

Exploring climate change adaptation in coffee-based farming systems: strategies and determinants among smallholder farmers in Western Ethiopia

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HIGHLIGHTS

- The study explored climate change adaptation measures in coffee-based farming systems and their key determinants.
- A cross-sectional household survey was combined with longitudinal climate data.
- Temperature and rainfall showed increasing trends, which aligned with farmers' perceptions.
- Rainfall irregularities were identified as the major climatic risk to coffee production.
- Farmers adopted different adaptation options, with agroforestry being the dominant strategy.

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ABSTRACT

Coffee is a vital source of livelihood for smallholder farmers in Western Ethiopia. However, climate change poses significant threats to coffee productivity and sustainability, increasing the vulnerability of coffee producers. Therefore, coffee farmers need to adapt to the effects of climate change to sustain their livelihoods. This study explores the adaptation strategies in coffee farming systems and their determinants in the West Wallaga Zone, Western Ethiopia. Data were collected from a cross-sectional survey of 642 selected households, five key informant interviews, and five focus group discussions, complemented by long-term climate records (1981–2020). Quantitative analyses were conducted using the Mann-Kendall test, Sen's Slope estimator, and a Multinomial Logit (MNL) model in R 4.4.1 and STATA/MP 17.0. Qualitative analysis was performed thematically. The results show a significant increase in mean annual temperature ($0.02\text{ }^{\circ}\text{C yr}^{-1}$) and total rainfall (6.46 mm yr^{-1}), with farmers' perceptions closely matching observed trends. Key informant interviews and FGDs indicated delayed onset of rainfall, abrupt cessation, and prolonged summer rains as the most critical perceived risks. Nearly 94.86% of households had adopted at least one adaptation measure, most commonly agroforestry (50.78%), crop diversification (15.73%), improved coffee varieties (11.06%), soil and water conservation (10.44%), and pest management (6.85%). However, 5.14% of households were non adopters. The MNL results revealed that age, family size, education level, farmland size, and credit access significantly influenced farmers' adaptation choices. Prioritizing agroforestry and improved coffee varieties, and aligning interventions with the socioeconomic factors shaping farmers' decisions, can enhance their adaptation options.

Practical Implication

Understanding the adaptation strategies of coffee-farming

systems, and the factors influencing farmers' choices of specific adaptation measures is crucial for enhancing resilience, informing policy, supporting livelihoods, promoting sustainable practices, facilitating knowledge transfer, addressing socio-economic factors, and contributing to global agricultural knowledge. This study provides several practical insights for strengthening the resilience

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of coffee-farming systems across diverse regions worldwide. The adoption of agroforestry, soil and water conservation, pest management, crop diversification, and improved coffee cultivars among the 642 surveyed households demonstrates that farmers are already investing in climate-adaptive practices. These findings carry important implications for policy, practice, and local development.

1. Strengthening economic and livelihood resilience: The adoption of climate-smart agronomic practices reduces the risk of coffee yield losses and stabilizes household income. Supporting these practices through improved extension services, input access, and timely climate information can enhance the economic resilience of rural communities whose livelihoods are highly climate-sensitive.

2. Enhancing local food security through diversification: The observed adoption of crop diversification highlights that households are reducing their dependence on coffee production alone. Policies that promote diversified farming systems can enhance household food availability and safeguard families against market or climate shocks.

3. Environmental sustainability and ecosystem conservation: The extensive use of agroforestry and soil conservation measures contributes to improved soil health, biodiversity conservation, and carbon sequestration. Scaling these practices can deliver both local ecological benefits and broader climate-mitigation co-benefits.

4. Targeting support based on determinants of adaptation: The determinants identified: age, family size, education, farm size, and access to credit, indicate that adaptation choices are shaped by household characteristics and resource endowments.

- **Older farmers** may rely on traditional knowledge, while younger farmers may be more receptive to innovation; extension programs should tailor training to both groups.
- **Family size** affects labor availability; labor-intensive practices may require targeted support for small households.
- **Education level** enhances the uptake of climate-smart innovations, underscoring the importance of farmer training and awareness programs.
- **Farm size** determines the range of feasible adaptation practices; smallholders require more intensive support to overcome land-related constraints.
- **Access to credit** is essential for investing in improved cultivars and conservation technologies; strengthening rural credit systems can accelerate adoption.

5. Policy and institutional implications: Effective adaptation in coffee-farming systems requires integrated support that integrates agricultural advisory services with financial access, climate information, and market linkages. Interventions aligned with these determinants will be more effective than comprehensive, non-differentiated programs.

In conclusion, promoting adaptation in coffee-farming systems requires a better understanding of the various strategies farmers employ as well as the socio-economic and institutional factors that influence their decisions. Policies and programs that take these contextual variables into account can improve the effectiveness of adaptation efforts, promote long-term resilience, and ensure the sustainability of both coffee production and rural livelihoods under changing climatic conditions.

frequency and intensity of extreme events such as droughts, floods, and heatwaves, posing substantial challenges to agricultural systems worldwide (Cogato et al., 2019; Vogel et al., 2019). The impacts are particularly severe in developing countries, where smallholder farmers are highly vulnerable to climate-induced extremes due to their dependence on rain-fed agriculture and limited adaptive capacity (Ariom et al., 2022; Ozdemir, 2022). As a result, the urgency of adapting to the impacts of climate change is gaining widespread recognition and has emerged as a critical issue on the global stage (IPCC, 2022). However, many developing nations face significant constraints including inadequate technology, financial resources, and institutional support, which hinder their ability to implement effective adaptation measures (Li et al., 2019).

Agriculture, central to Ethiopia's economy, food security, and rural livelihoods, is inherently sensitive to climatic variability and extremes (Alemu & Mengistu, 2019). Like in many developing countries, Ethiopian agriculture is mainly rain-fed and dominated by smallholder farmers, making it particularly vulnerable to climate-induced shocks (Bitew & Minala, 2025). Climate change are already affecting major crops and farming systems across the country through various pathways, including: shifts in the spatial suitability of key crops such as teff, maize, wheat, and coffee (Evangelista et al., 2013; Ginbo, 2022; Moat et al., 2017), alterations in trophic interactions and pest-disease dynamics within agroecosystems (OCHA, 2022); declines in crop productivity driven by recurrent droughts, heat stress, and rainfall variability (Habte et al., 2023; Tefera et al., 2025); and impacts on crop quality, including nutrient composition and secondary metabolites, particularly for export crops such as coffee (Chekol et al., 2024). These climate-induced stressors have worsened rural poverty and increased food insecurity in Ethiopia, where livelihoods rely heavily on climate-sensitive subsistence production systems (Feleke et al., 2025).

Despite their importance in the national food supply, most Ethiopian smallholders lack sufficient resources, information, and institutional support to cope with climate risks (Gezie, 2019; Zeray, 2025). Strengthening adaptive capacity within the agricultural sector has therefore become a national priority under Ethiopia's Climate Resilient Green Economy (CRGE) strategy (Paul & Weinthal, 2019). Enhancing farmers' resilience is essential not only for ensuring food security but also for sustaining the livelihoods of millions of rural households who are highly exposed to climatic shocks (Abraham et al., 2014; Tambo & Wünsch, 2017).

Coffee, a globally traded and economically significant crop (Vegro & de Almeida, 2020), is one of the most widely cultivated agricultural commodities in developing countries like Ethiopia and across the globe (Bilen et al., 2023). Its strong dependence on specific climatic conditions makes it particularly vulnerable to the increasingly unpredictable effects of climate change (DaMatta et al., 2019; Pham et al., 2019). Rainfall patterns and amounts, optimum temperature ranges, and sunshine are critical environmental elements that influence the phenology of coffee plants, as well as the yield and quality of the beans (DaMatta, 2018). As temperatures rise, rainfed coffee production will decline at lower elevations (Bunn et al., 2015; Gruter et al., 2022), while limited suitable land remains available at higher altitudes where the crop could relocate, which may endanger coffee production (Bracken et al., 2023). Global projections indicate that areas suitable for *Coffea arabica* production are decreasing due to changing temperature and precipitation patterns in major coffee-producing regions in Africa, Mesoamerica, and Central and South America (Bunn et al., 2015; Ovalle-rivera et al., 2015). Furthermore, it is expected that the consequences of climate change would exacerbate the severity and frequency of pests and diseases (Jaramillo et al., 2009), reduce growth, flowering, and fruiting (Camargo, 2010), and decrease or fluctuate coffee yields (Jayakumar et al., 2017; Tavares et al., 2018). Without appropriate adaptation measures, this biophysical impact will significantly affect the livelihoods of small-scale coffee producers and other stakeholders within the value chain (Pham et al., 2019). Therefore, building climate resilience with in perennial cropping

1. Introduction

The continued increase of greenhouse gas (GHG) emissions is driving persistent climatic shifts, characterized by higher temperatures and altered in weather patterns (IPCC, 2021; Xi-liu & Qing-xian, 2019). These changes manifest in rising average temperatures and a greater

systems, especially for high-value cash crops like coffee, is increasingly important.

Adaptation in coffee-based systems generally falls into two broad categories. The first focuses on strengthening the resilience of coffee agroecosystems through agronomic and ecological interventions, including heat- and drought-tolerant varieties, pruning and grafting, agroforestry integration, pest management (Harelimana et al., 2022; Pappo et al., 2021; Rahn et al., 2018). It also includes landscape-level actions, such as afforestation, reforestation, and protection of water catchments (Minang et al., 2016). The second category aims to strengthen the adaptive capacities of farming communities by diversifying income sources, improving access to financial services and seasonal forecasts, providing climate related training and ensuring control over critical resources (Poncet et al., 2024). Moreover, this adaptation also requires enabling environments through access to climate information, investment credit, training programs, crop insurance, and early warning systems (Verburg et al., 2019). However, the design and implementation of effective adaptation measures require learning from past experiences and a clear understanding of the socioeconomic factors that shape farmers' choices (Diro et al., 2022; Eise et al., 2021; Rahn et al., 2018; Yayeh et al., 2023).

Coffee is the backbone of the Ethiopian economy (Davis et al., 2012) and the main source of income for over 16 million farmers (Moat et al., 2017). Despite its significances, the average green coffee yield has declined from 0.72 t/ha in 1993 to 0.64 t/ha in 2019 (Ayele et al., 2021), which is below the global average of 0.8 t/ha and significantly lower than yields in major coffee-producing countries like Brazil (1.65 t/ha), Vietnam (2.71 t/ha), and Colombia (1.04 t/ha) (Ayele et al., 2021;

Melese & Kolech, 2021). Various factors contribute to this decline in productivity, but climatic stresses are increasingly recognized as a dominant constraint (Akafu et al., 2025b; Moat et al., 2017; Sisay, 2018). In response, farmers have begun implementing various adaptation measures and agronomic adjustments. However, there is limited empirical understanding of these strategies and the factors influencing farmers' decisions to adopt, particularly in western Ethiopia. To address this gap, this present study aims to investigate the adaptation strategies used in coffee-based farming systems and identify the socioeconomic and environmental factors that influence farmers' decisions to adopt these practices in response to climate change and variability. The analysis is based on data collected from smallholder coffee producers in the West Wallaga Zone of Western Ethiopia

2. Methods and materials

2.1. Study Site Description

The study was conducted in five selected districts: Ganji, Gimbi, Haru, Homa, and Nolekaba, located in the West Wallaga Zone, Western Ethiopia (Fig. 1). Geographically, the area lies between 8°42'0" to 9°13'30" N latitude and 35°36'0" to 36°7'30" E longitude, with elevations ranging from 1053 to 2494 meters above sea level. The agroecology is dominated by mid-altitude zones (82.64%), followed by lowlands (7.76%) and highlands (9.6%) (Akafu et al., 2025a). Rain-fed agriculture plays a significant role in the economy of the study area, particularly with coffee serving as a vital cash crop across these five districts, where more than 1,026.02 square kilometers of land is allocated for its

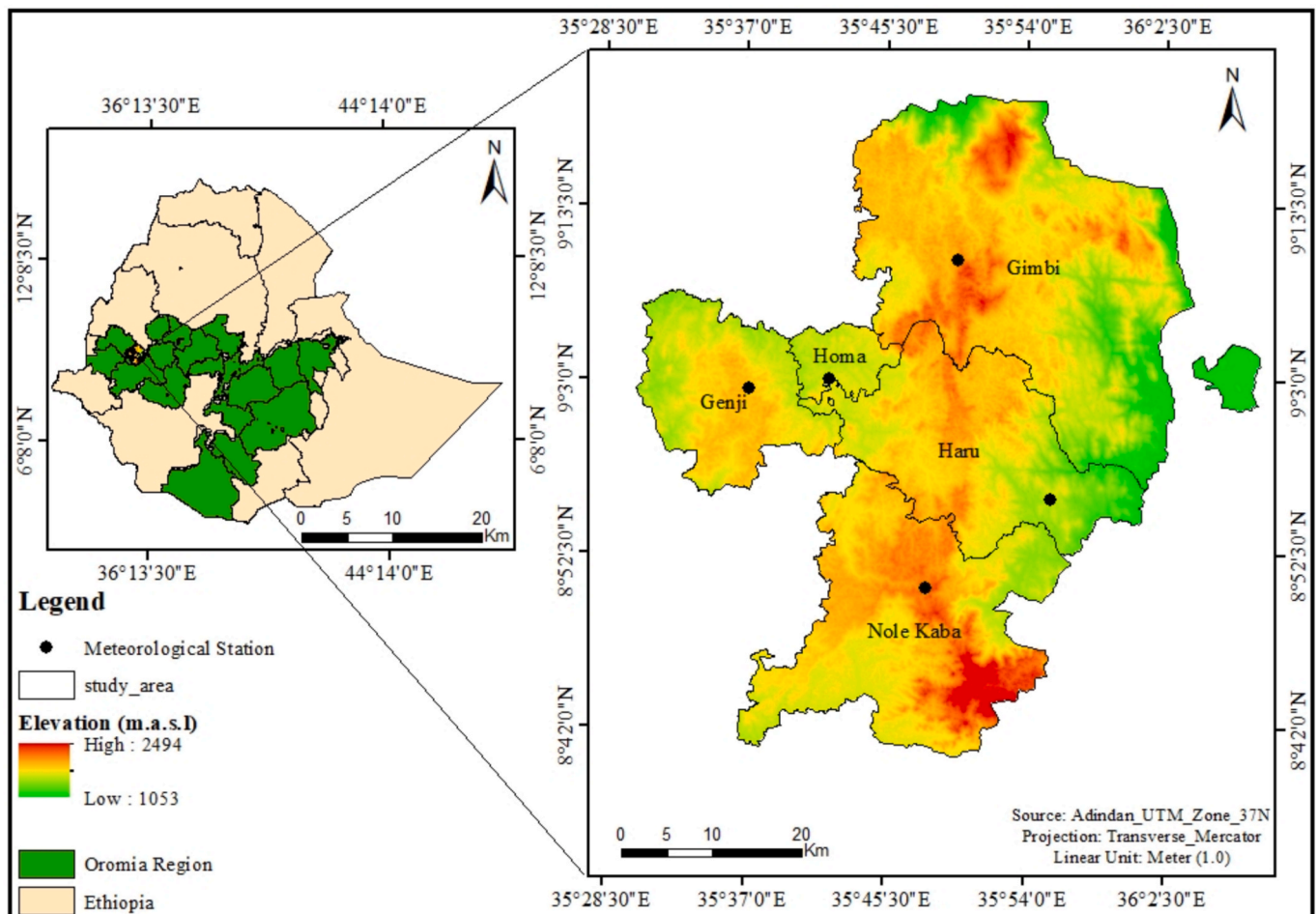


Fig. 1. Map of the study area.

cultivation. The livelihoods of farmers are characterized by a mixed crop-livestock production system with major cereal crops grown across the study area, including maize, teff, and barley. Cattle, sheep, poultry, beehives, goats, and donkeys are the major livestock raised. The average total annual rainfall varies from 1717 mm in Ganji to 1838 mm in Homa, while the mean annual temperature ranges from 20 °C in Gimbi to 23.1°C in Ganji. Land use in the area is characterized by 174,161 hectares (ha) of cropland, with 102,602 ha dedicated to coffee and 71,558 ha for cereals. Additionally, there are 57,224 ha of forest, 14,149 ha of pasture, and 35,997 ha designated for other uses (Akafu et al., 2025a). According to the Central Statistical Agency (CSA, 2023) the study area is estimated to have a total population of 419,451 (205,424 males and 214,024 females). Data collected by the authors from each district shows that the total number of coffee-producing farmers across the five districts is 48,918, with 44,757 being males and 4,161 females.

2.2. Sampling Procedure and Sample Size Determination

A multistage sampling technique was used to select the participants. In the first stage, West Wallaga zone was chosen purposefully because of its high potential for coffee production and because no previous studies had been conducted in this area. In the second stage, the districts of Ganji, Gimbi, Haru, Homa, and Nolekaba were purposively selected based on their coffee production potential, as indicated by Zonal agricultural data. In the third stage, villages involved in coffee production were stratified based on their coffee production potential. In the fourth stage, three villages per district, predominantly involved in coffee production, were selected using simple random sampling. The sample size was determined using the formula proposed by Kothari (2004) (eq.1) for the population, resulting in a total of 642 households (Ganji = 129; Gimbi = 135; Haru = 128; Homa = 125; Nolekaba = 125). Five key informants were purposively selected from agricultural extension officers, one from each district based on their direct experience working with coffee farmers. Additionally, five focus group discussions (FGDs) were conducted, one in each of the five districts. Each FGD consisted of five participants who were purposively selected based on their gender, education level, farming experiences, landholdings, participation in community-based organizations, and engagement with agricultural extension services.

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

Where 'n' is the desired sample size; 'N' is the size of the household heads unit in the study area; 'Z' is the standard variant at a given confidence level (1.96); 'e' is an acceptable error (the precision error 0.08); 'p' is the standard deviation of the population (0.5); and 'q' is the estimated proportion of attributes that are not present in the population (1-p).

2.3. Data Sources and Data Collection Techniques

Both primary and secondary sources of data were used for this study. The primary sources were collected from 642 coffee farmers through a cross-sectional household survey, supplemented by five key informant interviews, and five focus group discussions. Data collection was conducted between September 1 and October 30, 2023 using an interviewer-administered structured questionnaire that included a limited number of open-ended questions. The primary data consisted of the socio-demographic, farm, and institutional characteristics of the respondents, as well as their perceptions of climate change patterns over the last 30 years. It also included six adaptation strategies employed by farmers, assuming that each farmer employs a unique set of adaptation methods based on their specific contextual circumstances. Secondary data included monthly gridded temperature and rainfall records sourced from each district from 1981 to 2020, collected from the Ethiopian

Meteorology Institute (EMI). Aerial average climate datasets were used to validate farmers' perceptions of climate change. Furthermore, FGDs and key informant interviews were conducted to gain deeper insights into participants' knowledge regarding perceived climatic risks, the impacts of climate variability on the coffee production cycle, and the most effective adaptation measures

2.4. Definition of Variables and Working Hypothesis

In this study, the dependent variables are the adaptation strategies that farmers have adopted to respond to challenges in their agricultural practices based on relevant literature (Jawo et al., 2023; Verburg et al., 2019), and preliminary field observations. The field observation was conducted during the GPS point collection of the current coffee growing areas, which were used to model coffee suitability under different climate change scenarios for the West Wallaga Zone (Akafu et al., 2025b). Independent variables include the socio-demographic and economic characteristics of households, such as age, gender, educational attainment, family size, dependency ratio, and annual income. Additionally, it encompasses farm-related factors, including the farmers' agricultural experience, crop diversity, livestock diversity, land ownership, specific occupations, and the size of farmland. Institutional factors are also taken into account, encompassing the availability of communication devices, access to credit, and participation in farmers' group associations (Table 1).

2.5. Data Analysis Method

The Mann-Kendall (MK) test (Kendall, 1975; Mann, 1945) was used to detect the existence of trends in temperature and precipitation datasets, whereas the trend magnitude was quantified using the Sen method (Sen, 1968). Descriptive statistics were employed to illustrate farmers' perceptions and adaptation strategies, which were then visualized through graphics. Qualitative data collected through key informant interviews and focus group discussions (FGDs) were analyzed using thematic analysis.

Econometric Analysis

To identify the factors influencing farmers' adaptation decision to climate change, a Multinomial Logit (MNL) model was employed using STATA/MP 17.0. The MNL approach is suitable for analyzing multiple, unordered categorical outcomes, as it estimates the probability that a decision-maker selects one alternative among several discrete choices (Amare & Simane, 2017). In this framework, let y be the dependent variable representing the choice of adaptation strategy, which takes values from the set $\{1, 2, \dots, J\}$, where J is the number of available adaptation options. Let z denote a vector of explanatory (independent) variables that influence this choice. The probability that a farmer chooses option j , given the vector z , is modeled as Eq: 2

$$P\left(y = \frac{j}{z}\right) = \frac{\exp(zB_j)}{1 + \sum_{h=1}^{J-1} \exp(zB_h)} \text{ for } j = 1, 2, \dots, J-1 \quad (2)$$

Where:

B_j is a vector of coefficients associated with outcome j ,
 z is a $1 \times K$ vector of explanatory variables (with the first element typically set to 1 for the intercept term).

Note: One of the categories "no adaptation measures" was used as the base or reference group, and its coefficient vector is normalized to zero. Thus, probabilities are calculated only for the remaining $J-1$ alternatives, allowing comparison of each strategy's likelihood relative to not adopting any measure (Belay et al., 2017).

The six strategies considered in the analysis are:

1. Agroforestry systems

Table 1
Description of variables, their types, and farmers' adaptation measures.

Variable	Description	Variable type and description
Dependent Variable		
Adaptation	Farmers' adaptation options	<i>Categorical</i> : 1 = Agroforestry, 2 = Crop diversification, 3 = Improved coffee varieties, 4 = Pest management, 5 = Soil and water conservation, 6 = No adaptation measures
Perception	Farmers' perceptions of climate change	<i>Categorical</i> : Farmers' perceptions of temperature and rainfall trends, and the length of the dry season; 1 = Increase, 2 = Decrease, 3 = No change, 4 = Don't know
Independent variables	Abbreviation	Variable type and description
Age	AGE	<i>Continuous</i> : Age of the household heads (years)
Gender	GEND	<i>Binary</i> : 1 = Male, 0 = Female.
Occupation	OCUP	<i>Binary</i> : 1 = Farming as primary occupation, 0 = Otherwise
Education	EDLE	<i>Binary</i> : 1 = Completed at least primary education, 0 = Otherwise
Family size	FMLS	<i>Continuous</i> : Number of household members
Dependency ratio	DPR	<i>Continuous</i> : Ratio of dependents (<15 or > 65 years) to working-age population (15–64 years)
Income	INCM	<i>Continuous</i> : Total annual household income (ETB)
Livestock diversity	LVSD	<i>Continuous</i> : Inverse of number of livestock species owned + 1
Farmland ownership	FRML	<i>Binary</i> : 1 = Landowner, 0 = Not landowner
Farmland size	FRMS	<i>Continuous</i> : Total farmland area (hectares)
Farming experiences	FRMP	<i>Continuous</i> : Years engaged in farming
Access to extension services	AES	<i>Binary</i> : 1 = Yes, 0 = No
Farmers association members	MFA	<i>Binary</i> : 1 = Yes, 0 = No
Access to saving and credit	ASCR	<i>Binary</i> : 1 = Yes, 0 = No
Access to communication device	COMD	<i>Binary</i> : 1 = Yes, 0 = No

2. Soil and water conservation practices
3. Crop diversification
4. Improved coffee varieties
5. Pest management technique
6. No adaptation measures (base category)

While MNL model indicate the direction and significance of relationships between explanatory and dependent variables, they do not directly express the magnitude of effects in terms of probabilities. To address this, marginal effects were calculated (Abid et al., 2015). The marginal effect of a one-unit changes in an independent variable Z_k on the probability of choosing strategy j is given by Eq:4

$$\frac{\partial P_j}{\partial Z_k} = P_j (B_{jk} - \sum_{h=1}^j P_h B_{hk}) \quad (3)$$

Where:

P_j is the predicted probability of choosing strategy j ,
 B_{jk} is the coefficient of variable z_k for outcome j ,
 Z_k includes variables related to household, farm, and institutional characteristics.

3. Results and discussions

3.1. Farmers Perceptions of Climate Change

Fig. 2 illustrates farmers' perceptions of long-term trends in three key climatic variables over the past 30 years. The results show that around 85% of respondents noticed a rise in temperature, while 5% observed a decline. Additionally, 7% reported no change, and the remaining 3% indicated they lacked knowledge of temperature trends. Regarding rainfall patterns, 87.4% of the respondents reported a change in rainfall distribution over the past 40 years. Among them, 69% perceived an increase in rainfall, while 18.4% reported a decrease. The remaining 5% of farmers perceived no change, and 8% indicated that they were unaware of rainfall trends. When asked about changes in the length of the dry season, 53.1% of farmers reported an increase, and 25.5% noted a decrease. Meanwhile, 13.2% perceived no change, and 8.1% stated that they lacked knowledge about changes in the duration of dry seasons.

3.2. Comparing Farmers' Perceptions with Empirical Data

Figs. 3 and 4 illustrate observed trends in temperature and rainfall for the period of 1981–2020. The Mann-Kendall test indicates a statistically significant upward trend for both variables over the study period. Sen's slope estimator indicates that the mean maximum, mean minimum, and mean average temperatures increased by 0.03 °C/year, 0.02 °C/year, and 0.02 °C/year, respectively (all $P = 0.000$). Rainfall also exhibited an overall increasing trend, with annual totals rising by 6.46 mm/year ($P = 0.000$). Seasonal analyses showed average increases of 2.13 mm/year during the main rainy season ($P = 0.165$), 2.21 mm/year during the small rainy season ($P = 0.037$), and 1.71 mm/year in the dry season ($P = 0.095$). These observed changes closely aligned with farmers' perceptions, who reported warmer temperatures and increased rainfall, indicating a high level of climate awareness. This indicates a high level of climate awareness from lived experience, although some differences remain, reflecting limitations in capturing subtle climate changes (Bryan et al., 2013).

3.3. Perceived Climate Risks and Their Impacts on Coffee production

Key informant interviews with agricultural extension officers and focus group discussions with coffee farmers identified multiple climate risks affecting coffee production in their locality. The most commonly reported risks include irregular rainfall distribution, shortened rainy seasons, rising temperatures, and increased pest and disease pressure, all of which led to reduced coffee yields. However, uneven spatial and temporal distribution of rainfall emerged as the main concern. Farmers and extension officers articulated this risk in relation to the coffee production cycle from three distinct perspectives: i) *Delayed Onset of Rainfall*: In years when rainfall starts late, a delay in the onset of rainfall

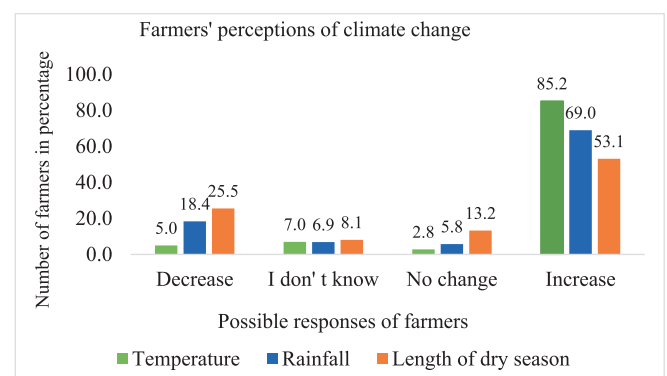


Fig. 2. Farmers' perceptions of climate change over the past 30 years.

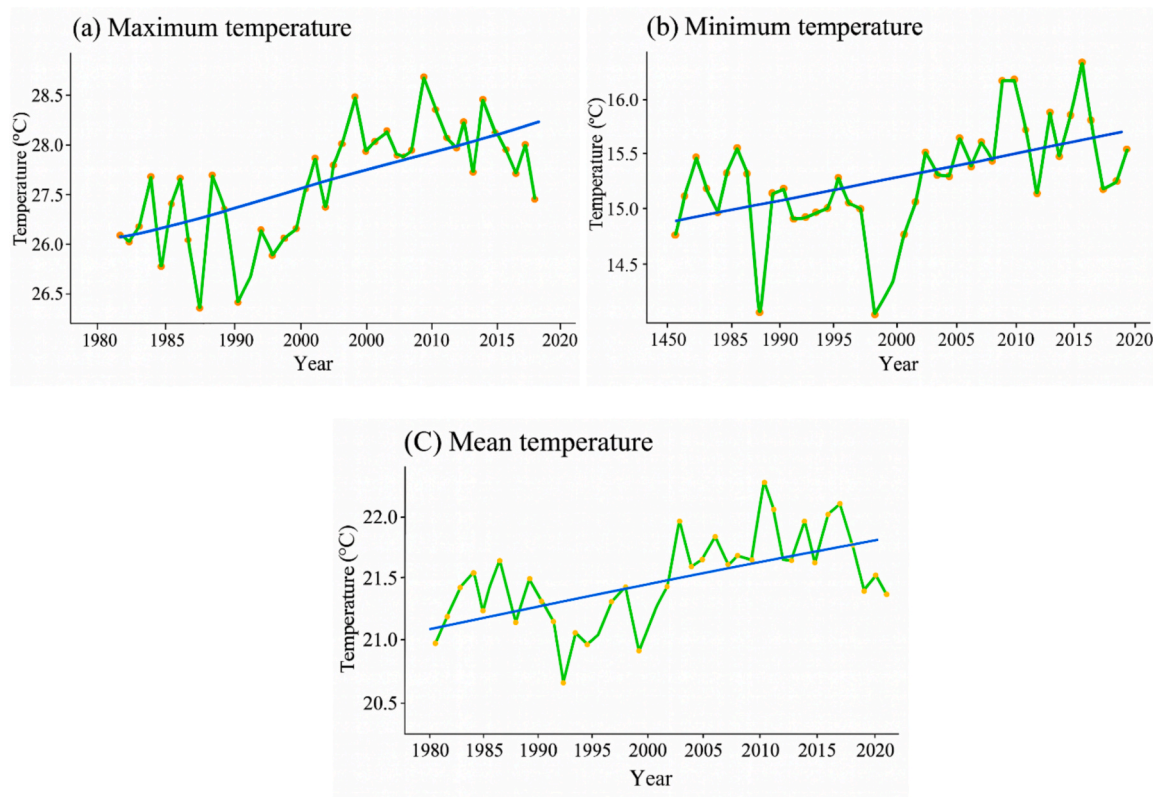


Fig. 3. Trends of mean annual, maximum, and average temperatures in the study area from 1980 to 2020.

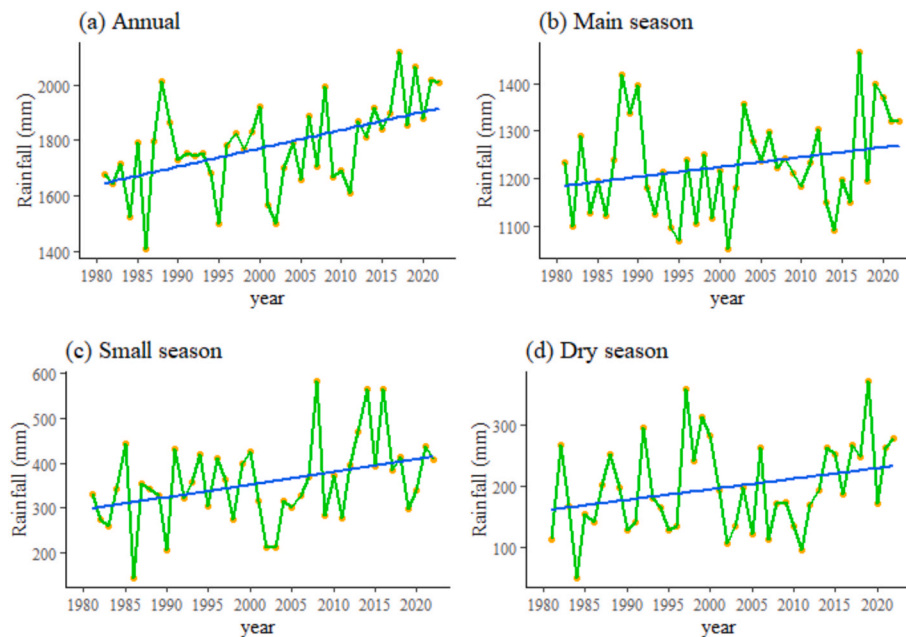


Fig. 4. Trends in total annual and seasonal rainfall of the study area from 1980 to 2020.

negatively affects the blooming phase of coffee plants, as inadequate moisture during this critical period leads to poor flowering, which in turn causes inconsistent and reduced yields. ii) *Abrupt Cessation of Rainfall*: In certain years, rainfall begins on time and triggers flowering, but it may suddenly cease before the flowering phase is complete. This shortens the blooming period, causing flowers to wither and fall prematurely, and hinders fruit development. iii) *Prolonged Rainfall into Summer*: In certain years, rainfall arrives as expected, and initial plant

growth is successful. However, an extended rainy period during the summer months disrupts the ripening process of coffee cherries. This excessive moisture exposure leads to premature darkening, shriveling, and, in many cases, drying on the branches before reaching full ripeness. Furthermore, FGDs and interviews with key informants have identified agroforestry systems as the most effective adaptation measures commonly employed by farmers. These perceptions highlight both farmers and extension officers understanding of how climate variability,

particularly changes in rainfall timing, duration, and intensity, affects the coffee production cycle. Their observations emphasized the critical need for timely and evenly distributed rainfall to ensure consistent flowering, fruit development, and high harvest quality.

3.4. Farmers Adaptation Strategies

Fig. 5 presents the adaptation measures employed by smallholder coffee farmers in response to climate change. The results revealed that about 94.86% of farmers had implemented at least one adaptation practice, with agroforestry systems being the most widely adopted strategy. Other commonly used measures include the adoption of improved coffee varieties, crop diversification, pest management, and soil and water conservation practices. Notably, 5.14% of farming households did not adopt any adaptation measures. This is consistent with previous studies (Asfaw et al., 2018; Bryan et al., 2013), which suggest that some farmers, despite recognizing climate change, lack the capacity to adapt. This indicates that awareness of climate risks does not always lead to actions. Limited financial resources, inadequate access to credit, labor shortages, land constraints, and insufficient climate information and extension services are potential barriers to adoption (Eise & Rawat, 2021; Obsi et al., 2023).

3.4.1. Agroforestry Systems

In the study area, coffee is traditionally cultivated under a diverse canopy of shade trees, forming agroforestry systems that integrate fruit, nut, and timber species used by farmers for domestic needs. This traditional practice supports a multifunctional farming ecosystem and reduces the economic and social vulnerabilities of coffee producers (Poncet et al., 2024). In this study, 51.78% of the surveyed households reported implementing agroforestry systems on their coffee farms as an adaptation strategy to climate change and variability. The benefits of coffee-based agroforestry systems are well documented. These trees help farmers diversify their sources of income, mitigate climate change by sequestering carbon dioxide (Vaast et al., 2015), and enhance coffee yields while improving bean size and quality (Cassamo et al., 2023; Rahn et al., 2018). Additionally, agroforestry creates favorable microclimatic conditions by reducing average air temperatures (Carvalho et al., 2021), supports vital ecosystem services (Pantera et al., 2021), and enhances food security for rural households (Ghimire et al., 2024). Furthermore, it improves soil health by facilitating nutrient cycling and erosion prevention, and reduces water loss from both crop transpiration and soil evapotranspiration (Dollinger & Jose, 2018). However, the integration of shade trees has notable implications for coffee productivity. Shade tree diversity, structural characteristics, and canopy cover can significantly affect both yield and quality (Jawo et al., 2023; Nesper et al., 2017). Overall, while agroforestry systems provide substantial ecological and economic benefits, their design and management must be

carefully optimized to achieve a balance between coffee production and environmental sustainability.

3.4.2. Improved Coffee Varieties

In the study area, 15.73% of households included in the survey chose to adopt improved coffee varieties as a strategic measure to address the challenges posed by the changing climate. Previous studies have highlighted several advantages of these varieties, including greater tolerance to high temperatures (Pappo et al., 2021), greater resistance to pests and diseases (Vossen et al., 2015), and adaptability to both full-sun and shaded cropping systems (Marie et al., 2020). Hybrid coffee cultivars, in particular, have been shown to produce earlier and higher yields than traditional coffee cultivars (Bertrand et al., 2011; Kahsay et al., 2023), with superior performance under full-sun conditions relative to indigenous *Coffea arabica* (Marie et al., 2020). Despite these potential benefits, the adoption of improved varieties in the study area remains limited. This could be due to the high purchase costs of seedlings, which can hinder smallholder farmers. Increased productivity often requires greater labor inputs and higher investments in agricultural inputs, such as fertilizers (Kahsay et al., 2023). Farmers may also be concerned about the long-term sustainability and profitability of hybrid varieties (Turreira-García, 2022), while insufficient knowledge about which varieties are best suited to specific local contexts further constrains their adoption (Verburg et al., 2019). Addressing these barriers will require improving farmers' access to affordable, high-quality planting materials, providing clear guidance on variety-environment matching, and ensuring long-term performance guarantees.

3.4.3. Crop Diversification

The cultivation of coffee as a sole crop increases the vulnerability of smallholder coffee farmers to yield losses due to environmental changes, thereby reducing household income (Jawo et al., 2023). Crop diversification is a risk mitigation strategy that can reduce the impacts of biological threats, such as pest infestations, market fluctuations, and climate-related shocks, especially when the crops within a farming system have varying sensitivities to weather conditions (Poncet et al., 2024). In the study area, while most farmers rely primarily on coffee production as their main income source, 11.06% of respondents reported diversifying their production by integrating cereal crops, such as maize, teff, and barley. This practice helps meet household food needs while supplementing farm income. However, the adoption rate remains low, mainly because of small landholdings that limit the space available for additional crops. Other constraints include household labor availability, access to improved seeds (Anderzén et al., 2020), and degraded land that requires costly rehabilitation before it can be used productively (Acosta-Alba et al., 2020). Overall, crop diversification depends on several factors that operate in various ways and across different scales. When effectively implemented, diversification can strengthen resilience to climate change while providing economic benefits to smallholder coffee farmers (Morel et al., 2020).

3.4.4. Soil and Water Conservation (SWC)

Soil and water conservation practices are essential for the management of sustainable coffee farms, as they help maintain the ecological balance necessary for long-term productivity while mitigating the adverse impacts of climate variability (Nzeyimana et al., 2019). In the study area, 10.44% of the interviewed households identified SWC as their primary strategy for addressing the challenges posed by climate change. Farmers implement a range of practices under this approach, including mulching, terracing, shade management, and intercropping. Mulching is a common practice among small-scale farmers, especially during periods of high temperature and drought. It improves soil nutrient levels, enhances fertility, and increases coffee yields (Bucagu et al., 2013; Nzeyimana et al., 2019), while controlling soil erosion and restoring degraded soil (Mwango et al., 2016). Terracing, especially in steep highland coffee-growing areas, reduces water runoff, minimizes

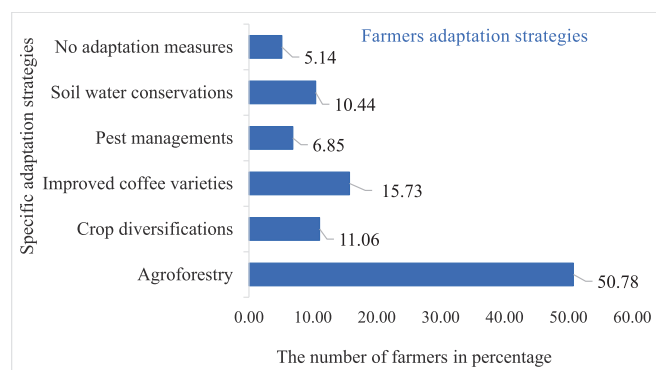


Fig. 5. Coffee farmers' adaptation measures to climate change over the past 30 years.

soil erosion, and prevents landslides (Villatoro-sánchez et al., 2015). Terraces also help preserve soil moisture content, maintain soil organic carbon levels, and retain essential macronutrients such as nitrogen, phosphorus, and potassium, which are easily lost from sloped lands through runoff (Do et al., 2023). Intercropping coffee with fruit trees or other crops enhances soil organic carbon through the accumulation of organic residues (Asten et al., 2011), supports the soil water balance, and provides ecosystem services (Pokharel et al., 2023). Additionally, intercropping optimizes plant water use, improves soil physicochemical properties, and enhances the yield and quality of associated crops (Chen et al., 2019). Overall, SWC measures enhance the resilience of coffee production systems to climate change by conserving soil and water resources, improving farm productivity, and maintaining ecological functions. Promoting the adoption of such practices is essential for building climate-resilient, sustainable, and adaptive coffee production in response to increasingly variable and extreme climatic conditions.

3.4.5. Pest Management

Losses in coffee production due to pest attacks can reach 50% (Rosado et al., 2021). Therefore, effective pest management is critical for reducing yield losses and sustaining coffee production. In this study, 6.85% of households identified pest management as their primary adaptation strategy, employing shade management, weed control, intercropping and pesticide application. Shaded coffee systems have been shown to have varying effects on pest and disease incidences. While shaded systems may increase the risk of fungal diseases, such as coffee leaf rust (*Hemileia vastatrix*) (Gagliardi et al., 2020), they can reduce the incidence of coffee berry borer (*Hypothenemus hampei*) (Nesper et al., 2017). Proper vegetation management in shaded systems can enhance ecological services, foster natural enemy competition, and improve pest control (Perfecto et al., 2014). Diversified shade and intercropping have been reported to enhance natural pest control by supporting predators, such as birds, ants, and lizards (Gonthier et al., 2013; Rosado et al., 2021). Although chemical control remains in use, overreliance may cause resistance and environmental harm (Harelimana et al., 2022). Ecological approaches such as maintaining shade diversity, fostering beneficial organisms, and integrating weed control appear to offer more sustainable, climate-resilient pest management (Chain-guadarrama et al., 2019; Sinu et al., 2021).

3.5. Factors Influencing Adoption of Adaptation Strategies

Tables 2 and 3 display the parameter estimators and the marginal effects of adaptation strategies, respectively. These tables contain fifteen explanatory variables categorized into socioeconomic, farm, and institutional determinants. However, in the following section, we chosen to interpret and discuss only five explanatory variables that showed statistical significance at a probability level of 10% or lower.

Age of household heads: The age of household heads had a positive relationship with the adoption of improved coffee varieties but a negative correlation with the implementation of SWC practices, at a statistically significant level of 10%. The marginal effect revealed that each additional year in the age of the household head increases the likelihood of adopting improved varieties by 6.8% but decreases the likelihood of adopting SWC by 3.3%. Older farmers may prefer improved varieties because of their experience and familiarity with crop innovations, whereas younger farmers are more inclined toward SWC, which is labor-, capital-, and time-intensive. Similar mixed effects of age on adaptation choices have been reported by Amare & Simane (2017) and Belay et al. (2017).

Family size: Family size exhibited positive influences with the adoption of crop diversification and pest management practices, with statistically significant levels at 10% and 1%, respectively. The marginal effects indicate that for each additional household member, the likelihood of adopting crop diversification increases by 3.1% and pest management by 4.5%. This suggests that larger household labor capacity is

Table 2
Parameter estimates of the multinomial logit model for farmers' adaptation strategies.

Variable	Agroforestry			Crop diversification			Improved coffee varieties			Soil and water conservations			Pest management		
	Coef.	St Err.	P> z	Coef.	St Err.	P> z	Coef.	St Err.	P> z	Coef.	St Err.	P> z	Coef.	St Err.	P> z
AGE	0.481	0.334	0.150	0.644	0.374	0.085	0.761	0.344	0.027*	-0.028	0.457	0.051*	0.168	0.467	0.718
GEND	-0.419	0.708	0.554	0.599	0.725	0.409	0.400	0.695	0.565	-15.113	1123.61	0.989	0.251	1.011	0.804
EDLE	1.532	0.687	0.026*	0.365	0.517	0.480	0.035	0.497	0.943	2.192	0.773	0.005**	1.048	0.785	0.182
FMLS	0.554	0.386	0.151	0.826	0.419	0.049*	0.491	0.392	0.210	0.946	0.511	0.064	1.408	0.527	0.008**
DPR	0.086	0.192	0.656	0.006	0.209	0.978	0.014	0.196	0.943	-0.146	0.250	0.559	-0.066	0.249	0.792
AES	0.114	0.386	0.768	0.003	0.503	0.995	0.230	0.417	0.581	-0.337	0.522	0.519	0.023	0.392	0.954
OCCUP	0.536	0.481	0.265	1.499	0.717	0.037	0.983	0.704	0.163	-1.187	0.878	0.177	0.471	0.912	0.606
FRML	-1.015	0.618	0.100	-1.418	0.694	0.041	-0.949	0.655	0.147	-1.335	0.826	0.106	-2.092	1.214	0.085
FRMS	0.373	0.283	0.187	0.789	0.313	0.012*	0.080	0.288	0.782	0.556	0.380	0.143	0.666	0.388	0.086
FRMP	0.109	0.481	0.746	-0.231	0.377	0.540	-0.404	0.345	0.241	-0.052	0.444	0.906	0.194	0.473	0.682
LVSD	0.840	0.798	0.293	-0.734	0.837	0.380	0.897	0.803	0.264	0.991	0.935	0.289	-14.681	1158.1	0.990
INCM	-0.392	0.268	0.144	-0.304	0.294	0.300	0.076	0.273	0.782	-0.580	0.341	0.089	-0.232	0.363	0.523
COMD	-0.010	0.403	0.980	0.069	0.439	0.875	-0.029	0.411	0.944	0.566	0.534	0.288	-0.366	0.584	0.531
MCBO	0.037	0.370	0.921	-0.151	0.407	0.710	0.029	0.375	0.840	-0.822	0.554	0.138	-0.391	0.512	0.445
ACCR	2.296	0.761	0.003**	-1.813	0.785	0.021*	1.999	0.765	0.009**	-3.351	0.830	0.000***	-1.807	0.833	0.130
Diagnostics															
Base category no adaptation measure															
Number of observations 642															
LR Chi-Square 167.77															
Prob > chi2 0.0000															
Log-likelihood -908.37003															
Pseudo R-Square 0.0845															

Note: *, **, and *** denote significant at 10%, 5% and 1%, respectively.

Table 3
Estimated marginal effects of the multinomial logit model on farmers' adaptation strategies.

Variable	Agroforestry			Crop diversification			Improved coffee varieties			Soil and water conservations			Pest management		
	dy/dx	St Err.	P> z	dy/dx	St Err.	P> z	dy/dx	St Err.	P> z	dy/dx	St Err.	P> z	dy/dx	St Err.	P> z
AGE	-0.007	0.038	0.848	0.022	0.030	0.476	0.068	0.036	0.059	-0.033	0.020	0.103	-0.019	0.020	0.333
GEND	0.206	28.113	0.994	0.233	11.061	0.983	0.325	17.782	0.985	-0.881	65.294	0.989	0.081	5.326	0.988
EDLE	0.145	0.049	0.003*	0.037	0.036	0.296	-0.025	0.046	0.587	0.082	0.044	0.066	-0.068	0.036	0.064
FMLS	-0.026	0.039	0.505*	0.031	0.031	0.315	-0.034	0.036	0.342	0.019	0.021	0.385	0.045	0.022	0.041*
DPR	0.022	0.020	0.269	-0.003	0.015	0.853	-0.002	0.019	0.894	-0.011	0.010	0.308	-0.005	0.010	0.615
AES	0.016	0.040	0.683	-0.004	0.021	0.858	0.026	0.030	0.390	-0.024	0.022	0.273	-0.011	0.037	0.760
OCCUP	0.093	0.051	0.071	0.037	0.038	0.331	-0.069	0.051	0.179	0.002	0.024	0.017*	0.057	0.035	0.176
FRML	0.026	0.071	0.709	-0.051	0.057	0.374	0.034	0.071	0.628	-0.013	0.035	0.705	-0.058	0.060	0.331
FRMS	0.001	0.029	0.982	0.066	0.024	0.006**	-0.075	0.027	0.006**	0.011	0.016	0.499	0.017	0.016	0.289
FRMP	0.074	0.039	0.054*	-0.021	0.030	0.491	0.079	0.035	0.023*	0.002	0.019	0.917	0.018	0.020	0.386
LVSD	0.333	23.764	0.989	0.150	11.99	0.990	0.278	18.649	0.988	0.085	5.490	0.988	-0.855	63.944	0.989
INCM	-0.057	0.028	0.040*	-0.012	0.022	0.590	0.078	0.026	0.003**	-0.021	0.014	0.123	0.000	0.015	0.996
COMD	-0.002	0.044	0.964	-0.009	0.033	0.785	-0.005	0.041	0.909	0.036	0.023	0.114	-0.021	0.025	0.398
MCOB	0.038	0.041	0.346	-0.013	0.032	0.673	0.037	0.037	0.316	-0.047	0.026	0.074	-0.018	0.022	0.403
ACCR	-0.090	0.043	0.039*	0.036	0.034	0.279	0.003	0.040	0.933	-0.079	0.022	0.000***	0.014	0.020	0.485

Note: *, **, and *** denote significant at 10%, 5% and 1%, respectively.

advantageous for labor-intensive practices, which is consistent with previous findings by Bryan et al. (2013), and Mossie & Chanie (2024).

Education attainment of the household heads: Education level showed a positive correlation with the adoption of agroforestry and soil and water conservation practices, significant at the 5% and 1% levels, respectively. The marginal effects indicate that each additional year of education increases the likelihood of adopting agroforestry and soil-water conservation by 14.5% and 8.2%, respectively. These results, consistent with Abid et al. (2015) and Obsi et al. (2023), suggest that higher education enhances farmers' capacity to adopt climate change adaptation practices.

Farmland size: Farmland size was positively and statistically significantly related to crop diversification at the 10% level. The marginal effect indicates that each additional hectare increases the likelihood of adopting crop diversification by 6.6%. This suggests that farmers with larger landholdings are more inclined to diversify crops as a climate adaptation strategy, which is consistent with the findings of Abid et al. (2015) and Belay et al. (2017).

Access to credit: Access to credit has mixed effects on adaptation practices. It negatively influenced crop diversification and SWC at the 10% and 1% significance levels, respectively, while positively affecting agroforestry and improved coffee variety adoption at the 5% level of significance. Specifically, a unit increase in credit access decreased the likelihood of crop diversification by 3.6% and SWC by 7.9%, but increased agroforestry adoption by 9% and improved variety use by 0.3%. These results suggest that credit facilitates investment in capital-intensive innovations but may hinder labor-intensive practices, such as diversification and SWC, which require more immediate labor inputs. Similar patterns were observed by Mairura et al. (2021) and (Moahid & Maharjan, 2020), who noted that credit access influences farmers' decisions regarding resource-intensive investment.

4. Conclusions and Recommendations

This study explored climate change adaptation strategies in coffee-based farming systems and their determinants in the West Wallaga zone, Western Ethiopia. Farmers perceived significant increasing temperatures, rainfall variability, and longer dry seasons, leading to risks such as delayed rainfall onset, abrupt cessation, and prolonged summer rains. In response, most households implemented at least one adaptation measure most commonly agroforestry, soil and water conservation, crop diversification, improved coffee varieties, and pest management. However, some farmers remained non-adopters due to influence of barriers such as financial constraints, limited farm size, and poor access to climate information. Multinomial logit results showed that adaptation choices were significantly influenced by household head age, family size, education, farm size, and access to credit, underscoring the importance of capacity and institutional support. Addressing these challenges requires targeted, locally tailored interventions such as raising awareness, building capacity, promoting farmer-to-farmer learning, and improving access to credit, technology, and climate information. Strengthening institutional support and integrating indigenous knowledge with scientific innovations are essential to sustain coffee production under climate change. The findings offer practical guidance for policymakers and stakeholders in designing effective agricultural adaptation policies.

5. Limitation and Future Research Direction

This study examined five major adaptation measures widely adopted by coffee farmers. However, it did not explore in detail how these strategies were implemented. For example, the research had not identified the dominant types of trees species used in agroforestry systems, the types of improved coffee varieties planted due to climate change or the crops selected for diversification opportunities for adaptive benefits. Another limitation is the reliance on self-reported perceptions of climate

change and adaptation behavior, which may be influenced by recall bias or subjective interpretation. Additionally, the cross-sectional design limits the ability to establish causal relationships or to assess how adaptation strategies change over time.

Future research should place greater emphasis on in-depth qualitative investigations to better understand the motivations and implementation of specific adaptation practices. Longitudinal studies could capture changes in adaptation behavior over time, while experimental approaches would allow a more rigorous assessment of the affordability, feasibility, and overall performance of different strategies under changing climatic conditions.

CRediT authorship contribution statement

Tesfaye Akafu: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Diriba Korecha:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Weyessa Garedew:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization. **Abayineh Amare:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cliser.2026.100647>.

Data availability

Data will be made available on request.

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