing planting date		Crop diversification		Improved variety		Income diversification		Irrigation	
	Coef.	P-value	Coef.	P-value	Coef.	P-value	Coef.	P-value	Coef.	P-value	Coef.	P-value
Age	-0.015	0.315	-0.009	0.395	-0.001	0.874	-0.011	0.265	-0.037	0.004***	-0.010	0.342
Farming experience	0.018	0.236	0.014	0.217	-0.002	0.834	-0.005	0.595	0.029	0.026**	-0.001	0.890
Educational status	0.142	0.612	0.513	0.008***	0.205	0.275	0.341	0.042**	0.379	0.052*	0.306	0.097*
Household size	0.052	0.713	0.073	0.451	0.024	0.797	0.004	0.954	-0.113	0.259	0.009	0.922
Land size	-0.215	0.564	-0.217	0.448	0.015	0.954	-0.228	0.387	-0.085	0.773	-0.074	0.803
Livestock in TLU	-0.079	0.465	-0.063	0.410	-0.110	0.139	-0.036	0.580	0.065	0.377	-0.086	0.229
Annual income	0.0002	0.297	5.56	0.972	0.0001	0.297	0.0004	0.001***	-9.55e	0.579	0.000	0.000***
Access to extension	0.693	0.018**	0.806	0.000***	0.734	0.000***	0.208	0.279	0.171	0.465	0.411	0.068*
Access to credit	-0.107	0.700	0.008	0.964	-0.236	0.224	0.414	0.015**	0.326	0.115	0.479	0.014**
Access to information	0.586	0.000** *	0.747	0.002***	0.712	0.002***	0.218	0.288	0.449	0.078*	-0.037	0.872
Training access	0.295	0.307	-0.019	0.927	0.049	0.803	0.010	0.956	0.432	0.043**	-0.250	0.220
Member of local organization	0.713	0.006** *	0.054	0.773	0.255	0.156	0.089	0.594	0.052	0.783	0.123	0.509
Constant	-979	0.295	-1.19	0.071**	-805	0.213	-1.37	0.024**	-935	0.178	-2.37	0.000***

Source own collected data (2023) ***, **, * at 1%, 5%, and 10% significance levels respectively

Number of observations = (267) Log likelihood = -640.10433 Wald chi2 (72) = 231.21 Prob > chi2 = 0.0000

Likelihood ratio test of rho21 = rho31 = rho41 = rho51 = rho61 = rho32 = rho42 = rho52 = rho62 = rho43 = rho53 = rho63 = rho54 = rho64 = rho65 = 0: chi2 (15) = 184.606 Prob > chi2 = 0.0000

Household income: The findings showed that improved varieties, irrigation, and income diversification were all significantly and positively influenced by the farm household income of both male and female household heads (Tables 10 and 11). A unit increase in on-farm and off-farm income increased the probability of selecting the improved varieties and irrigation as an adaptation option. This is because of the capacity to purchase inputs and irrigation facilities. A female key informant noted that low-income female farmers often forgo improved crop varieties due to affordability issues. Female farmers also engaged in petty trading of agricultural and consumer goods as a key off-farm adaptation strategy, as it aligned well with their traditional gender roles. The income attained from such activities in turn increased women's resilience to climatic hazards by enhancing adaptive capacity. It also empowered them by subsequently improving their decision-making influence within the household. Farmers with more financial resources used more strategies for adjusting to climate change and variability. Similarly, Megersa et al. (2022) and Mihiretu et al. (2019) noted that farmers with higher incomes who had developed the capacity to overcome the capital constraint to invest in new technologies, as well as sources of capital in non-agriculture income diversification were more likely to choose a combination of adaptation strategies.

Access to credit service: The MVP model result shows that access to credit services is positively and significantly associated with improved varieties, irrigation, and income diversification for female household heads. Access to credit services, on the other hand, has a significant association with the use of improved varieties and irrigation of the adaptation options for male household heads (see Table 11). A unit increase in access to credit services for female household heads increases the likelihood of the use of improved varieties, irrigation, and income diversification as an adaptation option. However, discussions among female farmers revealed that credit services are often inaccessible to them due to various barriers. Access to affordable credit raised farmers' financial means and ability to meet the transaction expenses associated with desired adaptation choices. Farmers with credit access were more inclined to take adaptation risks knowing investments demand owned or borrowed capital. This underscores the need for accessible microfinance services to strengthen female farmers' adaptive capacity. This finding aligns with Asfaw et al. (2019), who noted that elevated credit access positively impacts the adoption of irrigation a key climate adaptation approach by enabling requisite agricultural investments.

Access to climate information: The result shows that access to climate information positively and significantly affected both male-headed and female-headed households. A unit increase in access to climate information is associated with SWC, crop diversification, and changing planting date at a 1% significance level for a male-headed household; on the other hand, crop diversification and irrigation for the female household head at a 5% significance level (see Table 10). Household heads are more likely to SWC, crop diversification, changing planting dates, and irrigation as adaptation strategies in response to climate change if they have access to climate information from various media, such as radio, television, and telephone. In focus group discussions, male farmers noted that they often receive climate information during meetings or from neighbors, whereas women face barriers to participation in such gatherings. Regarding strategies for obtaining weather and climate information, female farmers commonly don't access to radio and television and restricted informal social networks, whereas male farmers had access to television, radio and both formal and informal social networks. Additionally, male farmers had greater access to local agricultural extension agents, while female farmers tended to engage more with non-governmental organizations focused on reducing gender vulnerabilities and inequalities. The study revealed gender differences in information channels, with women exhibiting relatively constrained communication pathways compared to their male counterparts. These findings align with research from Asrat and Simane (2018) that highlight the significant and positive role of climate information in enhancing farmers' adaptation choices. Similarly, Maja et al. (2023) found that access to climate information increases the likelihood of changing planting dates.

Training access: The result shows that access to training significantly influenced soil and water conservation for male household heads at a 5% significance level (see Table 11). On the other hand, access to training significantly influenced income diversification for female household heads at a 5% significance level (see Table 10). Knowledge acquired from training equips smallholders with the technical know-how required to implement adaptive measures within their agricultural systems. The reason could be that female household heads who have received training will help to know the kinds of off-farm jobs they are engaged in addition to the knowledge gained from the training. A key informant district officer noted that trained female household heads are better informed about potential off-farm job opportunities, in addition to the skills acquired through training. The study found that training helped raise farmers' awareness of

climate change characteristics and enriched their understanding of various adaptive techniques. This result is in line with Asfaw et al. (2019) reported that short-term training and informational access play a crucial role in improving smallholder farmers' ability to adapt.

Membership in local organization: Membership in a local organization has a significant and positive influence on the use of improved variety at a 5% significance level for female household heads and SWC at a 5% significance level for male household heads (table 10 and 11). Focus group discussions revealed that interactions among farmers in these groups enhance awareness, build social capital, and facilitate knowledge sharing regarding improved varieties and soil and water conservation as adaptation strategies. This is consistent with Ngigi et al. (2017) membership in a social group increases skill and knowledge of climate adaptation options such as small-scale irrigation and the use of improved variety. Similarly, Yirga (2020) noted that membership in a social group is to expose farmers to a variety of ideas, information, and training, which may help to change the attitudes of women farmers toward new adaptation options.

4.7. Gendered Impact of Adaptation Strategies on Household Welfare

The third objective of this study was to evaluate the impact of climate change adaptation strategies on household welfare, specifically focusing on food consumption expenditure and income levels. To analyze the effects of these adaptation measures, the study employed an endogenous switching regression (ESR) model. The first stage of ESR involved binary probit estimation, and the results are summarized in Table 12. The probit model demonstrated a good fit for the data, as indicated by a Wald Chi-squared statistic of 70.98 with a significance level of $P = 0.000$. This robustness suggests that the model is effective in capturing the relationships between variables of interest.

Influential Factors on Adaptation Decisions: The model results indicated that various household, socio-economic, and institutional factors significantly influenced the decisions regarding adaptation strategies.

The results reveal a significant negative relationship between the age of the household head and the likelihood of adapting climate change strategies for both female- and male-headed households. This implies that, as farmers grow older, their probability of engaging in adaptation

strategies decreases. Younger farmers are more inclined to adapt to climate change measures because of their willingness to take risks, greater exposure to new information, and greater adaptability to technological innovations. This finding aligns with Ojo and Baiyegunhi (2020), who also reported that a negative correlation between age and the adoption of climate change adaptation strategies.

Table 14 Decision of adaptation strategies: Probit model

	Male HH			Female HH		
Number of obs.	267			129		
Wald chi2(12)	70.98			53.38		
Prob > chi2	0.0000			0.0027		
Pseudo R2	0.7488			0.8180		
Variables	Coef.	Robust Std. Err.	Marginal effects	Coef.	Robust Std. Err.	Marginal effects
Age of HH	-.068***	.025	-.006	-.139***	0.044	-.001
Education of HH	1.26***	.302	.135	2.12***	0.647	.024
ADULEQU	.095	.129	-.009	-.027	0.345	-0.000
Land size	.470	.541	.046	3.05*	1.64	.025
TLU	-.054	.103	-.005	-.581*	0.302	-.004
Extension	.797***	.301	.101	1.38*	0.771	.020
Member in LO	.594*	.307	.064	2.89***	1.03	.063
Information on CC	2.80***	.412	.573	.551	0.583	.004
_cons	1.107	1.205		5.79**	2.45	

***, **, and * significant at the 1, 5, and 10% probability levels, respectively

The education level of both male and female household heads showed a positive and significant association with the likelihood of adapting climate change adaptation strategies. Farmers who have attended formal education are better equipped to understand the benefits of adaptation strategies and are more likely to implement them than those with little or no formal education. Educated farmers have greater capacity to process and apply climate-related information, enabling them to adopt innovative and effective adaptation techniques. This finding is supported by Asfaw et al. (2019), who emphasized the role of education in accelerating the adaption of knowledge-intensive technologies. Similarly, Maja et al. (2023) highlighted that education enhances a household head's ability to actively seek, assess, and utilize new information on climate change and adaptation strategies, thereby increasing the likelihood of successful adaptation. Notably, the impact of education is stronger for women than for men, implying that educated women are more proactive in implementing adaptation strategies. This may be because

educated women understand climate risks better, have greater autonomy, and have improved access to resources.

For female-headed households (FHHs), larger land size significantly increases the likelihood of implementing climate change adaptation strategies. In contrast, for male-headed households (MHHs), land size does not exhibit a significant impact. This discrepancy can be attributed to the fact that women often have limited access to land; therefore, those who possess land are more inclined to invest in adaptation strategies. For female farmers, land size is a crucial factor for resilience, as it directly influences their capacity to implement practices that can mitigate the effects of climate change. These findings are consistent with those of Zakari et al. (2022), who emphasized that access to larger land size enables farmers to implement crop diversification as part of their adaptation strategy. Megersa et al. (2022) and Mihiretu et al. (2019) also found that wealthier farmers were more likely to invest in agricultural innovations further strengthening their resilience to climate change.

Conversely, the relationship between livestock ownership and adaptation strategies revealed a different dynamic. While having more livestock does not influence adaptation among male farmers, it appears to reduce the probability of adaptation among female farmers. This may be because women in livestock-dependent households are more likely to rely on their livestock as a safety net, leading to reluctance to adopt crop-based adaptation strategies. This reliance suggests that women may require tailored adaptation interventions that address their specific needs, such as access to drought-resistant fodder or improved veterinary services. These resources could help them better manage their livestock while also integrating crop-based strategies.

Farmers who have access to information from extension agents and are members of farmer organizations are more likely to implement climate change adaptation strategies. This is largely because such information enhances farmers' awareness of climate change issues and provides them with new knowledge on technological measures to address these challenges. Although access to extension services increases the likelihood of adaptation for both men and women, it is particularly impactful for women. Women often face greater barriers to accessing extension services, therefore when they receive guidance; they are more likely to act on it. These findings are consistent with Maja et al. (2023) who found that extension services significantly increase

the likelihood of farmers adjusting their planting dates in response to climate change. Similarly, Megersa et al. (2022) reported a positive correlation between greater access to extension services and the adoption of various climate change adaptation options.

Membership in local organizations increases the adaptation probability for both genders but is much more influential for women. Social and economic exclusion in agriculture poses significant challenges for women; therefore, being part of a local organization helps them access shared resources, information, and financial services, making it a crucial enabler of adaptation. Previous studies have support this relationship, indicating that farmers who engage with extension services and are part of farmer organizations are more inclined to implement adaptation strategies (Asrat and Simane, 2018; Belay et al., 2017; Maja et al., 2023).

These findings underscore the critical role of information and support networks in promoting effective adaptive practices among farmers. For male farmers, access to climate change information significantly increased the likelihood of adaptation. Men may have greater access to formal climate information sources (radio, TV, and training programs), allowing them to respond better. Women may rely more on informal networks (e.g., family and community discussions), which may not provide sufficient technical knowledge for adaptation. These findings corroborate the work of Asfaw et al. (2019), who emphasized that short-term training and access to information are essential for enhancing the adaptive capacity of smallholder farmers.

The analysis further indicates that male-headed households are significantly more likely to implement climate change adaptation strategies compared to female-headed households. This trend may be explained by the generally greater access that male-headed households have to agricultural information, extension services, and labor resources. These advantages facilitate the implementation of effective adaptation measures. In contrast, female-headed households often face heightened constraints regarding access to credit, land ownership, and labor availability, which limits their capacity to adapt successfully. These findings align with the study by Zakari et al. (2022), who reported a higher likelihood of adaptation among male-headed households. The barriers faced by female-headed households, including social norms, economic constraints, and limited access to supportive networks, contribute to lower rates of adaptation.

After determining the factors influencing adaptation decisions, the second-stage Endogenous Switching Regression (ESR) model assesses the impact of adaptation on food consumption expenditure and household income. The results from the ESR model-based Average Treatment Effect on the Treated (ATT) and Average Treatment Effect on the Untreated (ATU) for key outcome variables related to climate change adaptation practices are presented in Tables 13 and 14. The primary outcome variables analyzed in this study included food consumption expenditure and household income measured in Birr. The ESR results indicate that adaptation strategies lead to an increase in both food consumption expenditure and household income for female-headed households (FHH) and male-headed households (MHH). However, the magnitude of the impact and potential gains from adaptation vary significantly by gender, highlighting the existing inequalities in access to resources and adaptation benefits.

Table 15 Endogenous switching regression model result (average treatment effects) FHH

Sub-samples		Decision stage female HH		
Food consumption expenditure	consumption	To adapt	Not to adapt	Treatment effect
Farm households that adapted		(a) 6967.773	(c) 6004.712	ATT=963.061 (3.93***)
Farm households did not adapt		(d) 6068.391	(b) 4209.346	ATU=1859.046 (6.45***)
Heterogeneity effects		2758.427(10.14***)		TH = -895.985**
Household income				
Farm households that adapted		(a) 5462.216	(c)4399.074	ATT=1063.142 (4.23***)
Farm households did not adapt		(d) 4927.717	(b) 2985.428	ATU=1942.288 (5.05***)
Heterogeneity effects		2476.787(7.57***)		TH= -879.146 ***

Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$ Cells (c) and (d) denote the counterfactual outcomes, while (a) and (b) show the actual outcomes

ATT average treatment effect on the treated

ATU average treatment effect on the untreated

Households that implemented climate adaptation strategies had significantly higher food consumption expenditures compared to non-adapting households. This suggests that adaptation strategies can contribute to improved food security by increasing agricultural productivity and ensuring a stable food supply. Farmers who practice crop diversification, improved water and soil management, and climate-smart irrigation techniques are better able to sustain food availability even during periods of climate stress.

For female-headed households that implemented adaptation strategies, their food consumption expenditures increased significantly. However, if they had not adapted, food consumption expenditure would have declined by Birr 963.06 (ATT). In contrast, male-headed households that adapted would have seen their food consumption expenditure decline by a much higher Birr 3561.95 had they chosen not to do so.

Table 16 Endogenous switching regression model results (average treatment effects) MHH

Sub-samples	Decision stage male HH		
Food consumption expenditure	To adapt	Not to adapt	Treatment effect
Farm households that adapted	(a) 7127.715	(c) 3565.765	ATT=3561.95 (17.45***)
Farm households did not adapt	(d) 5501.051	(b) 4823.77	ATU=677.2807 (2.85***)
Heterogeneity effects	2303.945 (11.44***)		TH = 2884.669**
Household income			
Farm households that adapted	(a) 5227.385	(c) 1897.065	ATT=3330.321 (13.31***)
Farm households did not adapt	(d) 4469.824	(b) 3399.424	ATU=1070.4 (6.74***)
Heterogeneity effects	1827.961 (7.08***)		TH= 2259.921 ***

Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$ Cells (c) and (d) denote the counterfactual outcomes, while (a) and (b) show the actual outcomes

Given an average family size of 2.36 adult equivalents for FHHs and 3.1 adult equivalents for MHHs, the ATT for food consumption expenditure at the household level would have dropped by Birr 2272.82 for FHHs and Birr 11042.04 for MHHs did not implement climate change adaptation strategies. This indicates that although adaptation benefits both genders, male-headed households experience greater absolute benefits from adaptation.

Conversely, the potential gain from adaptation is greater for non-adapting female-headed households. If these households had implemented adaptation strategies, their food consumption expenditures would have increased by Birr 1859.04 (ATU). Meanwhile, non-adapting male-headed households would have only seen a small increase in Birr 677.28, which they chose to adapt. This suggests that female-headed households that have not yet adapted stand to gain more if they overcome adaptation barriers, implying that they face greater structural and financial challenges rather than a lack of potential benefits.

The ESR results further indicated that the likelihood of a decline in food consumption expenditure among female and male-headed climate change adapters would be 13.82% and 49.97%, respectively, if they did not adapt adaptation strategies. In contrast, if non-adapting female- and male-headed households were to implement adaptation strategies, their chances of increased food consumption expenditure would rise by 30.63% and 12.31%, respectively. Heterogeneity effects provide further insights into these disparities. For female-headed households, the heterogeneity effect for food consumption expenditure is 2758.43 (significant at the 1% level), whereas for male-headed households, it is 2303.95 (also significant at the 1% level). This suggests that the benefits of adaptation strategies are not only greater for male-headed households, but also that these households are more resilient to the impacts of climate change, as evidenced by their higher income levels and food expenditures. These findings align with those of previous research highlighting the positive impact of climate change adaptation strategies on household welfare (Asmare et al., 2019; Di Falco et al., 2011; Mogess and Degu, 2021; Sileshi et al., 2019).

Both male and female farmers benefit from adaptation strategies, but the magnitude of the impact, access to resources, and barriers to adaptation differ significantly between genders. The findings indicate that adaptation has a significant positive impact on household income, enabling households to achieve higher agricultural yields, improved market access, and greater economic resilience than non-adapting households. Adaptation strategies such as the adoption of drought-tolerant crops and efficient water management practices enhance farm productivity, thereby increasing household earnings. Additional income allows farmers to invest in better agricultural inputs, education, healthcare, and other essential needs, there by contributing to overall household well-being.

The findings reveal that the average income for female-headed and male-headed households that implemented adaptation strategies would have decreased by Birr 1063.14 and 3330.32, respectively, had they not adapted. Conversely, if non-adapting female-headed and male-headed households had implemented these strategies, their average incomes would have increased by Birr 1942.29 and 1070.40, respectively. The results indicate that farm households that implemented at least one adaptation strategy experienced a 19.4% and 23.94% increase in income for female- and male-headed households, respectively, compared to those that did not.

These findings are consistent with those of previous research (Berhe et al., 2017; Ojo and Baiyegunhi, 2020; Zakari et al., 2022), which reported that adaptation practices contribute to higher household income levels.

However, the income gap between adapting and non-adapting households is larger for men, suggesting that male-headed households have more resources to leverage the adaptation benefits. Insights from focus group discussions and key informant interviews revealed that female-headed households face greater financial and institutional barriers, limiting their ability to fully benefit from adaptation. Many women do not own land or have insecure tenure, making it difficult for them to invest in adaptation strategies. This lack of secure land rights limits their willingness to make long-term investments in improvements such as irrigation or climate-smart technologies. Additionally, Women struggle to access loans to invest in improved seeds, irrigation systems, and other critical resources for adaptation. Moreover, women face a double workload, balancing farm activities with household responsibilities such as childcare and food preparation. This dual role can hinder their ability to fully engage in adaptation efforts. Furthermore, extension services frequently target male farmers, there by contributing to a significant knowledge gap regarding climate adaptation strategies among female farmers.

Robustness Checks

To ensure the consistency and reliability of our ESR results, we conducted additional robustness checks using Propensity Score Matching (PSM) and Instrumental Variables (IV) estimation. These alternative approaches help address potential selection bias and endogeneity in adaptation decisions.

Propensity Score Matching (PSM):

The study implemented nearest-neighbor and kernel matching methods to estimate the Average Treatment Effect on the Treated (ATT). The PSM results confirm that adopting climate change adaptation strategies significantly increases both food consumption expenditure and household income, with estimates comparable in sign and magnitude to the ESR results. This suggests that selection bias based on observable characteristics does not drive the main findings.

Instrumental Variables (IV) Estimation: To address potential endogeneity of adaptation decisions, we employed a two-stage least squares (2SLS) regression using distance to the nearest extension office as an instrument. The IV estimates indicate a positive and significant effect of

adaptation on both outcome variables, consistent with ESR results, reinforcing the causal interpretation of the impacts.

Table 17 Robustness check results (ATT estimates) ESR, PSM, and IV

Outcome Variable	Household Type	ESR (ATT)	PSM (ATT)	IV (2SLS)
Food Consumption Expenditure	Female HH	963.06***	974.53***	932.23***
	Male HH	3561.95***	3480.08***	3542.31***
Household Income	Female HH	1063.14***	1065.57***	1042.68***
	Male HH	3330.32***	3286.97***	3324.02***

(Source own survey 2022) Significance levels: *** $p < 0.01$

The consistency of the ESR results with both PSM and IV estimates provides strong evidence that climate change adaptation strategies significantly enhance household welfare, measured by both food consumption expenditure and income. Gendered differences persist across methods: male-headed households capture larger realized gains, while female-headed households have higher potential gains if supported to adopt adaptation strategies. These robustness checks confirm that the observed gender disparities are not driven by methodological artifacts or sample selection bias.

5. SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1. Summary

Climate change poses substantial challenges, particularly for resource-limited communities such as smallholder farmers, where vulnerability varies drastically based on gender. The impact of climate change has been pronounced in the North Wollo zone of Ethiopia, exacerbating the existing socioeconomic inequalities. Specifically, male-headed and female-headed households experience distinct vulnerabilities owing to differing access to resources, information, and support systems. Gender dynamics in Ethiopia are influenced by various sociocultural factors, including land ownership, access to education, and participation in decision-making processes, which particularly disadvantage female-headed households. These women often face higher levels of economic stress and limited social capital, making their adaptive capacities to climate variability significantly lower than those of men.

Despite the critical role that gender plays in shaping vulnerability to climate change, the existing literature and policy frameworks often provide a generalized perspective that fails to adequately

address these nuanced differences. The problem statement highlights a crucial gap in the understanding of how socioeconomic constraints uniquely affect female-headed households, leading to suboptimal adaptation strategies. Prior research has demonstrated that merely examining the proportion of female-headed households in vulnerability assessments may not fully capture the complex factors influencing adaptive capacity.

Therefore, this study seeks to investigate the specific vulnerabilities and adaptation strategies of male- and female-headed households, providing insights that can inform policy and practice. The overarching objective of this study was to comprehensively investigate the gender dimensions of vulnerability and adaptation strategies to climate change among smallholder farmers in the North Wollo zone of Ethiopia. The specific objectives were to evaluate how gender influences vulnerability to climate change and variability among smallholder farmers. To explore how male-headed and female-headed households perceive climate change and variability, and the determinants influencing their choices of adaptation strategies. To investigate the impact of different climate change adaptation strategies on household welfare, particularly focusing on food consumption expenditure and income differences between genders.

The study utilized a multistage random sampling technique to ensure that both male- and female-headed households were adequately represented in the sample. The North Wollo Zone consists of multiple districts, each with distinct agricultural practices and climatic impacts. Given resource constraints, this study focused on three specific districts: Wadila, Lasta, and Habru. Data were collected from 396 randomly selected smallholder farmers and supplemented with qualitative insights from focus group discussions and key informant interviews. The analysis employed inferential and descriptive statistics with appropriate statistical tests (Chi-square tests and t-tests) as well as the Livelihood Vulnerability Index (LVI) and the Intergovernmental Panel on Climate Change Vulnerability Index, multivariate probit model, and endogenous switching regression model for impact analysis.

The results from the study indicated marked disparities between male- and female-headed households regarding vulnerability and adaptation strategies to climate change. Female-headed households were found to be particularly vulnerable due to several socio-economic factors, including their reliance on rain-fed agriculture, limited access to irrigation facilities, smaller landholdings, and lower levels of crop diversification. Additionally, these households face

significant barriers related to inadequate infrastructure, restricted access to financial resources, and weaker social networks. In contrast, the analysis revealed that male-headed households exhibited greater adaptive capacity. The findings suggest that they had better access to livestock, agricultural services, training opportunities, and educational resources, allowing them to implement more effective adaptation strategies, such as crop diversification, improved seed varieties, and soil conservation practices.

This study highlights critical gender disparities in climate change perceptions and adaptation strategies. While both male- and female-headed households recognized changes in rainfall and temperatures, more male-headed households reported using adaptation strategies, suggesting that women may have less access to climate information. The specific strategies employed also varied with differences in planting dates, irrigation, crop diversification, improved varieties, and soil and water conservation practices. The findings reveal the gender inequalities that contribute to these disparities.

The multivariate probit model showed that factors influencing adaptation strategies differ based on the household head's gender. Female-headed households face significant barriers, including limited land rights, low access to extension service, and training on adaptation strategies, and financial constraints, which hinder their ability to effectively adapt. The significant role of landholding size in FHH adaptation underscores the importance of securing land resources for women. Additionally, the challenges related to credit access highlight the financial barriers unique to female farmers that hinder their ability to choose new practices. These findings indicate that the adaptation challenges faced by FHHs are not only distinct, but also more pronounced because of systemic gender inequities. To enhance climate adaptation, it is essential to address these barriers.

This study highlights the significant impact of climate change adaptation strategies on both food consumption expenditures and household income among farmers. The findings reveal that households that adapt to these strategies experience substantial benefits including increased food consumption and enhanced income levels. Specifically, farmers who implemented adaptation practices were less likely to face declines in food expenditure, while those who did not adapt suffered notable financial losses. These findings underscore the critical role of various socioeconomic, institutional, and demographic factors in influencing farmers' decisions to adapt

to climate adaptation strategies. The income gap between adapting and non-adapting households is more pronounced for male-headed households, suggesting that they have more resources to benefit from climate adaptation strategies. Female-headed households face significant financial and institutional barriers, including insecure land tenure, limited access to loans for investments in climate-smart technologies, and the burden of balancing farm work with household responsibility. Additionally, extension services often prioritize men, resulting in a knowledge gap regarding climate adaptation among female farmers.

The results underscore the importance of collecting and analyzing gender-disaggregated data to inform both research and policy, ultimately fostering equitable resilience-building strategies to address the impacts of climate change on vulnerable communities. This study proposes that effective climate adaptation should incorporate a deeper understanding of gendered experiences to ensure comprehensive and sustainable solutions that promote rural livelihoods amidst climate change.

5.2. Conclusion and Recommendations

This study investigated the gender dimensions of vulnerability and adaptation strategies to climate change among smallholder farmers in the North Wollo zone of Ethiopia, with particular attention to the differences between male- and female-headed households. The findings reveal that female-headed households (FHHs) are more vulnerable to climate variability due to structural and socioeconomic constraints, including smaller landholdings, limited access to irrigation, restricted financial resources, weaker social networks, and lower access to extension and training services. While both male- and female-headed households experience similar exposure to climate hazards, FHHs are more sensitive, reflecting the multidimensional nature of vulnerability, where limited adaptive capacity amplifies the impact of climate shocks.

The study highlights that gender inequalities in resource access and control strongly influence the choice and effectiveness of adaptation strategies. Male-headed households benefit from better access to land, credit, extension services, and information, enabling them to adopt multiple adaptation strategies such as crop diversification, improved seed varieties, irrigation, and soil conservation more effectively than female-headed households. Female-headed households, despite possessing knowledge and skills, face barriers that limit the implementation of these strategies, resulting in lower adaptive capacity and higher overall vulnerability.

The Endogenous Switching Regression (ESR) models, confirms that adaptation strategies significantly improve household welfare, measured in terms of food consumption and income. Households that adopt adaptation strategies experience higher food security and income stability, while non-adopters face greater losses. However, the benefits of adaptation are disproportionately higher for male-headed households due to their greater access to complementary resources, reinforcing the need for gender-sensitive interventions.

Overall, the study underscores the importance of integrating a gender perspective in climate adaptation policies and programs.

Recommendations

Secure land and resource rights for women

Ministry of Agriculture and local land offices should formalize women's land ownership and promote joint titles.

Strengthen gender-sensitive extension services

District Agricultural Offices and NGOs should provide targeted training, demonstration plots, and female extension agents to reach women farmers effectively.

Improve women's access to credit and inputs

Microfinance institutions and cooperatives should offer low-interest loans and subsidized seeds, fertilizers, and irrigation equipment to female-headed households.

Promote women's participation in decision-making

Community development offices and cooperatives should ensure women's representation in climate adaptation committees and provide leadership training.

Use gender-disaggregated data for planning

Ministries, research institutions, and the National Meteorological Agency should collect and analyze data by gender to inform targeted adaptation policies.

Support long-term research and monitoring

Universities and NGOs should conduct longitudinal studies to evaluate the effectiveness of adaptation strategies and gender-sensitive interventions.

Implementing these recommendations will reduce gender-based disparities in vulnerability, enhance the effectiveness of climate adaptation, and improve household welfare, particularly for female-headed households.

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Appendix table 2 Multivariate probit model result FHH

Multivariate probit (SML, # draws = 5) Number of obs = 129
 Wald chi2(72) = 969.55
 Log pseudolikelihood = -254.25845 Prob > chi2 = 0.0000

	Coef.	Robust Std. Err.	z	P> z	[95% Conf. Interval]	
IRRGACCES						
AGE	-.045286	.0746551	-0.61	0.544	-.1916073	.1010354
FAREX	-.010026	.0487861	-0.21	0.837	-.105645	.085593
ADULEQU	-.0157705	.3534281	-0.04	0.964	-.7084768	.6769359
LANDSIZ	-.8123037	.9901746	-0.82	0.412	-2.75301	1.128403
TLU	-.4029904	.2548512	-1.58	0.114	-.9024896	.0965088
CREDACCE	1.31491	.5242727	2.51	0.012	.2873545	2.342466
EXTENSION	-.326836	.703799	-0.46	0.642	-1.706257	1.052585
TRAINING	-.2978816	.4917854	-0.61	0.545	-1.261763	.6660001
EDUCA	1.490895	.6170346	2.42	0.016	.2815289	2.70026
INFO	1.244286	.5816594	2.14	0.032	.1042549	2.384318
ANUALIN	.0001516	.000125	1.21	0.225	-.0000933	.0003966
COOP	-.7353011	.4086479	-1.80	0.072	-1.536236	.065634
_cons	-3.962444	1.828952	-2.17	0.030	-7.547124	-.377644
incomediversifi						
AGE	-.0165026	.0256811	0.64	0.520	-.0338314	.0668366
FAREX	-.0189125	.0288881	-0.65	0.513	-.0755322	.0377072
ADULEQU	.0367923	.2433045	0.15	0.880	-.4400758	.5136603
LANDSIZ	-.1546281	.6755362	-0.23	0.819	-1.478655	1.169398
TLU	-.1395432	.1639498	-0.85	0.395	-.4600879	.1817925
CREDACCE	.7205213	.3291358	2.19	0.029	.075427	1.365616
EXTENSION	.7330066	.480059	1.53	0.127	-.2078917	1.673905
TRAINING	.3805757	.3593034	1.06	0.290	-.323646	1.084797
EDUCA	-.0460416	.3776817	-0.12	0.903	-.7862841	.6942008
INFO	-.0124156	.3333936	-0.04	0.970	-.6658551	.641024
ANUALIN	.0000864	.0000351	2.46	0.014	.0000177	.0001551
COOP	-.1681815	.3156976	-0.53	0.594	-.7869375	.4505746
_cons	-3.025144	1.089158	-2.78	0.005	-5.159853	-.8904338
improvedvar						
AGE	-.0692542	.0434346	-1.59	0.111	-.1543845	.0158761
FAREX	.0963416	.0427207	2.26	0.024	.0126106	.1800726
ADULEQU	-.0091394	.2648436	-0.03	0.972	-.5282232	.5099445
LANDSIZ	-.3691018	.872415	-0.42	0.672	-2.079004	1.3408
TLU	.1110101	.1670743	0.66	0.506	-.2164494	.4384696
CREDACCE	1.343521	.4381409	3.07	0.002	-.4847808	2.202261
EXTENSION	-.214629	.6067188	-0.35	0.724	-1.403776	.974518
TRAINING	-.6487459	.4139512	-1.57	0.117	-1.460075	.1625835
EDUCA	.3258982	.4842803	0.67	0.501	-.6232737	1.27507
INFO	.1161166	.4404918	0.26	0.792	-.7472314	.9794645
ANUALIN	.0001824	.0000621	2.94	0.003	.0000607	.0003041
COOP	1.719829	.371857	4.62	0.000	.9910028	2.448655
_cons	-5.742209	1.686191	-3.41	0.001	-9.047082	-2.437335
plantingdate						
AGE	-.0435374	.0249883	-1.74	0.081	-.0925135	.0054388
FAREX	.078916	.035988	2.19	0.028	.0083807	.1494512
ADULEQU	-.2324809	.2112889	-1.10	0.271	-.6465996	.1816378
LANDSIZ	2.091046	.9055985	2.31	0.021	.3161054	3.865986
TLU	-.0500547	.165513	-0.30	0.762	-.3744541	.2743448
CREDACCE	.0836139	.433156	0.19	0.847	-.7653562	.932584
EXTENSION	.726686	.4303986	1.69	0.091	-.1168797	1.570252
TRAINING	.0097964	.596471	0.02	0.987	-1.159265	1.178858
EDUCA	.2941198	.5164637	0.57	0.569	-.7181305	1.30637
INFO	-.1196674	.3964825	-0.30	0.763	-.8967589	.6574241
ANUALIN	.0000668	.0000364	1.83	0.067	-4.64e-06	.0001382
COOP	-.1734496	.3343718	-0.52	0.604	-.8288064	.4819071
_cons	-1.318729	.9937218	-1.33	0.184	-3.266388	.6289301
croppdiver						
AGE	-.101775	.0230275	-4.42	0.000	-.146908	-.056642
FAREX	.0518259	.042949	1.21	0.228	-.0323526	.1360044
ADULEQU	-.0512745	.3264883	-0.16	0.875	-.6911798	.5886308
LANDSIZ	1.645769	.7059347	2.33	0.020	.2621624	3.029375
TLU	-.0120265	.1707271	-0.07	0.944	-.3466454	.3225924
CREDACCE	-.3669676	.3464759	-1.06	0.290	-1.046048	.3121126
EXTENSION	.4887618	.4111251	1.19	0.235	-.3170286	1.294552
TRAINING	.2630913	.3174086	0.83	0.407	-.359018	.8852007
EDUCA	.4475366	.4468452	1.00	0.317	-.4282638	1.323337
INFO	.7473665	.322004	2.32	0.020	.1162502	1.378483
ANUALIN	-.0000106	.0000485	-0.22	0.827	-.0001056	.0000844
COOP	.3712364	.4854713	0.76	0.444	-.5802698	1.322743
_cons	1.707078	1.714974	1.00	0.320	-1.654208	5.068365
soilcon						
AGE	-.0526699	.0244631	-2.15	0.031	-.1006168	-.0047231
FAREX	.0458834	.0262226	1.75	0.080	-.005512	.0972788
ADULEQU	-.2592999	.2303992	-1.13	0.260	-.710874	.1922743
LANDSIZ	-1.012729	1.168201	-0.87	0.386	-3.302361	1.276904
TLU	.1518986	.1507295	1.01	0.314	-.1435258	.4473231
CREDACCE	-.2037193	.5063843	-0.40	0.687	-1.196214	.7887756
EXTENSION	.9627319	.4301379	2.24	0.025	.1196771	1.805787
TRAINING	.9245023	.3647367	2.53	0.011	.2096314	1.639373
EDUCA	-.2111802	.4734945	-0.45	0.656	-1.139212	.7168521
INFO	.1166872	.4418476	0.26	0.792	-.7493181	.9826925
ANUALIN	.000036	.0000393	0.92	0.359	-.000041	.000113
COOP	.4222658	.4985586	0.85	0.397	-.5548911	1.399423
_cons	-.8058013	1.274769	0.63	0.527	-1.692701	3.304304

Appendix table 3 Multicollinearity test for variables in the MVP model

. corr AGE FAREX ADULEQU LANDSIZ TLU CREDACCE EXTENSION TRAINING EDUCA INFO ANUALIN COOP
(obs=267)

	AGE	FAREX	ADULEQU	LANDSIZ	TLU	CREDACCE	EXTENS~N	TRAINING	EDUCA	INFO	ANUALIN
AGE	1.0000										
FAREX	0.5430	1.0000									
ADULEQU	0.0126	0.3742	1.0000								
LANDSIZ	-0.0640	0.0919	0.3806	1.0000							
TLU	-0.0227	0.2249	0.4140	0.2937	1.0000						
CREDACCE	-0.1206	0.0261	0.1474	0.1917	0.1813	1.0000					
EXTENSION	-0.1989	0.0205	0.1593	0.2277	0.1125	0.2548	1.0000				
TRAINING	-0.0265	0.1226	0.3054	0.2617	0.0930	0.0559	0.0140	1.0000			
EDUCA	-0.1866	0.0300	0.1510	0.1098	0.1115	0.1387	0.1955	0.0033	1.0000		
INFO	-0.2798	-0.0491	0.0042	0.1481	0.1177	0.2009	0.3967	0.2437	0.1854	1.0000	
ANUALIN	-0.1705	0.0170	0.0967	0.1347	0.1036	0.1618	0.3218	0.0199	0.3228	0.3984	1.0000
COOP	-0.1145	-0.0073	0.0650	0.0051	0.0715	0.0403	0.1666	0.0077	0.1201	0.1927	0.1532

	COOP
COOP	1.0000

. corr AGE FAREX ADULEQU LANDSIZ TLU CREDACCE EXTENSION TRAINING EDUCA INFO ANUALIN COOP
(obs=129)

	AGE	FAREX	ADULEQU	LANDSIZ	TLU	CREDACCE	EXTENS~N	TRAINING	EDUCA	INFO	ANUALIN
AGE	1.0000										
FAREX	0.5892	1.0000									
ADULEQU	-0.1613	-0.0638	1.0000								
LANDSIZ	-0.4213	-0.3040	0.3454	1.0000							
TLU	-0.1152	-0.0420	0.4474	0.0576	1.0000						
CREDACCE	-0.3279	-0.1243	0.0399	0.3078	0.0917	1.0000					
EXTENSION	-0.4214	-0.1841	0.2011	0.4678	0.0081	0.4300	1.0000				
TRAINING	-0.4896	-0.2362	0.1666	0.3475	-0.0876	0.3910	0.4817	1.0000			
EDUCA	-0.2688	-0.2266	0.1172	0.3577	0.0501	0.4178	0.6718	0.4217	1.0000		
INFO	-0.3456	-0.1968	0.0225	0.3652	-0.1438	0.2034	0.4055	0.5327	0.3095	1.0000	
ANUALIN	-0.3645	-0.0922	0.1133	0.4667	-0.0133	0.5697	0.7144	0.5090	0.6021	0.4486	1.0000
COOP	-0.2676	-0.1546	0.0853	0.3147	-0.0032	0.3780	0.3960	0.3121	0.3177	0.3643	0.4821

	COOP
COOP	1.0000

Appendix table 6 Conversion factor for tropical livestock unit (TLU)

No	Livestock Type	Conversion factors
1	Ox	1.10
2	Cow	1.00
3	Heifer	0.50
4	Bull	0.60
5	Calves	0.20
6	Sheep	0.01
7	Goat	0.09
8	Donkey	80.50
9	Horse	0.80
10	Mule	0.70
11	Camel	1.25
12	Poultry	0.01

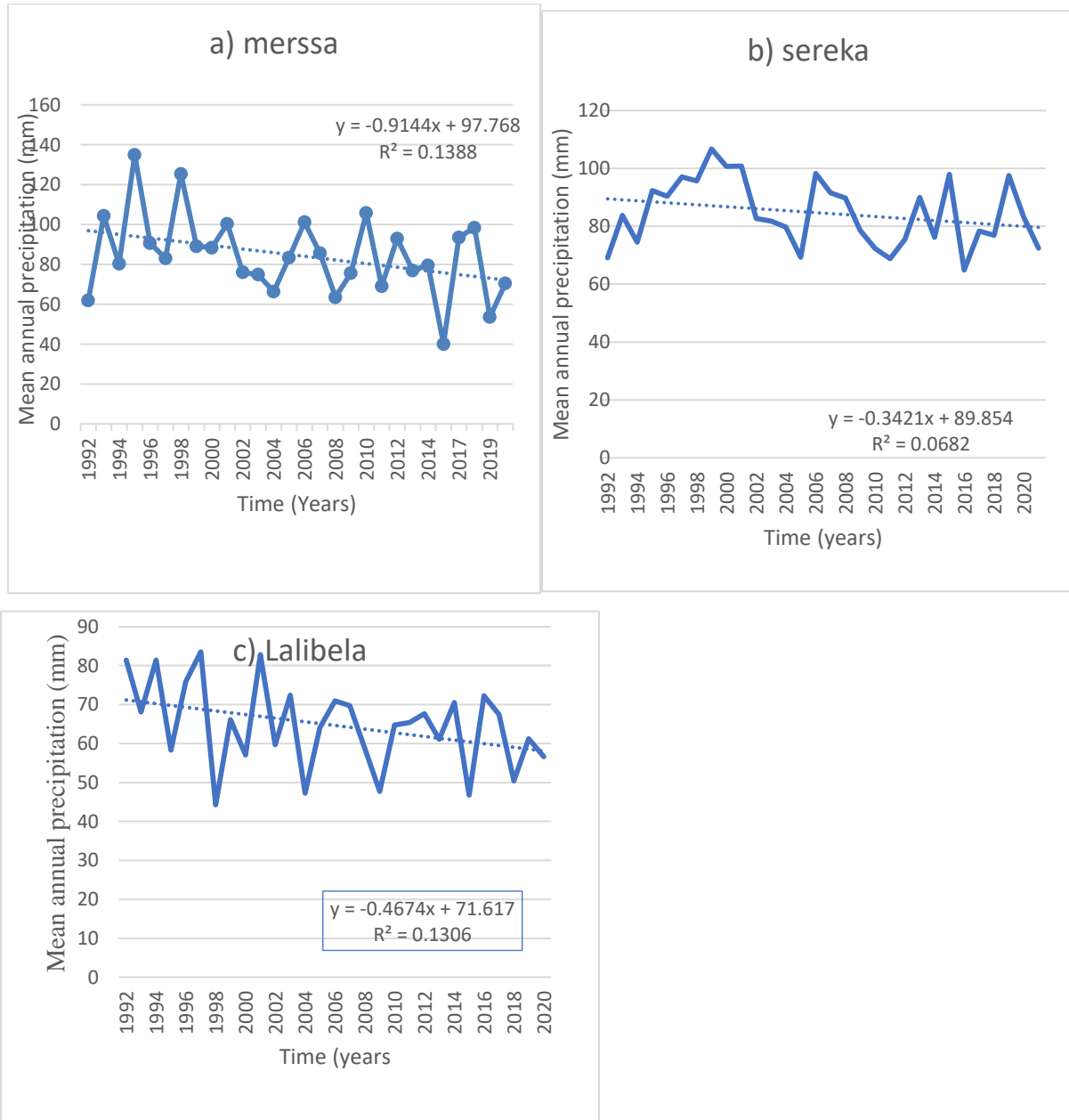
Source: Storck et al. (1991).

Appendix table 7 Conversion factor used to compute adult equivalent

No	Age group (years)	Male	Female
1	Less than 10	0.6	0.6
2	10-13	0.9	0.8
3	14-16	1.0	0.75
4	17-50	1.0	0.75
5	Greater than 50	1.0	0.75

Source: Storck et al. (1991)

Appendix Figure 1 Mean annual rainfall trends for three weather stations in north wollo zone (1992-2020)



Appendix Figure 2 Mean annual minimum and maximum for three weather stations in north wollo zone (1992-2020)

