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Potentials of coffee-based agroforestry system in enhancing adaptive capacity of local people for climate change: The case of Sidama National Regional State, Ethiopia

Dissertation thesis

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Declaration

I hereby declare that the content presented in this thesis, "*Potentials of coffee-based agroforestry system in enhancing adaptive capacity of local people for climate change: The case of Sidama National Regional State, Ethiopia*", submitted as a partial fulfilment of the requirements for the Ph.D. at Faculty of Tropical AgriSciences, Czech University of Life Sciences Prague, is my work unless listed in the references and acknowledgements sections. I also confirm that this work has not been previously submitted, nor is it currently submitted, for any other degree to this or any other university.

Prague, 2025

……………………
Tariku Olana Jawo

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List of Abbreviations

A	Agree
ACE	Abundance coverage-based estimator
AD	Strongly Agree
AFS	Agroforestry systems
AG	Aboveground
AGB	Aboveground Biomass
AGC	Aboveground Carbon
ANOVA	Analysis of variance
BD	Bulk density
BG	Belowground
BGB	Belowground Biomass
BGC	Belowground Carbon
C	Carbon
CAFS	Coffee-based agroforestry systems
CC	Climate Change
CE	Carbon equivalent
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station Data
CIAT	International Centre for Tropical Agriculture
cm	centimetre
CO_2	Carbon dioxide
CZU	Czech University of Life Sciences Prague
DBH	Diameter at breast height
DSA	Disagree (DSA),
ECFF	Ethiopian Coffee Forest Forum
EFRLS	Ethiopia’s Forest Reference Level Submission
EPCC	Ethiopian Panel on Climate Change
eqv	Equivalent
F	Frequency
FAO	Food and Agriculture Organization
FGDs	Focus Group discussions
FSCS	Full Sun Coffee Systen
GDP	Gross Domestic Product
GLM	General Linear Model
GPS	Global Positioning System
ha	hectare
$ha^{-1}yr^{-1}$	hectare per year
ICE	Incidence coverage-based estimator
ICO	International Coffee Organization
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
Kg	Kilogram
KIs	key Informants
LOI	Loss on ignition

m	meter
masl	meter above sea level
Mg C	Mega ton of carbon
mm	Millimeter
MV	monetary value
N	Nitrogen
n	number of samples
N	total number of households
N	Neutral (N)
NGOs	Non-governmental Organizations
NMA	National Meteorological Agency
NRS	Number of Respondents
P	Price
PAs	Peasant Associations
PRA	Participatory Rural Appraisal
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PRS	Percentage of Respondents
RA	Relative abundance
RD	Relative Dominance
REDD+	Reducing emissions from deforestation and forest degradation
RF	Relative Frequency
SD	Standard deviation
SDA	Strongly Disagree
Seq	sequestration
SI	Severity Index
SOC	Soil Organic Carbon
SPSS	Statistical Package for Social Sciences
SSA	Sub-Saharan African
TC	Total Carbon
TCI	The Climate Institute
Tmax	Maximum temperature
Tmin	Minimum temperature
UNCOMTRAD	United Nations Commodity Trade Statistics Database
UNCTAD	United Nations Trade and Development
UNDP	United Nations Development Program
UNEP	United Nations Environmental Protection
US	United States of America
US$	United state dollar
USDA	United States Development Agency
W	Weight
WAI	Weighted Average Index
Z	soil depth in cm

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Abstract

Smallholder farmers in Ethiopia typically depend on rain-fed agriculture, which is vulnerable to climate change (CC) due to the erratic nature of rainfall. Likewise, the CC models predict that enhanced climate variability hardly affects coffee-growing regions. Coffee (*Coffea arabica*) is the main cash income for 15 million smallholder farmers in Ethiopia. Therefore, exploring farmers' adaptation strategies to CC is essential for reducing the potential impacts of such changes, which are often reflected in reducing yields and, thus, lower income for farmers. Practicing agroforestry is among the adaptation strategies farmers can use to overcome the impact of CC and enhance their resilience. Agroforestry is an ecologically based farming practice that integrates trees into the farm to increase productivity while providing wider ecosystem services, including enhanced biodiversity and improved soil properties. So far, few studies have focused on the adaptive roles of agroforestry systems (AFS) in reducing farmers' vulnerability to CC in Ethiopia, but limited information is available about coffee-based agroforestry (CAFS) in eastern Africa, despite its global importance in the coffee production system. Therefore, the main aim of this study was to empirically assess the adaptation strategies of smallholder farmers to CC with a special emphasis on CAFS and their roles in improving the key ecosystem properties that contribute to ecosystem resistance and resilience to changing climate in the Sidama region, Ethiopia. In total, 351 coffee farmers along an elevation gradient (1,600 – 2,000 masl) were randomly selected for household interviews, complemented with key informants, focus group discussions, and field observations. A sample-based protocol was followed for the empirical measurements such as yields and growth of coffee, for the inventory of vegetation structure and diversity, soil macrofauna diversity, and soil data collection. For an inventory of woody species, litter, fine root and soil data collection, 108 plots were randomly selected, constituting 72 and 36 plots, CAFS and full sun coffee system (FSCS), respectively. Several indices were computed to measure farmers' perception of CC and measure diversities. The highest severity index was recorded for the rising temperature, followed by the uncertainty of rainfall distribution, increasing number of hot days, late-onset, and reduced amount of rainfall, predominantly in lower elevations. Rising temperatures and rainfall uncertainty have reduced coffee yields and bush density in the low elevations. As the most important CC adaptation strategies, the respondents practice tree planting (agroforestry), application of compost, terrace construction, modification of farming calendar, and crop diversification. In total, 31 perennial plant species representing 27 genera and 20 families were identified and recorded in CAFS. The perennial species Shannon diversity index significantly differed among the studied elevations ($p < 0.001$) and was higher for the mid, followed by high and low elevations. However, we observed a weak relationship between shade species diversity and biomass carbon stocks. CAFS had significantly higher ecosystem carbon stocks than FSCS ($p < 0.05$). The highest C stocks were found in soil, followed by biomass C, fine root, and litter in the CAFS and FSCS. The C income in CAFS was 70% higher than the FSCS. The mean coffee yield was slightly higher for coffee grown in FSCS than in CAFS; however, there was no significant difference. High soil macrofauna diversity observed in CAFS. There was a strong relationship between the Shannon diversity of shade trees and soil macrofauna diversity. This study confirms that farmers' perceptions are more important in shaping the applied adaptation strategies. Shade trees can reduce coffee crops against microclimatic extremes that will likely become more prevalent in a changing climate and reduce drought stress. CAFS has higher ecosystem carbon stocks, enhances biodiversity conservation and microbial diversity, and improves soil fertility compared to FSCS. Hence, CAFS could retain shade tree and soil macrofauna species, accumulate more C, and provide additional benefits from C credits that help the farmers adapt and mitigate CC while improving their livelihood.

Keywords: Agroforestry, carbon stock, coffee yield, ecosystem services, elevation gradient, Ethiopia, farmers' perception, severity index, shade trees, Sidama

1 Introduction

1.1 Background and justification of the study

Climate change (CC) and variability will affect food security by decreasing both food availability and accessibility on a global scale (FAO 2018; Tschora & Cherubini 2020). In particular, rainfed agriculture in the tropics is vulnerable to water and heat stress, which in turn will reduce the growing seasons of crops (FAO, 2018; Tschora & Cherubini 2020). A number of studies have documented that CC is highly affecting smallholder farmers' rainfed agriculture in Africa (e.g. Kurukulasuriya & Mendelsohn 2008; Bryan et al. 2009; Ramirez-Villegas & Challinor 2012; Emediegwu et al. 2022), especially in Sub-Saharan African (SSA) countries (Zougmoré et al. 2016). In SSA, CC models predict an increase in annual temperatures, and erratic rainfall affects the agricultural production system and exacerbates food insecurity (IPCC 2019; Porter et al. 2014; FAO 2018). Numerous studies have identified the impact of CC on farming activities and weather-dependent livelihood systems of smallholder farmers (e.g. IPCC 2014; Pachauri et al. 2014). CC and extreme weather events reduce crop yield (IPCC 2018), increase incidences of pests (Jarvis et al. 2012; Waha et al. 2012), reduce income (Kabubo-Mariara & Karanja 2007), affect and destabilize food prices (Wossen et al. 2018) and make food insecure for smallholder farmers (Schlenk & Lobell 2010). The high vulnerability of smallholder farmers to CC is related to poverty, lack of adaptive technology, lack of credit and rain-fed dependent agriculture (e.g. Bruckner 2012; Rodima-Taylor et al. 2012; Allen et al. 2014; Burke et al. 2015). The agricultural sector in Ethiopia accounted for 38 % of GDP in 2022 (World Bank 2024) and 73% of total employment (FAO 2019). The sector is vulnerable to CC and variability (Deressa 2009) owing to increasing average temperature and erratic and variable rainfall (NMA 2007; EPCC 2015). The country's average minimum and maximum temperatures have increased by around 0.25^0C and 0.1^0C, respectively, over the past decade (NAM 2007; Jawo et al. 2022) and are expected to increase by 2.7^0C to 3.4^0C by the end of the century (Tadege 2007; Jawo et al. 2022). This anticipated CC poses enormous threats to the livelihood of small farmers, including coffee producers.

Coffee (*Coffea* sp.*L.*) is one of the most traded commodities worldwide after oil (Davis et al. 2012; Fenton et al. 2012) and in 2014 more than 8.5 million tons were produced by 26 million small farmers in 52 countries with an export value of 39.3 billion US$ (ICO 2016). Globally, over 80 million people have been cultivating, processing, transporting and marketing coffee (Santos et al. 2015). In the world, over 70% of coffee is produced by smallholder farmers having less than 10 ha of land (Fridell 2014) and their main source of income (Bunn et al.

2015). Globally, Arabica coffee (*Coffea arabica* L.) accounts for the most significant proportion (60%), whereas robusta coffee (*Coffea canephora* L.) shares 40% (FAO 2015). Arabica coffee has a high market share because of its good taste, giving it a substantial premium in global markets. Ethiopia is the primary origin of Arabica coffee, which grows under native shade trees. The country is a leading African producer (Abu & Teddy 2013) and ranked fifth globally in Arabica coffee exports (ICO 2015). Ethiopia in 2021 produced 456,000 tons of green beans from 685,000 hectares (FAOSTAT 2021). Coffee is the major cash crop, as it supports the livelihood of 15 million smallholder farmers (USDA 2014) and is the most export-earning commodity in Ethiopia (Tefera 2012). Coffee contributes to the livelihood of many smallholder farmers and the national economy, however, the production of coffee is being severely impacted by CC and variability. Recent studies indicated that severe CC impacts on Arabica coffee production and its productivity are tightly linked to climatic variability (Camargo 2010; Killeen et al 2016). Moat et al. (2017) also indicated that the bio-climatically suitable space for Arabica coffee will decline, and the impact of CC could reduce the suitable area for growing by 50% globally by the year 2050 (Bunn et al. 2015).

Climate modelling studies projected significant effects of CC on coffee crop, including reductions in suitable areas (Zullo et al. 2011; Davis et al. 2012), yield losses (Gay et al. 2006) and extinction of wild populations of Arabica coffee in Ethiopia (Davis et al. 2012). For instance, an increase in temperature and a change in rainfall patterns were observed in coffee-growing regions across South America (Khalyani et al. 2016) and reduced coffee yield and quality, as well as increased the occurrence of pests and diseases (DaMatta et al. 2007; Jaramillo et al. 2011; Davis et al. 2012; Baca et al. 2014; Bunn et al. 2015). The study by Imbach et al. (2017) has shown that the total current areas suitable for coffee growing in South America will decrease by 73% and 88% for mid and high warming scenarios, respectively. Other studies have also reported that the climatic suitability of Arabica coffee will decline significantly in South America in the next decades (Schroth et al. 2009; Rahn et al. 2014). Davis et al. (2012) modelling study showed that by 2080, Ethiopia's projected suitable area for coffee production will decrease by 90% and yield loss if adaptation measures are not taken.

To reduce the adverse impact of CC on agriculture, adaptation and mitigation should be considered a decisive component of a policy response to CC and variability (Deressa et al. 2009; Gbetibouo 2009). Understanding the impacts of CC on coffee production and the adaptive capacity of smallholder farmers will provide fundamental information for the development of CC adaptation policy (Juhola & Kruse 2015). It is also crucial in designing appropriate adaptation strategies (Yesuf et al. 2008; Hannah et al. 2017), especially in Ethiopia, which is highly dependent on coffee production. An adaptive capacity combines available personal, community and societal strengths, attributes and resources harnessed to adjust to the surrounding conditions, reduce adverse impacts, and take advantage of opportunities (IPCC 2012). Enhancing the adaptive capacity of smallholder farmers plays a vital role because adaptation offers opportunities to build resilience to CC (Harley et al. 2008). Addressing resilience is imperative in Ethiopia's coffee sector to continue contributing to the long-term economic and social well-being of the farmers and other stakeholders participating in the sector (Hirons et al. 2018).

Agroforestry practice is an ecologically based farming practice that integrates trees into farming systems, contributing to CC mitigation while potentially enabling adaptation to CC (Mbow et al. 2014; Vaast et al. 2016). The practice also strengthens the system's ability to cope with the adverse impacts of a changing climate and contributes to CC mitigation through enhanced carbon sequestration (Verchot et al. 2006). This is due to the C storage potential of the system in standing biomass and soil (Montagnini & Nair 2004; Schoeneberger 2008).

AFS promote agroecosystem sustainability through enhancing nutrient cycling and conservation, ash deposition, and maintaining high species diversity (Montagnini et al. 2015) and favours microbial activity and their diversity (Ferreira et al. 2011; Rodrigues et al. 2015; Zake et al 2015). In addition, it also increases the microbial population and organic matter content in soil (Chander et al. 1998; Souza et al. 2012) and prevents nutrient losses (Mutual et al. 2005). Several studies indicated that smallholder farmers integrate trees in coffee production systems and the trees generate substantial ecosystem services, including conservation of biodiversity and native tree species (Jha et al. 2014; Vanderhaegen et al. 2015; De Beenhouwer et al. 2016), carbon sequestration (van Rikxoort et al. 2014; De Beenhouwer et al. 2016; Cerda et al. 2017) and soil protection and maintenance (Meylan et al. 2017). Coffee landscapes have more significant conservation potential in fragmented landscapes with long histories of human cultivation. Rapid increment of the human population enhances the need for more agricultural land, which leads to disturbance and even loss of forests, which in turn results in reduced soil fertility and crop productivity. Research findings showed that coffee-based agroforestry systems (CAFS) improve the quality of the landscape and play an important role in the conservation of native plant species (Perfecto et al. 1996; Perfecto & Vandermeer 2002) and mitigate increasing CO_2 concentration by sequestering carbon. Shade trees can mitigate coffee plants against microclimatic extremes that are likely to become more prevalent in a changing climate (Hirons et al. 2018) and reduce drought stress (Perfecto et al. 2007; Lin 2007).

To achieve a strategic approach to climate adaptation, the Climate Change National Adaptation Program of Action of Ethiopia (NAPA 2007) strategy considers agroforestry for increased use of trees on farmland for intensification, diversification, and buffering of farming systems to improve the resilience of agroecosystems and livelihood strategies of small farmers. Studies in Ethiopia indicated that agroforestry is one of the CC adaptation strategies for smallholder farmers (e.g Deressa et al. 2009; Amogne et al. 2018). It enhances the adaptive capacity of smallholder farmers to CC by delivering multiple benefits, including food provision, additional income and ecosystem services. For instance, a study conducted in Gedeo, South Central Ethiopia (Negash & Kanninen 2015) shows that the soil fertility enhancement roles of the AFS improve land productivity and households' resilience by providing diversified products for sale or home consumption. The availability of many trees and shrubs in AFS in southern Ethiopia contributes to the diversification of tree products and the sustenance of agricultural systems in the face of CC (Abebe 2005). A similar study in the North-Western part of Ethiopia shows that agroforestry enhances the livelihood of local people by providing agroecological services (Linger 2014). Thus, integrating trees into the farmland is a common strategy for smallholder farmers to adapt to CC and variability in Ethiopia (Deressa et al. 2009).

Several empirical studies and literature reviews so far focused on coffee agroecology (e.g. Davis et al. 2012; Perfecto & Vandermeer 2015) or structural issues in the international coffee market and value chain (Petit 2007; Arslan & Reicher 2010), but the low emphasis has been given to the adaptation role and ecosystem services of CAFS in reducing vulnerability to CC, particularly in Ethiopia or East Africa in general. Moreover, few studies have reported the CC mitigation potential of CAFS under smallholder farmers' management (Thangata & Hildebrand, 2012) and the relationship between shade species diversity and biomass C stocks (Asigbaase et al. 2021). According to Hameso (2015), irregular rainfall patterns and rising temperatures threaten coffee production in Sidama, South-eastern, Ethiopia. However, no scientific evidence confirms these climate events' impact on coffee production in the study region. Moreover, no empirical evidence has explored the linkage between coffee grower farmers' perception of CC, adaptation, and mitigation strategies in CAFS in the most important coffee growing regions in Ethiopia. Studying the linkages plays a significant role in informing policymakers to develop strategies and action plans in managing coffee agroecosystems and reducing the impact of CC on coffee production, improving smallholder farmers' livelihoods.

There is also a need for more scientific knowledge about diversity and the use values of tree species along an elevation gradient, and the synergies between floristic diversity and coffee production in CAFS of Sidama, Ethiopia. Furthermore, few scientific studies investigated the effect of AFS on soil health, specifically soil macrofauna diversity and abundance in East Africa, Asfaw & Zewudie (2021). The diversity of soil macrofauna in CAFS compared to the full sun coffee system (FSCS) has been less studied. Therefore, this study aimed to elucidate the farmer adaptation strategies to CC and evaluate the effect of shade trees on soil carbon, coffee yield, growth and soil microbial diversity. This study also envisioned contributing to designing CC adaptation strategies, conserving CAFS and recognizing the ecosystem services they provide to the local communities. Furthermore, this scientific study advances literature by addressing the knowledge gaps in the roles of CAFS in enhancing the adaptive capacity of smallholder farmers.

1.2 Objectives and hypotheses of the thesis

1.2.1 General Objective

The overall objective of the study was to assess smallholder coffee-based farmers' adaptation strategies to climate change with a special emphasis on coffee-based agroforestry system and their role in enhancing biodiversity and carbon sequestration, thereby contributing to farmers' and ecosystem's resilience to changing climate on agricultural landscape of Sidama National Regional State, Southern-eastern Ethiopia.

1.2.2 Specific objectives

The specific objectives were:

(i) To explore smallholder coffee farmers' perceptions and adaptation strategies of CC;

(ii) To assess perennial species diversity, ecosystem carbon stocks and carbon income in CAFS along an elevation gradient;

(iii) To examine the relationship between perennial species diversity and biomass carbon stocks;

(iv) To evaluate the effect of shade species diversity on soil macrofauna and coffee growth and yield.

1.2.3 Research Hypothesis

(i) Coffee-based farmers already perceived CC and have various experiences and strategies to adapt, which differ according to elevation and environmental conditions.

(ii) We expected different vegetation structures and diversity, ecosystem carbon stock, and carbon income along an elevation gradient in CAFS.

(iii) We expected a positive relationship between perennial species diversity and biomass carbon stocks.

(iv) We hypothesize that woody species diversity also impacts soil macrofauna diversity and abundance, coffee growth and yield.

1.3 Significance of the study

The management of agroecosystems for CC adaptation and mitigation is increasingly recognised. With increasing areas of degraded lands and agricultural expansion in Ethiopia, agroforestry has become a robust land-use system that enhances ecological functioning and improves the livelihoods of smallholder farmers. There is a lack of scientific evidence on the potential of CAFS for CC adaptation and mitigation in Ethiopia. Moreover, several authors' reviews provided conceptual models and theoretical bases for the potential of CAFS in CC mitigation and adaptation (e.g. Nair and Nair, 2003; Montagnini and Nair, 2004). However, empirical field studies have not been undertaken substantially to justify these theories and assumptions, particularly in East Africa. Moreover, little has been reported concerning the potential CAFS for CC adaptation, C ecosystem stock and soil macrofauna conservation under smallholder management. Therefore, this study contributes to designing appropriate CC adaptation and mitigation strategies and providing information for policymakers to develop a cost-effective adaptation and mitigation program. The study's outcome also provides pioneering ideas for different stakeholders (policymakers, NGOs, and development organisations) to evaluate their development interventions for further improvement of agroforestry practices at the farm and landscape level. Moreover, the study generates empirical evidence on the potential of CAFS for enhancing local people's adaptive capacity, the recognition of the ecosystem services they provide to the local communities and will inform and guide policymakers to integrate agroforestry as part of CC adaptation and mitigation strategies in the study region and beyond.

1.4 Outline of thesis and linkages

The thesis comprises the general research methodology, three already published articles and one manuscript submitted to the scientific journal (here presented as separate chapters), followed by a general discussion, conclusion, and recommendations. The general research methodology is explained in Chapter 2. The chapter provides basic information (socioeconomic and biophysical) about the study areas and procedures followed in selecting the research sites. It highlights the methods of data collection and analysis. Moreover, more emphasis has been placed on linking the objectives and the data collection methods.

Chapter 3 is based on our review paper that highlights the global significance of coffee production and discusses and synthesizes the impact of CC on coffee production and small farmers' adaptation strategies. This chapter gives background information and an introduction to the more thematically focused sections. Based on theoretical background information from the review paper, we developed a research proposal with appropriate methodologies to empirically elucidate smallholder coffee farmers' perception of CC and their adaptation strategies along an elevation gradient in southeastern Ethiopia. Moreover, our studies give insight into the potential of CAFS in CC mitigation by sequestering C, the conservation of biodiversity and soil macrofauna, and its effects on coffee yield and growth. Smallholder farmers' management of CAFS helps them adapt and mitigate CC, which is of both national and international significance.

Chapter 4 focuses on farmers’ perceptions of CC compared to long-term meteorological data and the identification of suitable adaptation strategies and barriers to adaptation. Moreover, determinants of CC perception and adaption, future sustainable coffee management, and policy intervention are discussed.

In Chapter 5, we evaluated the diversity of perennial plant species, ecosystem C stocks, and C income in CAFS. This section quantified biomass and soil C stocks in the different coffee production systems (CFAS and FSCS) and studied the relationship between perennial species diversity and biomass C stock. The ecosystems' C stocks and C income from the CAFS species are presented and discussed.

Chapter 6 examines the effect of shade species diversity on soil macrofauna diversity and coffee yield. In this chapter, shade species diversity, soil macrofauna diversity and coffee yield are linked and related. The importance of their linkages in helping small farmers pursue climate-resilient coffee production systems and mitigating CC are discussed.

Finally, in Chapter 7, the results are summarized and discussed, the implications for sustainable management of coffee agroecosystems are outlined, and overall conclusions are drawn. Moreover, to enhance the productivity of CAFS, policy recommendations are provided, and future research directions are given.

2 Methodology

2.1 Study area

In Ethiopia, coffee is grown in humid evergreen forests at altitudes ranging from 1,200 to 2,100 masl (Moat et al. 2017). Ethiopia's five major coffee-growing areas are Sidama, Yigachefe, Limu, Teppi/Bebeka. The first two were located in the Southeast, whereas the last three were located in the southwest part of Ethiopia. The study region, Sidama, is one of Ethiopia's coffee Arabica producing regions. Sidama region has a total population of 3.4 million (CSA 2012). The region is located between $5^0$45'-$6^0$45'N latitude and 38^0-39^0 E longitude, covering a total area of 7,672 km^2. The elevation of Sidama ranges between 500 and 3,500 masl, having three ecological zones with an annual mean temperature of 10^0C to 29^0C and annual rainfall ranges between 801mm and 1,600 mm (Abebe 2005). The distribution of rainfall is bimodal, with long (June – September) and short (March – May) rainy seasons (Mellisse et al. 2018). The most common soil types in the Sidama AFS are eutric nitosols, pellic vertisols, orthic acrisols, chromic luvisols and euctric fluvisols (Abebe 2005).

The region's total area under coffee cultivation is around 73 thousand ha, and the total estimated production obtained per annum is 50 thousand tons, with an average yield of 0.64 tons ha^{-1} (Tadesse et al. 2020). Sidama National Regional State has 36 districts. The study districts, Dale and Wensho, are among the central districts of Sidama National Regional State, with high coffee production and have different elevations (Figure 2–1). Dale and Wensho are found between 6°50′30″N and 38°32′0″E and 06°45′11″N and 38°30′16″E, respectively. Wensho elevation ranges from 1,750 to 2,149 masl, whereas Dale elevation ranges from 1,500 to 1,850 masl. Wensho topography and agroecology are characterized as cooler and to some extent milder compared to other districts in the Sidama region (Doda 2019). Wensho district has a mean annual rainfall and temperature ranging from 1,200 mm to 1,600 mm (Molla and Asfaw, 2014) and 18^0C to 21^0C, respectively (Moges et al. 2013). Dale district receives a mean annual precipitation of 858 – 1,600 mm and a mean annual temperature ranges from 11^0C to 28.4^0C (Atinafu et al. 2017).

In both districts, coffee and enset (*Ensete ventricosum* L.) are mainly integrated into traditional AFS. Enset, also called "false banana,'' is a herbaceous perennial crop primarily grown in central, south-west and southern Ethiopia, which supports the livelihoods of around 20 million people. *Albizia gummifera* (*J.F.Gmel.*) *C.A.Sm, Cordia Africana* Lam and *Millettia ferruginea* (Hochst) are the most commonly used shade trees AFS in the study region. Also, other tree species integrated in CAFS in the study region are *Afrocarpus falcatus* (Thunb*)*, *Grevillea robusta* A.Cunn, *Sapium ellipticum* (Hochst.) Pax, *Ficus vasta* Forrsk, *Ficus thonningii* BI. *and Croton macrostachys* (Hochust).

Figure 2- 1. Coffee agroforestry systems of Sidama (Photo: Tariku 2021)

Coffee production is accompanied by subsistence production of maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), haricot bean (*Phaseolus vulgaris* L.), and soybean (*Glycine max* L.) together with animal husbandry. Avocado (*Persea americana* M.), mango (*Mangifera indica* L.), and banana (*Musa* spp.) are the main fruit species cultivated in the area both for household consumption and income generation.

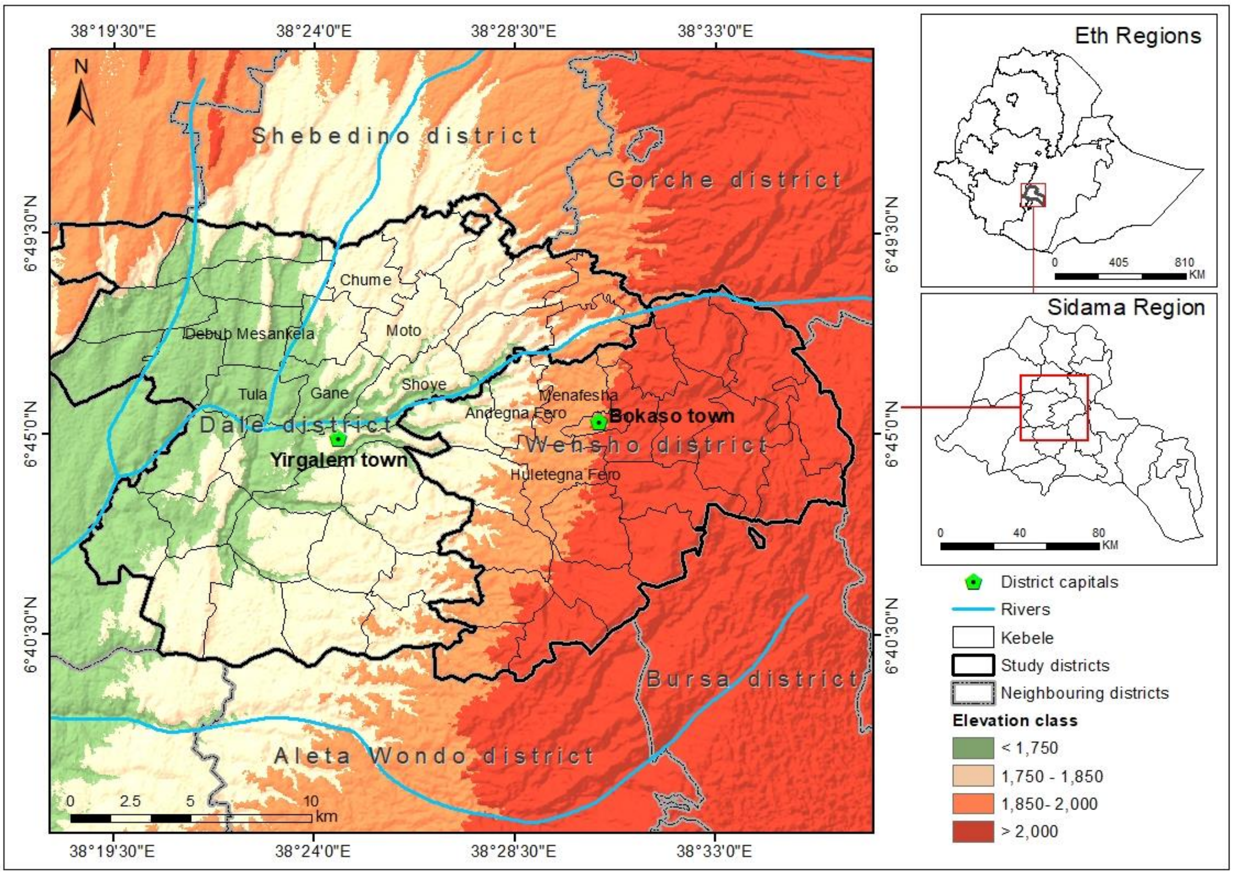

Figure 2- 2. Map of the study area

2.2 Study design and site selections

Our fieldwork started with collecting secondary data to identify potential districts for the study objectives. Dale and Wensho Districts were purposively selected due to their representatives to coffee growing elevation gradient (high 1,850 – 2,000 masl, mid 1,750 – 1,850 masl and low 1,600 – 1,750 masl), as well as high coffee production. Then, nine Kebeles or peasant associations (PA), the lowest administrative units in Ethiopia, were purposively selected from each elevation to undertake the study. We used a simple random method by defining the population (smallholder coffee producers), and the number of respondents included in the study was determined using Yamane's (1967) methodology.

A total of 351 farmers representing 127 from high, 138 from mid, and 86 from low elevations) were selected using a random (lottery) number generator for household interviews. Of those, 54 representative farmers/farms were also selected for vegetation diversity, coffee growth, carbon stock and soil health evaluation to link smallholder coffee producers' climate adaptation and mitigation strategies.

Sample farms of CAFS and FSCS were selected for coffee yield harvest and growth measurement along an elevation gradient using key informants, and their location was georeferenced with GPS. A total of 54 (36 CAFS and 18 FSCS) representative farms were selected, and a 20 × 20 m permanent sample plot was established at each farm. Soil, litter and fine root data were also collected from 54 farms, one plot sampled per farm.

Figure 2- 3. Farm selection with district coffee experts, development agent, coffee farmer and GIS expert Menafesha Kebele, Wonsho district (Photo: Tariku, 2021)

2.3 Data collection

Key informant interviews, stakeholder consultations, focus group discussions, household interviews, and field observation were employed. The households were interviewed with the help of semi-structured and structured questionnaires. To triangulate the information captured through the interview, we also made farm observations. Information related to households' socio-demographic characteristics, perceived impacts of CC and variability, adaptation strategies, determinants of adaptation and adaptation barriers was collected using a semi-structured questionnaire (Appendix A, Tables 1 and 2). To evaluate rainfall and temperature data (1983 – 2020), we used Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) version 2.0 and the maximum (Tmax) and minimum (Tmin) temperature from the observational reanalysis hybrid.

Figure 2- 4. Household interview, Moto Kebele, Dale District (Photo: Tariku, 2021)

Figure 2- 5. Discussion with key informants and development agent Gane district, Dale district (Photo: Tariku, 2021)

A nested sample plot of 20 m x 20 m with the three subplots 5 m x 5 m across the diagonal of the main plot was established. All trees/shrub species with DBH ≥ 2.5 cm were identified and measured to determine their basal area and tree density. Above (AGB) and belowground standing biomass (BGB) C stocks of woody species, bananas (*Musa* spp.) and coffee were determined from DBH ≥ 2.5 cm and tree height ≥1.5 m. The standing biomass C stock's gross monetary value was estimated from the age of the shade trees and the farms.

Figure 2- 6. Vegetation (a) and coffee bush density (b) inventory, Chume Kebele, Dale district (Photo: Tariku, 2021)

To evaluate soil carbon stocks, a total of 486 soil samples (54 farms x 3 subplots x 3 soil depths, 0–20 cm, 20–40 cm, and 40 60 cm) were collected. The collected soil samples were dried at room temperature, milled and passed through a 2 mm sieve and soil organic carbon concentrations were determined using the Walkley and Black method. Similarly, the same number of soil samples were collected separately for bulk density determination. The soil samples were oven-dried for 24 hours at 105^0C. The bulk density (Mg m^{-3}) was calculated using the core sampler's volume (7 cm diameter and 10 cm height, 384.85 cm^3) and the sample's weight.

Figure 2- 7. Soil data collection, Tulla, Dale district (Photo: Kassahun, 2022)

Fine root samples (< 2 mm diameter) were collected from the soil samples for the three depths (0–20 cm, 20–40 cm and 40–60 cm). The soil samples were drenched for 30–40 minutes to facilitate the soil aggregates breakdown, washed and extracted by hand and passed through a 2 mm sieve. The samples were dried at room temperature for one day and then oven-dried at 70°C for 24 hours. The oven-dried fine root was grinded and the C content was determined through the loss on ignition (LOI) method at 550^{0}C for 2 hours. Moreover, a total of 162 litter samples were collected.

Figure 2- 8. Fine root data collection form sample soil, Wonod Genet College of Forestry and Natural Resources laboratory, Ethiopia (Photo: Tariku, 2022)

Figure 2- 9. Litter data collection Gane Kebele, Dale district (Photo: Tariku, 2021)

In addition, a soil macro-fauna metal frame (25 cm x 25 cm x 10 cm depth) was placed in the soil, and the soil monolith was extracted. Finally, coffee yield harvested, and growth parameters were measured in the plot designed for the measurement of trees/shrubs and soil data collection.

Figure 2- 10. Soil monolith extraction Chume Kebele, Dale district (Photo: Tariku, 2021)

Figure 2- 11. Soil macrofauna collection Chume keble, Dale district (Photo: Tariku, 2021)

2.4 Data analysis

The Mann–Kendall test was used for meteorological data to analyze temperature and rainfall trends (1983 – 2020). The severity Index was used to measure farmers' perceptions of CC and the perceived impact of CC on coffee production. Weighted Average Index was used to rank farmers' adaptation strategies and factors hindering CC adaptation**.** Species richness estimator (E (estimate), Chao 1, Jack 1, ICE, ACE) and diversity indices (Shannon, Simpson and Fisher's alpha) were computed to evaluate the diversity of perennial species in CAFS. The AGB and BGB of woody species were estimated using species-specific allometric equations developed for trees grown on farmland (Kuyah et al. 2012a, b), coffee (Negash et al. 2013) and banana (Kamusingize et al. 2017). The total biomass C stock (TCS) of woody species and other perennial plants was calculated as the sum of AGC and BGC. Total ecosystem C stocks were determined by summing the biomass C stocks (AGC and BGC), litter, fine root and SOC. The gross monetary value (MV) of total standing biomass C stocks was estimated as MV = CE*P, where CE is the CO_2 equivalent of C stocks (CE = C stocks x 3.7), and P is the unit price (US $) of CE (Somarriba et al. 2013). All statistical analyses were done using R-software, Statistical Package for Social Sciences (SPSS) and Excel spreadsheets.

3 Results

3.1 The impact of climate change on coffee production of small farmers and their adaptation strategies

Adapted from: Jawo TO, Kyereh D, Lojka B. 2023. The impact of climate change on coffee production of small farmers and their adaptation strategies: a review, Climate and Development 15:(2), 93-109, DOI: 10.1080/17565529.2022.2057906

This literature review discusses and synthesizes (i) the impact of climate change on Arabica coffee production and (ii) small farmers' adaptation strategies to pursue climate-resilient coffee production. Finally, we recommended adaptation options and needs at the farm and landscape levels to safeguard coffee production from the projected impacts of CC. This chapter addresses aim (i) the impact of climate change on coffee production of small farmers and their adaptation strategies.

Authors contribution: The authors compiled and summarized the latest literature and analyzed the available data and wrote the manuscript.

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Abstract

Recent CC models predict that coffee production and the livelihood of millions of farmers will be hardly affected by CC. Climate changes pronounced in increasing temperature and rainfall variability will reduce the bio-climatic suitable areas, growth, and yield of coffee and will induce the occurrence of pests and diseases. Understanding the extent of the climate-driven impact on coffee production and farmers' adaptation strategies is vital in sustaining coffee productivity. In the form of in-depth analysis, this review begins by contextualizing CC and coffee production and gives insight into the impact of CC on coffee suitability areas, growth, yield, and the incidence of pests and diseases. It further examines the adaptation strategies pursued by farmers to reduce the impacts of CC. Site-specific adaptation strategies implemented by farmers to minimize detrimental effects of CC include (i) selecting appropriate shade tree species and their optimal management, (ii) farmers training, (iii) soil fertility maintenance and protection, and (iv) pests and diseases management. Moreover, improving farmers' access to weather information, fair markets, and technology will enhance their adaptive capacity to CC. Finally, designing adaptation policies and building the existing practices help the small farmers to pursue climate-resilient coffee production.

Keywords: climate-resilient; growth and yield; livelihood, pest and diseases; adaptive capacity

3.1.1 Introduction

Climate change affects the livelihood of small farmers as rainfall and temperature variability reduces their agricultural production and income (Lipper et al. 2014). Climate variability has reduced global agricultural production (Porter et al. 2014), and warming trends are likely to reduce global yield by roughly 1.5% per decade (David & Sharon, 2012). Recently, there has been an increased concern on the substantial rise in the minimum night temperature and its effect on tropical crops (Bapuji et al. 2014). On a global scale, the minimum temperatures increased twice the maximum temperatures (de los Milagros Skansi et al. 2013) and reduction in the amount and changes in the rainfall pattern limit the availability of water to plants (Santos et al. 2015). Climate change effect on rain-fed agriculture and human welfare is generally expected to be adverse in the future (Samberg et al. 2016) and will challenge the livelihood of millions of people worldwide (Adesina, 2010), particularly small farmers. The changes in environmental conditions have a severe impact on the farming activities of small farmers (DaMatta et al. 2010) who have small areas of land usually less than 10 ha and depend on their farm as the primary source of income and food security (Nagayets 2005). In the world, 75% of the world agriculture is practised by small farmers (Lowder et al. 2016), comprise 60% of the agricultural labour force (Fyfe 2002) and supply more than 80 % of developing countries' food consumptions (UNEP 2013). Despite representing a large proportion, climate variability coupled with low agricultural productivity, low capital and low adaptive capacity (Bruckner 2012) makes small farmers rain-fed agriculture especially vulnerable to climate extremes. Small farmer coffee producers are already highly affected by changing climate because of limited resources to address costly adaptation strategies (Jaramillo et al. 2011).

Coffee (*Coffea sp.L.*) is one of the most heavily traded commodities (Davis et al. 2012), consumed beverages (Priscila et al. 2019) and more than 2.25 billion cups are consumed daily around the world (TCI 2016). The annual coffee marketing is estimated to be more than 90 billion US$ worldwide (International Coffee Organisation 2015). Coffee significantly contributes to the socio-economic development of coffee-producing countries by being the main export earner and also supporting the livelihoods of more than 120 million people worldwide (TCI, 2016), particularly small farmers (Laderach et al. 2017). Globally, over 70% of coffee is produced by small farmers (Fridell, 2014) and coffee is their main source of cash income (Bunn et al. 2015b). Arabica coffee (*Coffea arabica* L.) accounts for the largest proportion (60%), whereas Robusta coffee (*Coffea canephora* L.) shares 40% worldwide (FAO, 2015). Robusta coffee is more heat tolerant but more susceptible to low temperature than Arabica coffee (Wintgens 2012). Arabica coffee is mainly grown in tropical high lands (Ovalle-Rivera et al. 2015) and has higher consumer demand than Robusta coffee because of its better taste (Mehrabi & Lashermes 2017). Arabica coffee grows best at 18–22^{0}C while Robusta coffee is productive at 22–28^{0}C, but outside these optimum temperature ranges, both species' growth, yield and bean quality decline (Magrach & Ghazoul 2015).

Numerous studies indicated that climate change is expected to have a significant impact on coffee suitable areas, particularly Arabica coffee (Davis et al. 2012; Bunn et al. 2015b; Magrach & Ghazoul 2015; Ovalle-Rivera et al. 2015) and its genetic resources (Davis et al. 2012). Arabica coffee is negatively affected by the changing climate (Chemura et al. 2016; Donatti et al. 2018) due to sensitiveness to high temperatures and changing rainfall patterns (Bunn et al. 2015a). Increased temperature, erratic rainfall and prolonged drought periods are commonly befallen in coffee cultivating areas (Ericksen et al. 2011). These environmental conditions substantially affect suitable coffee areas (Fain et al. 2017; Tavares et al. 2018), yield and quality (Bunn et al. 2015a), and the livelihood of small farmers and enhance their vulnerability to climate change (Drabo, 2017).

Research efforts have been underway in predicting the impacts of CC on coffee production (Davis et al. 2012; Jaramillo et al. 2013) and adaptation measures to be taken. In coffee growing regions, CC is expected to increase temperature, alter rainfall patterns and enhance climate variability that will have a severe effect on coffee growth, yield and quality (Ovalle-Rivera et al. 2015; Laderach et al. 2017). Understanding the extent of climate-driven impacts and small farmers' CC adaptation strategies will be vital in maintaining coffee productivity and improving livelihoods (Pham et al. 2019) and reducing food insecurity (Di Falco & Marcella 2013). To make the coffee production systems more resilient to changing climate, adaptation measures have to be developed and implemented by the small farmers (Lipper et al. 2014). Therefore, this review discusses and synthesizes (i) the impact of climate change on Arabica coffee production, and (ii) small farmers' adaptation strategies to pursuing climate-resilient coffee production. Finally, we recommend adaptation options and needs at the farm level to safeguard coffee production from the projected impacts of CC.

3.1.2 Methods

Systematic review

We conducted a systematic review of the literature on the impact of CC on coffee production and small farmer adaptation strategies. A systematic review is a detailed review of high-quality and relevant existing literature to address the formulated objectives (Littell et al. 2008). It uses specific and reproducible methods to identify, select, evaluate and synthesize systematically all relevant empirical scientific studies that pertain to the objective set in the paper. According to Bowler et al. (2010), a systematic review involves formulating a detailed and comprehensive review procedure with an acceptable searching strategy for literature and clearly defining the main eligibility criteria for inclusion and exclusion of candidate studies. Moreover, Pickering et al. (2015) stated that categorizing the selected literature on a specific research topic requires a systematic and reproducible approach for a comprehensive survey. Eligible literature and studies then are subjected to screening and evaluation of objectives for quality and relevance.

Search strategy and data sources

Searching for relevant studies and literature was conducted using internet search engine databases of peer-reviewed scientific journal publishers and different academic and development organizations websites. We searched for high-quality studies and literature and used a comprehensive and structured search strategy combined with key terms and phrases.

Journal articles

Published scientific papers were searched and accessed between February to May 2020 through the Czech University of Life Sciences Prague (CZU) links to databases and websites of e-journals. The main e-journal publishers and links accessed through the CZU were Scopus, Google Scholars, Web of Science and Science Direct. The keywords and phrases included in the search algorithm for this review paper were the combination of ‘’climate’’ and ‘’coffee’’, ‘’impacts’’, ‘’effect’, ‘’land suitability’’, ‘’yield’’, ‘’growth’’, ‘’production’’, ‘’pest, ‘’diseases’’, ‘’shade trees, ‘’adaptation’’, ‘’climate-resilient’’, ‘’income diversification’’, ‘’soil conservation’’. The abstract, title and keywords of original research articles published in peer-reviewed academic journals were searched and examined. Moreover, we explored the literature to identify small farmers adaptation strategies and gaps to recommend the best adaptation practices and future research needs to produce climate-resilient coffee production.

Unpublished studies

Search for relevant unpublished studies was conducted by using websites and databases of academic institutions, NGOs, local and international research organizations, and international organizations. The keywords used in the search were mainly adapted from the previous search strategy to fit the information sought from the different local and international organizations.

Identification and selection of studies

Identifying and selecting the relevant papers for this review paper were adapted from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram (Moher et al. 2009) (Figure 3-2). Four hundred thirty-six potentially eligible records were found and retrieved from the above databases using the keywords and phrases search terms listed. As a result, 75 of the 350 records were excluded because they did not sufficiently focus on the impact of climate change and variability on coffee production, climate adaption strategies, the importance of shade trees for coffee production and coffee pests and diseases. From the remaining 275 records, 46 papers were excluded due to poor quality, limited significance, and fallibility of data. Finally, the most relevant papers meeting the objectives of the review were included. Hence, 229 studies were included in the review (Figure 3–2), and many of the papers had been conducted after 2010 (150 studies = 66.5%) (figure 3-1).

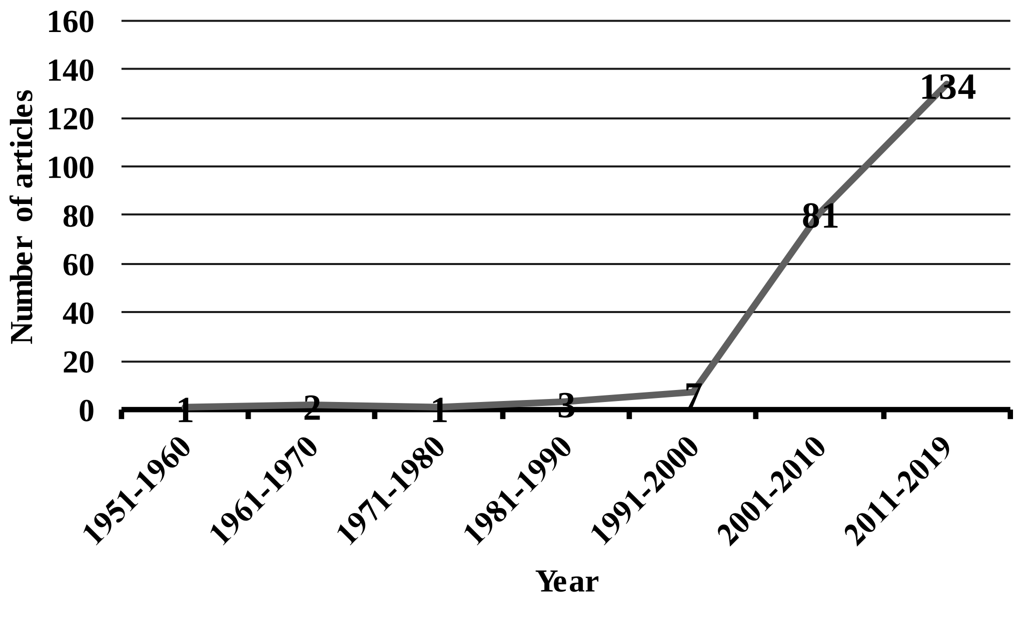

Figure 3- 1. The number of articles included and the year in which the article is published (adapted from Moher et al. 2009).

Data extraction and research quality assessment

We used both objective and subjective evaluation criteria to determine the quality of the studies and reports to be appropriate for inclusion in the paper. The main evaluation criteria included the theoretical basis and significance of the research; the trustworthiness of data sources; and the quality of the analysis. The information related to our objectives was systematically extracted from published journals and unpublished studies. A systematic empirical analysis, qualitative descriptions and synthesis, and narrations approach were used to critically analyze and interpret the findings.

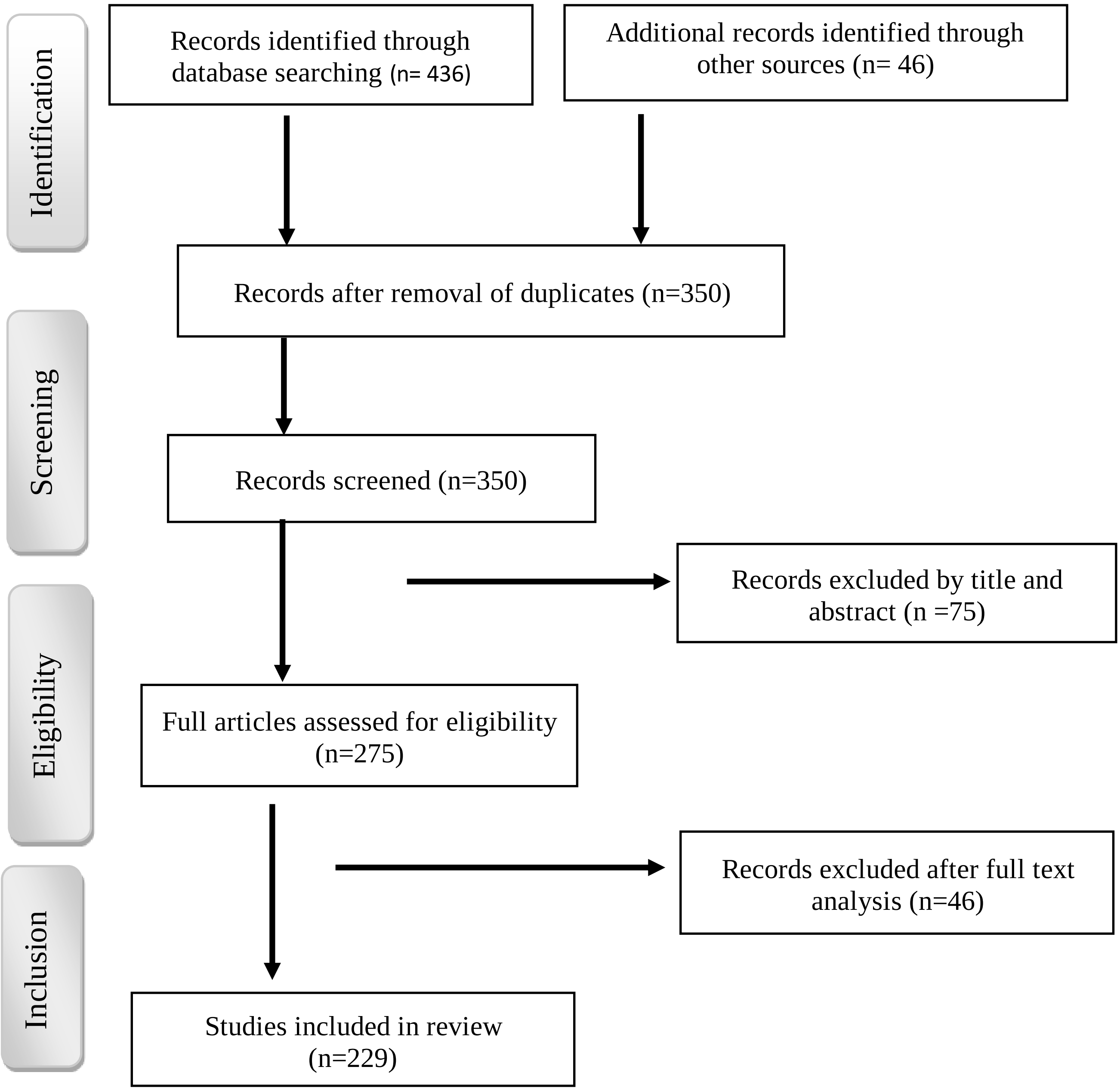

Figure 3- 2. Flowchart of the study and steps followed during the review process (adapted from Moher et al. 2009)

3.1.3 Results and Discussion

3.1.3.1 Climate change and coffee production

3.1.3.1.1 Current impacts

The evidence for CC is certain, and its impacts are already being felt in coffee production. Coffee is becoming increasingly stressed as the air temperature increases and rainfall decreases (ECFF, 2017). IPCC (2007a) predicts that the average global temperature will increase between 1.8^{0}C to 4^{0}C by the end of the twenty-first century. Based on this forecast, the coffee production system will face severe challenges in the coming decades (Baker & Haggar 2007; Camargo 2010). Coffee production mainly depends on the optimal rainfall and temperature to attain high yield and quality (Killeen & Harper 2016), but an increase in intensity and frequency of extreme weather events affects the production.

In Mesoamerica, the CC models predict reducing the amount of rainfall and increasing temperature (Imbach 2012) that will negatively affect coffee productivity, increase the incidences of pests and diseases and reduce suitable coffee areas (Laderach et al. 2011; Haggar & Schepp 2012). Climate modelling studies have also estimated that CC has significant effects on the coffee crop, including extensive reductions in suitable areas in Brazil (Zullo et al. 2011) and severe yield losses in Mexico (Gay et al. 2006). Similarly, CC is expected to increase temperature and change rainfall patterns (Khalyani et al. 2016) in coffee-growing regions across South America, reducing coffee yield and quality and increasing pests and diseases (Baca et al. 2014; Bunn et al. 2015b). TCI (2016) reported that in 2014, the Brazilian state of Minas Gerais produced around 25% of the country's coffee affected by severe drought and high temperatures and reduced coffee yields by about a third. In the Pacific region of Guatemala in 2005, Hurricane Stan resulted in the loss of 20% of the coffee harvest (worth 4 million US$) (Haggar et al. 2011). Moreover, it resulted in yield loss and extinction of the wild population of Arabic coffee in East Africa, particularly Ethiopia (Davis et al. 2012). The changes that influenced coffee production include an increase in the uncertainty of yearly weather patterns, remarkably variability in precipitation, an extension of the dry season, more extreme weather (heavier rain, hotter days) and warmer nights (Craparo et al. 2015).

Climate change can significantly affect the world market and is the primary factor responsible for the instability of global coffee production and marketing (ICC 2014). Climate change and variability impact the coffee industry from production to export (Dekens & Bagamb 2014), and small farmers receive higher volatility of coffee prices because CC puts pressure on the coffee value chain and leads to a more significant coffee supply chain fluctuation (Verburga et al. 2019). Reports indicated that more and more extreme weather events in major coffee-producing regions seem set to create supply shortages, and hotter conditions will impair flavour and aroma (TCI 2016). The volatility of the coffee market makes unstable the already precarious lives of small farmers by decreasing family income, food insecurity, and poverty (Jaramillo et al. 2011), with negative consequences on their wellbeing and social stability (Tucker et al. 2010). Furthermore, Bacon et al. (2014) also reported that extreme weather conditions highly affected many coffee communities because they live in a weak economic position and seasonal hunger (Table 3-1).

Table 3- 1. The predicted impacts of climate changes on coffee production

Impacts of climate change on coffee production	References
Loss of suitable areas for coffee cultivation	Davis et al. (2012); Bunn et al. (2015b); Moat et al. (2017); Ovalle-Rivera et al. (2015)
Loss of wild Arabica coffee	Davis et al. (2012); Moat et al. (2017)
Decrease growth and yield	Gay et al. (2006); Craparo et al. (2015)
Loss of beverage quality	Läderach et al. (2017)
Increased the incidence of pests and diseases	Avelino et al. (2015); Magrach & Ghazoul (2015)
High-temperature damages flowering	Pereira et al. (2008)
Delayed the development and ripening of coffee fruits	Pohlan and Janssen (2010)
Reduce the growth of individual fruits	DaMatta et al. (2007)

3.1.3.1.2 The impacts on coffee suitability areas

The changing climate in the coming decades is expected to alter the suitability of many current coffee production areas. Coffee suitable area is the area suitable for growing coffee (in terms of temperature, rainfall, soil and topography) or the area's ability to reach the potential yields to satisfy coffee growers. Arabica coffee is originally grown under a dense forest canopy in Eastern Africa, particularly understory of Ethiopian Afromontane rainforests (Reichhuber & Requate 2012). It grows in narrow bio-climatic conditions and flourishing at optimal weather conditions. Reports indicate that Arabica coffee is productive at an altitude range between 600 and 1900 masl (Ovalle-Rivera et al. 2015) and the optimal annual rainfall of 1200 – 1800 mm (Alègre 1959) but can also tolerate rainfall as low as 900 mm yr^{-1} (Mamo, 1992). The optimum mean annual temperature for Arabica coffee ranges from 18^0C to 22^0C (DaMatta & Ramalho, 2006), or up to 24^0C (Teketay 1999). For growth and the development of fruit, Arabica coffee might require around 23^0C/17^0C (day/night) temperature (Camargo 1985; Barros et al. 1999).

As Arabica coffee grows in narrow bio-climatic conditions (Teketay 1999), with increasing temperatures, rain-fed coffee production will decline at lower elevations and migrate to a higher elevation (Davis et al. 2012). Area suitability studies using Maximum Entropy (MaxEnt) methods for different countries such as Nicaragua (Läderach et al. 2010), Mexico (Morales et al. 2012; Schroth et al. 2009), El Salvador, Costa Rica, Honduras and Guatemala (Haggar et al. 2011; Läderach et al. 2010), Brazil, Tanzania and Vietnam (Haggar et al. 2011), Ethiopia (Davis et al. 2012), Haiti (Eitzinger et al. 2013), Uganda (Jassogne et al. 2013) and Indonesia (Schroth et al. 2014) indicated that climate change would substantially reduce the coffee suitable areas and move the coffee production to higher elevations (Table 3-2).

Table 3- 2. Projected suitable area loss for coffee production for different regions/countries

Regions/Countries	Projected suitable area loss (%)	Projected year	References
Ethiopia, Sudan, Kenya	90	2080	Davis et al. (2012)
Puerto Rico	84	2070	Fain et al. (2018)
Mexico	98	2050	Schroth et al. (2009)
Vietnam	20	2050	Ovalle-Rivera (2015)
Indonesia	33	2050	Schroth et al. (2014)
Brazil	36-64	2100	Tavares et al. (2018)
Nicaragua, Costa Rica, El Salvador	40	2050	Laderach et al. 2017)
South America	73-88	2050	Imbach et al. (2017)
Global	50	2050	Bunn et al. (2015a)

A study in South America by Imbach et al. (2017) has shown that the total current coffee production suitable areas will decrease by 73% and 88% for mid and high warming scenarios, respectively. Studies have also indicated that the climatic suitability of Arabica coffee will highly decline in the next decades in South America (Rahn et al. 2014). Davis et al. (2012) study shows that the accelerated global climate change might lose 65–100% of bioclimatic suitability for future indigenous Arabica coffee production distribution in Ethiopia by 2080. Similarly, present and future climate change model prediction on the distribution of indigenous Arabica coffee indicated a profoundly negative influence on coffee production and will continue to reduce the production of Arabica coffee in East Africa (Davis et al. 2012). Davis et al. (2012) further pointed out that the unsuitability of the bio-climatic area for Arabica coffee would place the coffee populations at risk and lead to severe stress.

The climate change in Ethiopia negatively impacts much of the current coffee farming landscape; however, substantial areas that were previously unsuitable for coffee will become suitable as the century progresses (Moat et al. 2017). This is due to the upslope shift of coffee growing suitability to higher altitude areas above 2000 m, and lower altitude areas worsen as the climate changes (Moat et al. 2017). Laderach et al. (2008) predicted that climate change shifts the altitude range for coffee to higher elevations from 1200 m to 1400 m in 2020 and

1600 m in 2050 in Central America regions. Most coffee-producing countries would lose area suitability while others would gain from variation in weather elements for a certain period (Ovalle-Rivera et al. 2015). For instance, a substantial loss in the total suitable area in less montane regions of Nicaragua, Honduras and Venezuela while expansion in Mexico, Guatemala, Colombia and Costa Rica (Ovalle-Rivera et al. 2015). The authors modelling study for East Africa also predicted that the climate suitable for Arabica coffee would shift from 400 – 2000 masl to 800 – 2500 masl. Uganda and Tanzania will lose coffee suitable area at elevations below 1,400 masl, while there would be a change in the suitability of the areas in Ethiopia and Kenya and will gain regions at higher elevations of 1500 – 2400 masl and become suitable.

Coffee will migrate to higher elevation areas to compensate for the increased temperature and shortage of rainfall in the lower elevation. The migration of coffee growing to the new suitable area will result in deforestation and profoundly challenge the forest resources conservation in biodiversity hotspots in the Amazon Basin, Indonesia, Papua New Guinea, Cameroon, Gabon and Congo basins (Meyfroidt et al. 2014). The establishment of coffee plantations in biodiversity hotspots will reduce tree density and diversity (Mendez et al. 2009; Perfecto et al. 2005) and decrease ecosystems functions (De Beenhouwer et al. 2013). Hence, the integration of coffee plantations to new forested land will require appropriate policies, forest conservation strategies and action plans implemented with the inclusion of the local communities.

3.1.3.1.3 The effect on coffee growth and yield

Climatic conditions determine coffee plants' vegetative and reproductive phases (Tavares et al. 2018). Recent modelling studies indicated that climate change reduces coffee flowering and fruiting (Villers et al. 2009), thus yields (Craparo et al. 2015; Ovalle-Rivera et al. 2015) and also quality (Ovalle-Rivera et al. 2015). The coffee phenology highly depends on the optimal rainfall distribution and decreasing the amount of rainfall affects the critical period of coffee crop development (Lin et al. 2008). Erratic rain affects coffee crop physiology, particularly during flowering stages, making coffee flowers various times throughout the year (Jassogne et al. 2013). It forces the small farmers to harvest small quantities of coffee yield and increase their production cost (Gay et al. 2006). Long rainy seasons decrease the photosynthesis process, reduce flowering and coffee tree fruit setting (CIAT 2010). Läderach et al. (2010) study also explained that the flowering of coffee is triggered at the beginning of the rainy season, but heavy rain results in the dropping of flowers and immature fruits development (Table 3-3).

Table 3- 3. The effects of temperature and rainfall on coffee production

The effects of temperature and rainfall on coffee production	References
Temperature above 35^{0}C inhibited germination	Barros et al. (1999)
Temperature exceeds 30^{0}C depressed growth	Franco (1958)
Temperature below 17–18^{0}C reduced growth	DaMatta et al. (2007)
Mean annual temperature below 18^{0}C depressed growth	DaMatta & Ramalho (2006)
Temperature exceeds 30^{0}C reduced photosynthesis and physiological activities	Camargo (2009)
Temperature below 18-20^{0}C reduced photosynthesis	Batista-Santos et al. (2011)
High air temperatures (30^{0}C and 24^{0}C, during day and night, respectively) resulted in deficient floral development and a large number of aborted flowers	Mes (1957)
Prolong dry season (shortage of rainfall) caused abortion of flowers	Camargo (1985)
Higher temperatures caused flowers to drop or fruit to ripen too quickly with low quality	DaMatta & Ramalho (2006)
Temperature above 23^{0}C, accelerated fruit development and ripening and leading to beverage quality loss	Camargo (1995)
Long dry season caused the ripening of immature coffee berries and reduced beverage quality	Frank (2017)
At annual rainfall exceeding 3000 mm, coffee pants developed leaf diseases from fungal infections	Pohlan & Janssen (2010)

Drought is considered the major environmental problem affecting coffee production in most coffee-growing countries and resulted in the loss of coffee yield by 80% in dry years (DaMatta et al. 2010). Studies indicated in Mexico, rain-fed coffee production decreased by 40–80% in the dry period of El Niño (DaMattaa et al. 2003). Coffee growing cycles are damaged by long drought stress but much more noticeable in the fruit bean-filling phase (DaMatta et al. 2018). Hotter dry seasons result in the ripening of immature coffee berries (Frank 2017), and high temperatures accelerate the development and ripening of coffee fruits, affecting the physical and beverage quality of coffee seeds (Pohlan & Janssen 2010).

Temperature is the significant noteworthy climate variable responsible for increasing and decreasing coffee yield (Craparo, 2012). Experimental studies have shown that the temperature above 25^{0}C significantly reduces coffee plants' net photosynthesis, and above 34 ^{0}C the net photosynthesis is approaching zero (Cannell 1976; Nunes et al. 1968). Studies also indicate that air temperatures exceeding 30^{0}C reduced photosynthesis (DaMatta & Ramalho 2006), stunted growth (Avelino et al. 2015) and resulted in deficient floral development, abortion of a large number of flowers and growth of tumours at the base of the stem (Bunn et al. 2015a; Camargo 1985; DaMatta & Ramalho 2006). High maximum temperature increases the chance of abortion of flowers and severely affects coffee yields (CIAT 2010; ICC 2009), particularly in the lower altitudes (Fournier & di Stéfano, 2004). For instance, with a 1^0C rise in the mean temperature, there is an average loss of green coffee yield by 116 kg ha^{-1} in East Africa (Craparo 2012). On the other hand, the temperature below 16^0C depressed coffee growth and development (Camargo 1985) and affected the flowering of coffee trees, hampered the drying of harvested beans and reduced the quality and quantity of coffee yield (Haggar et al. 2011). Moreover, heavy wind and storms can blow off coffee plants, flowers or fruits, and freezing temperatures can harshly damage the harvest and sometimes kill the plants, particularly at the young stages (Haggar & Schepp 2012).

3.1.3.1.4 The effect on coffee pest and diseases

Climate change influences the occurrence, distribution and severity of plant pests and diseases worldwide (Seidel 2014), and small farmers face the challenges of pests and diseases (Atallah et al. 2018). Temperature influences the reproduction, development and survival of the insect population (Ward & Masters 2007), and extremely high and low temperatures enhance the occurrence of pests and diseases by providing a warm and humid environment and necessary moisture for their growth. Elevation gradient is one of the analogues for global warming (Péré et al. 2013) and a geographical shift for the occurrence of pests and diseases to the higher altitudes (Jaramillo et al. 2009). Variation in temperature and precipitation differ the incidence and severity of insect pests and diseases along the altitudinal gradient (Kucel et al. 2016). Rising temperature expands the altitudinal range of coffee diseases (Bongase 2017) and creates conducive environmental conditions for the occurrence of pests (Panhuysen & Pierrot 2014). It will worsen pest prevalence like coffee berry borer (*Hypothenemus hampei*) in East Africa and parts of South America. According to Jaramillo et al. (2009) prediction, a 1^0C increase in temperature would lead to considerably faster development, a higher number of generations per coffee fruiting season and a shift in the geographical range for coffee berry borer.

Coffee berry borer and coffee white stemborer (*Xylotrechus quadripes*) have already benefited from increased African temperatures (Jaramillo et al. 2011; Kutywayo et al. 2013). In many coffee producing countries, the impact of coffee berry borer has been limited at altitude ranges from 1500 to 1600 masl (Jaramillo et al. 2009: Kyamanywa et al. 2012), but now observed at altitudes more than 1800 masl (Jaramillo et al. 2009; Kyamanywa et al. 2012). Avelino et al. (2006) reported that the warming temperature increased at higher altitudes. The resulting shifts in moisture accumulation will likely allow the coffee leaf rust (*Hemileia* *vastatrix*) to thrive in previously uninhabitable areas. Similarly, studies reported that the rising temperature and erratic rainfall create a conducive environment for the prevalence of coffee leaf rust at higher altitudes (Bebber et al. 2016). Kutywayo et al. (2013) stated that coffee white stem borers were more prevalent at low altitudes but significantly increased to a higher altitude in Zimbabwe. This confirms that the future climate change scenarios (Jassogne et al. 2013) are expected to extend the niche of coffee insect pests and diseases to higher altitudes with the increase in temperature (Kutywayo et al. 2013; Ovalle-Rivera et al. 2015) (Table 3-4).

Table 3- 4. The effects of climate variability on coffee pest and diseases

The effects of climate variability on coffee pest and diseases	Countries/regions	References
Climate variability resulted in the outbreak of coffee leaf rust in South America reduced coffee production by 10–70% between 1983 and 2013	South America	Avelino et al. (2015); Jha et al. (2014)
High temperature and erratic rainfall increased the occurrence of coffee leaf miner and coffee leaf rust	Brazil	Ghini et al. (2012)
The rising temperature increased the incidence of coffee berry borer	East Africa	Jaramillo et al. (2011)
A small increased in temperature enhanced the occurrence of coffee berry borer and seriously affected coffee production	Brazil, Mexico, Uganda	Assad et al. (2004); Gay et al. (2006)
Coffee production damaged by coffee leaf rust due to unusually high temperature and high-altitude rains in Central America in 2012	Central America	TCI (2016)
Warmer temperatures due to climate changes created more favourable conditions for coffee leaf rust in many coffee-growing regions	Coffee growing regions	Avelino (2013)
Increased rainfall in Colombia and elevated temperature in Ethiopia threatened the coffee at an alarming rate and created more conducive for pests and disease prevalence	Colombia and Ethiopia	Iscaro (2014)
Raised temperature and erratic rainfall increased the widespread occurrence of coffee berry borer	Ethiopia	Mendesil et al. (2003)
In 2050, the rising temperature will increase the infestation of coffee berry borer from a current 57% to 78% in Arabica coffee growing regions	Global studies	Magrach Ghazoul (2015)

The projected increases of pests and diseases reduce the coffee yield, quality and increase the production costs (Jaramillo et al. 2011), particularly for small farmers in Africa, Asia and Latin America (Baker et al. 2001). In Central America, the outbreak of coffee leaf rust in 2012 and 2013 affected 51.2% of the cultivated coffee area, caused the loss of greater than 264,000 jobs and resulted in economic losses of 479.2 million US$ (International Coffee Organization, 2013). A study indicated in Ethiopia, from 2002 to 2009, coffee berry borers reduced coffee yield by nearly 35% (FAO, 2009). In many coffee producing regions, drought, warm climatic conditions and irregular rainfall enhance the outbreak of pests and diseases and reduce coffee production.

3.1.3.2 Small farmers adaptation strategies

The concept of adaptation has got an enormous emphasis in recent years in climate change literature. The growing interest in adaptation is related to the political failure of climate change mitigation efforts, and focusing on mitigation alone will not address the expected impact of climate change (IPCC 2007b). Adaptation has emerged as a viable option for developing climate change policies and adaptation strategies (Schipper 2009). Small farmers should implement adaptation to climate change on the farm or landscape level (Lipper et al. 2014) to decrease the impact of climate change, reduce the high dependency on coffee yield and adapt to the high volatility of the coffee market (Rahn et al. 2014). Adaptation of small farmers to climate change varies from place to place, but the common adaptation strategies are CAFS (tree-based) production systems, diversifying land-use systems, pest and diseases management and soil and water conservation which are briefly discussed below.

3.1.3.2.1 Shade coffee production

CAFS or tree-based coffee production is a common practice by small farmers and one of the management techniques for adapting coffee to increasing temperature, erratic rainfall and drought (Lin 2007). Several studies indicated that shade trees on the farmland protect crops from extremely high temperatures (Lin 2007; Ricci et al. 2013), frosts and hails (Alvarenga et al. 2004), strong winds (Pezzopane et al. 2011) and diversifies income (Chengappa et al. 2017; Jezeer et al. 2017). CAFS reduce the incoming solar radiation (Lopez-Bravo, 2012), buffer and mitigate the coffee plants from microclimate variability (Gomes et al. 2016) and at optimal level enhance resource capture, such as light (Taugourdeau et al. 2014). These improve the resilience and adaptation of coffee farming systems to climate change and variability and reduce the coffee plants physiological stress (Coltri et al. 2019).

The importance of coffee shade management under changing climate has received acceptance from the small farmers. Appropriate shading buffers the adverse effects of rising temperatures (Hirons et al. 2018), improve the growing conditions of coffee (Perfecto et al. 2007) and increase coffee yield and quality (Lunz et al. 2005). Studies in Costa Rica by Siles et al. (2010a) indicate that compare to FSCS, under *Inga* spp. trees maximum temperature of coffee leaves reduced by 5^0C and minimum air temperature at night increased by up to 0.5^0C. Shade trees can also reduce the temperature in the coffee canopy by 2–3^0C (Vaast et al. 2006) and can even reduce high-temperature extremes by up to 5^0C (De souza et al. 2012). Shade trees in coffee farms lowering maximum air temperature compared with FSCS (Moreira et al.

2018) and decrease soil evaporation (Lin 2010). These findings agree with a study conducted in Ethiopia by Bote & Struik (2011) reported that CAFS reduce air and soil temperature, light intensity, transpiration rate and leaf temperature (Table 3-5).

Table 3- 5. Mean environmental variables between CAFS and FSCS (Bote & Struik 2011)

Environmental Variables	CAFS	FSCS
Air temperature (^{0}C)	25.5	26.7
Soil temperature (^{0}C)	19.7	20.8
Relative humidity (%)	59.7	55.1
Light intensity (lux)	557	1,193
Stomata conductance (mmol $m^{-2}s^{-1}$)	100	60
Transpiration rate (mmol $m^{-2}s^{-1}$)	1,090	1,140
Leaf temperature (^{0}C)	24.2	28.1
Leaf N content (mg g^{-1} leaf dry matter)	288	219

Shade trees in the coffee farm modify the local microclimate by reducing day air temperature (Moat et al. 2017), the light intensity by up to 60–80% (Muschler 1998), intercept 15–25 % of the rainfall (Vaast et al. 2014). Shade trees also increase relative air humidity (Moat et al. 2017) and plant organ wetness. Effective and well-managed shade can improve the productivity of coffee by reducing soil temperatures (Moat et al. 2017). In the FSCS, at the 2 cm depth, soil temperature was reported above 35^{0}C, while at 50% shade level, the soil temperature was below 21^{0}C (Muschler 1998; Staver et al. 2001). The transpiration rate from per unit leaf area of coffee grown under shade is lower than coffee grown in FSCS (Bote & Struik 2011; Perfecto et al. 2007). Arabica Coffee is shade demanded (DaMatta et al. 2004), and their leaves can maintain high photosynthetic performance under low light conditions (Franck & Vaast 2009). Nutman (1937), in his experimental study, revealed that under moderate shade level, the Arabica coffee plant photosynthetic rates were three times higher than the leaves of coffee grown in the FSCS. Moreover, shade trees make coffee plants more resilient and less likely affected by pests than coffee grows in FSCS (Table 3-6).

Table 3- 6. The potential of shade trees in the coffee farm to manage microclimate fluctuations and provide ecosystem services that enhance system resilience to climate variability

Effect of shade trees on microclimate and ecosystem services	Studied country/region	References
Shade tree (60–70) trees ha^{-1}) decreased air temperature by 2–3⁰C	Brazil	Camargo (2010)
Inga shade (205 trees ha^{-1}) decreased the daily maximum temperature by 4–5⁰C and reduced daily temperature fluctuations from 18⁰C in FSCS to 11⁰C in CAFS	Mexico	Barradas & Fanjul (1986)
Shade trees (25–50%) decreased coffee leaf temperature by 1–7⁰C compared with FSCS	Colombia	Siles et al. (2010a)
At warm environmental conditions and low elevation, shade levels from 40 to 60% can maintain air and coffee leaf temperatures below or close to 25⁰C	Costa Rica	Muschler (1998)
Low to moderate shade levels (10–60%) created a good balance between the environment and the coffee yield	South America	Cerda et al. (2017); Atallah et al. (2018)
30–45 % shade cover had a positive effect on coffee yields	Mexico	Soto-Pinto et al. (2000)
Shade trees on coffee farms reduced evapotranspiration by 25–35% compared with FSCS	Mexico	Barradas & Fanjul (1986)
The amount of nitrogen losses in CAFS is three times lower than FSCS	Costa Rica	Tully et al. (2012)
Carbon stock potential of CAFS is higher by 2.6 t C/ha than FSCS	Uganda	Tumwebaze et al. (2016)
The occurrence of erosion is less in coffee agroforestry where the underground is covered by 65% of leaf litter	Nicaragua	Blanco-Sepulveda (2015)

On the other hand, shade trees may compete with coffee plants for light (Charbonnier et al. 2013), water (Rahn et al. 2018), soil nutrients (Siles et al. 2010b), decreased coffee yield (Cerda et al. 2017), require intense labour for system management (Cerda et al. 2017) and change the attack pattern of insect pests and pathogens (Pumarino 2015). Excessive shading reduces the whole tree carbon assimilation and the formation of a flower bud (DaMatta et al. 2007) and decreases yield due to the death of productive middle and bottom primary branches (Kufa & Burkhardt 2013). Soto-Pinto et al. (2000) found that shade density above 50% has a negative effect on coffee yield. Furthermore, the presence of excess shade trees in coffee plantations reduces air movement and increases humidity, favouring the incidence of fungal diseases (Smith, 1981). Lópezbravo et al. (2012) also reported that increasing shade cover in coffee systems might favour diseases like coffee leaf rust. In general, the effect of shade on coffee production requires further research in identifying an optimal shade level to enhance the productivity of coffee, minimizing the negative connotation with CAFS and pursuing climate-resilient coffee production systems.

3.1.3.2.2 Diversification of production and income

Cultivating coffee as a single crop has made small farmers more vulnerable to periodic yield failure in the changing environment (Lin et al. 2008) and reduces their income. Hence, diversifying crop products and income sources enable small farmers to adapt to climate change (Paavola 2008). Diversification is identified as a coping strategy to withstand expected rainfall variability and seasonal fluctuations (Cooper et al. 2008) and make small farmers more resilient to volatile coffee markets and climate-related shocks (Makate et al. 2016). Diversification is a deliberate strategy to ensure subsistence, yield stabilization, risk reduction, use of family labour and increase resource productivity over time (Lin 2011). Integrating shade trees in coffee farm help to diversify income by providing tree products such as food and construction materials (Cerdan et al. 2012) and reduce the economic dependence on coffee production only (Rice 2008). Trees in CAFS can provide economic advantages by generating extra products (Donald 2004) and exploring alternative markets from selling timber (De Sousa et al. 2016). For instance, small farmers income derived from shade trees timber accounted for 28% in Peru (Rice, 2008) and 15–34 % in Costa Rica (Vaast et al. 2015). From managing shade trees, the small farmers also gain financial possibilities from the REDD (Reducing Emissions from Deforestation and Forest Degradation) programe (Rahn et al. 2014).

In Mexico, small farmers introduced and diversified fruit trees in the coffee farms as a coping strategy to climate variability (Ruiz Meza 2015). The farmers planted banana (*Musca* spp.) and high commercial fruit trees such as lemon (*Citrus limon*), orange (*Citrus sinensis*) and avocado (*Persea americana*) to compensate for the income lost from producing coffee (Ruiz Meza 2015) and diversified the sources of product and income (Jha et al. 2014). In India, traditional coffee growers supplement their income and adapt to climate variability by diversifying their coffee farm with different crops such as pepper (*Capsicum annuum*), Coorg mandarin (*Citrus reticulata*), lemon, areca nut (*Areca catechu*), banana, vanilla (*Vanilla planifolia*) and ginger (*Zingiber officinale*) (Chengappa et al. 2017). In Guatemala, CAFS help small farmers to diversify their crop production by intercropping with maize (*Zea mays*), bean (*Phaseolus vulgaris*), groundnut (*Arachis hypogaea*), banana and integration of beekeeping activities (Jassogn et al. 2013). Similarly, in Ethiopia, small farmers integrate annual crops, beekeeping activities and fruit trees into coffee production systems to generate income and mitigate the effect of coffee market fluctuation (Asfaw, 2003). Planting alternative crops in the coffee farm is a relatively common response by coffee farmers to low coffee prices and climate extremes (Eakin et al. 2006).

3.1.3.2.3 Pest and diseases management

Shade trees serve as a biological balance of agro-ecosystems, thereby contributing to the regulation of pests and diseases (Verchot et al. 2007) that occurred due to climate change. Climate change influences the management of coffee pests and diseases. The migration of coffee to suitable areas due to climate change induces and expands pests and diseases geographical ranges to migrate following the host coffee plants (Jaramillo et al. 2009). Studies indicated that the migration of coffee pests and diseases is hampered by shade tree management (Karp et al. 2013), good farm practices and soil fertility improvement (MacLean et al. 2003), integrated pest management (Liebig et al. 2016), farm monitoring and coffee pruning. Small farmers mostly manage shade trees, particularly tree pruning in coffee farms to control pests and diseases and with little or no pesticides and herbicides application to reduce management costs. Appropriate tree pruning can prevent pests and diseases in a coffee farm by thinning the dense crown, spreading and harbourage of pathogens within the same or adjacent trees. Tree pruning increases air circulation in the coffee farm and reduces the incidence of fungal diseases. Pruning shade trees in coffee agroforestry systems improves soil fertility through the subsequent decomposition of the pruned materials (van den Meersche et al. 2019) and thus help small farmers manage the occurrence of pest and diseases by increasing the vigorous of tree species.

Shade trees slow the larval development of coffee berry borer (Jaramillo et al. 2009). Karp et al. (2013) reported the availability of shade trees in coffee farms attracts bird and parasitoid wasps to reduce the occurrence of coffee berry borer. In Central America's coffee-producing regions, shade trees serve as a habitat for birds that are predators of coffee berry borer, which is the primary insect pest in coffee, causing loss of over 500 million US$ annually (Infante 2018). In their study in Indonesia, Kelin et al. (2002) found a high predator-prey ratio in more diverse traditional agroforestry systems compared to the intensified FSCS. On the other hand, shade trees in coffee agroforestry systems increase the abundance of coffee pests (Avelino et al. 2006; Jonsson et al. 2015). Therefore, the selection of appropriate shade trees species and optimal shade level should be put in place for a win-win situation.

3.1.3.2.4 Soil and water conservation

Conserving soil and water is essential in promoting coffee trees' growth, yield and productivity and influencing coffee beans' physical and chemical properties (Behailu et al. 2008). Increasing the resilience of coffee farming systems requires the implementation of different soil and water conservation practices. These include terrace construction, mulching, intercropping and shade management. In coffee growing regions, soil conservation activities are vital in steep highlands to reduce soil erosion and run-off. Application of mulch in the coffee farm is a common practice by small farmers during high temperature and drought periods. Mulch reduces soil evaporation (Jimenez et al. 2017), increases soil organic matter and improves the soil structure, porosity and soil biota on the topsoil (Zhao et al. 2017) and suppresses weed growth. A study in Rwanda by Roose & Ndayizigiye (1997) indicated that soil erosion reduced to less than one ton $ha^{-1}yr^{-1}$ after applying 20 tons $ha^{-1}yr^{-1}$ mulch in coffee plantations. Youkhana & Idol (2009) also reported that the application of mulch in coffee agro-ecosystems increases soil C and N contents.

The management of N-fixing trees in the coffee farm increases N availability and litter decomposition, thereby increasing the organic content of the soil, stabilizing soil against erosion and reducing the disturbance of soil (Mulumba & Lal 2008). It also reduces run-off and soil loss by protecting the watershed (Meza, 2015), improves soil moisture (Guimarães et al. 2014), increases nutrient cycling (Campanha et al. 2007) and favours the microbial activity and their diversity (Zake et al. 2015). Ataroff & Monasterio (1997) reported that low erosion occurrence in CAFS (0.73 tons $ha^{-1}yr^{-1}$) compared with FSCS plantations (1.57 tons $ha^{-1}yr^{-1}$). Also, litter falls from the trees used as mulch increase fertility of the soil (Jassogne et al. 2013), improve the nutrient cycle and reduce the utilization of N-fertilizer inputs (Rosenstock et al. 2014). The coffee shade system has relatively better total N, total C, K, Cation exchange capacity and soil organic matter than FSCS (Table 3-7) (Siles et al. 2010a). The availability of essential nutrients in the soil improves coffee yield and reduces the impact of changing climate.

Table 3- 7. Soil characteristics under the shade tree (*Inga densiflora*) and FSCS in San Pedro de Barva, Costa Rica Mean ± standard error (Siles et al. 2010a)

Soil properties (0–10cm depth)	Coffee production systems	
	Shaded	FSCS
Ph	4.67 ± 0.06	4.92 ± 0.24
Total C (%)	3.70 ± 0.16	3.60 ± 0.14
Total N (%)	0.36 ± 0.01	0.32 ± 0.01
Cation Exchange Capacity (cmol kg^{-1})	44.12	42.47
Ca (cmol kg^{-1})	5.22	6.25
Mg (cmol kg^{-1})	2.48	2.08
K (cmol kg^{-1})	2.34	1.50
Sand (%)	40.6 ± 0.7	36.9 ± 0.9
Silt (%)	37.1 ± 0.4	35.3 ± 1.0
Clay (%)	22.3 ± 0.7	27.9 ± 1.0
Bulk density	0.90 ± 0.05	1.0 ± 0.05

3.1.3.3 Recommended adaptation needs

Over the past decades, many studies on CC adaptation remain purely academic and miss the links between policies, action plans and implementation strategies. Policymakers in coffee-growing regions are aware of the importance of supporting small farmers, but they lack the necessary policies and information on the extent to which farmers are being affected by changing climate and how to support them. Inadequate policies and less commitment to implement adaptation strategies resulted in small farmers' deficient technical assistance and capacity buildings in climate change adaptation. Lack of precise meteorological data hinders understanding the exact impacts of climate variability on coffee production and thus impedes to design of appropriate adaptation strategies. Failure to implement adaptation strategies will endanger millions of hectares of a coffee farm in the coming decades and affect the livelihoods of millions of small farmers. Hence, adaptation is a valuable option for small farmers to lessen the adverse impact of CC.

The adaptations of small farmers to CC are determined by local ecological conditions, infrastructure development, access to extension services, technology and investment (Chhetri et al. 2010). The capacity of small farmers to adapt is dynamic and influenced by education, access to credit services, equity and social capital (Kruse et al. 2013). In the face of increasing climate variability, sustainable and financially feasible adaptation strategies are needed for small farmers who have limited access to infrastructure and technology (Lin 2007) and less information about weather events. Moreover, the perennial nature of coffee plants takes several years to implement the adaptation strategies at the farm level and limits small farmers' adaptation capacities (Laderach et al. 2017) and thus requires careful planning of adaptation strategies (Rahn et al. 2014) by targeting small coffee farmers and coffee agro-ecosystems.

Adaptation responses must be defined at the specific site or regional level because climate change and variability impacts are experienced locally. Prospective adaptation needs and options will be discussed with different stakeholders, particularly small farmers, who will implement best adaptation practices. Besides, more information is needed on how small farmers are vulnerable to climate change and their responses and experiences across different regions, farming systems and socio-economic conditions. Careful observation and assessment of coffee farms at local, national and regional levels will be required to see which interventions and/or combinations of adaptation measures would be most suitable. Accordingly, site-specific short and long-term adaptation strategies will be designed to lighten climate change impact on coffee production. Short-term adaptation strategies to climate change include providing short-term training, improving farming practices and management and better post-harvest handling to reduce the wastage of coffee yield. Long term strategies include selecting appropriate shade tree species and expanding their optimal management, diversifying product and income, enhancing soil fertility and maintenance, introducing and developing drought, pest and disease-resistant coffee varieties. Moreover, improving small farmers' access to information such as weather, market and technology and conserving the genetic resources of Arabica coffee. Managing and conserving the genetic resources of coffee is critical to advancing variety development, particularly concerning maintaining quality in drought-tolerant varieties that perform well under variable environments (Mehrabi & Lashermes 2017).

The implementation of short and long-term adaptation strategies will be realized through developing appropriate policies, strengthening institutions and developing adaptation frameworks at local, national and regional levels. Also, establishing and strengthening small farmers' cooperative institutions to coordinate and implement adaptation projects. Finally, small farmers' adaptive capacity buildings are increasingly embraced by the government and non-governmental organizations and other institutions as a means to improve socio-economic and ecological resilience to the changing environment. Building the existing practices and integrating indigenous knowledge of coffee producers help to maximize their adaptive capacity (Dinesh & Vermeulen 2016) and sustainable harvest of coffee yield (Table 3-8).

Table 3- 8.The recommended adaptation needs and options to address the environmental stresses and related challenges (adapted from Rahn et al. 2014; Schroth et al. 2009).

Activities	Issues to be addressed as a result of environmental factors and related challenges	Important considerations/ assumptions
Multi-strata shade management	-Reduce extreme temperature and intercept rainfall -Alleviate soil moisture deficit - Reduce the risk of drought -Limit the occurrence of pests and diseases - Reduce wind and storms	-Optimal shade level to reduce competition and the occurrence of pests and diseases -Appropriate selection of shade trees (high timber value and fix nitrogen) - Native tree species adapt to the local areas
Developing climate-resilient coffee varieties	-Coffee suitable area loss -Drought resistance and heat tolerant -Less susceptible to pests and diseases	-Focus more on local genetic resources -*In-situ* conservation of coffee genetic resources -Maintaining coffee quality and productivity
Irrigation	-Compensate the shortage of soil moisture and water shortage -Reduce the impact of drought	-Minimizing the effect of salinization -Low cost of construction

		-Low-cost credit and affordable for small farmers -Optimal use of water
Crop and income diversification	-Low-coffee yield and market fluctuation due to climate variability -Sustainable yield harvest -Ensure subsistence life and resource utilization	-Integration of fruit trees, honey production and livestock (zero-grazing) -Boundary planting -Avoid coffee farm replacement by other crops
Soil and water conservation	-Reduce soil erosion and run-off -Improve soil fertility	-Good soil and water conservation practices -Live barriers -Terrace construction -Use organic fertilizer (compost application) -Native tree species of having good leaf litterfall and a high decomposition rate
Pest and disease management	-Reduce the occurrence of coffee pests and diseases because of high temperature and erratic rainfall	-Diversification and optimal shade tree management for pest and diseases suppression -Capacity building on integrated pest management
Certification	-Minimizing international market fluctuation and better price for small farmers	-Cost of certification -Similar standards and guidelines among certificated international organizations -Enhance the knowledge of farmers about certification -Organic coffee production
Establishment of a strong institution	-Addressing the knowledge gaps through capacity buildings -Alleviating the shortage of financial means	-Minimizing corruptions -Acknowledge the traditional ecological knowledge of small farmers

3.1.4 Conclusion

This review paper highlights the fact that the negative impacts of climate change have been affecting the coffee sector. The effects are more conspicuous on small farmers who have less or no information about weather events with limited resources and technologies to address costly adaptation strategies. Climate change manifested as increasing temperature and altering rainfall patterns shifts the coffee suitability areas to higher altitudes, affects coffee plant growth and persuades the migration of coffee pests and diseases following the host coffee plants. Climate change impacts put the small farmers in a highly vulnerable condition if the adaptation measures are not taken. Adaptation in the coffee sector is needed to address the effects of climate change on coffee production and enhance small farmers' adaptive capacity. Adaptation to climate change varies from place to place, but the common adaptation practices implemented at the farm level are CAFS, diversifying incomes and products, pests and diseases management, and soil and water conservation. In several literatures, CAFS is one of the main adaptation strategies implemented in most coffee-producing regions. Shade management builds coffee farm resilience to various climate change-related threats, but further investigation will be needed to know the optimal shade level for coffee production. Finally, climate-resilient coffee production requires developing appropriate adaptation policies and strategies and conducting interdisciplinary research targeting small farmers.

3.2 Smallholder coffee-based farmers' perception and their adaptation strategies of climate change and variability

Adapted from: Jawo TO, Teutscherová N, Negash M, Kefyalew Sahle K, Lojka B. 2023. Smallholder coffee-based farmers' perception and their adaptation strategies of climate change and variability in South-Eastern Ethiopia, International Journal of Sustainable Development & World Ecology, 30 (5), 533–547, DOI: 10.1080/13504509.2023.2167241

This chapter examines farmers' CC perceptions and applied adaptation strategies of smallholder coffee-based farmers along an elevation gradient in Sidama National Regional State, Ethiopia. The study recommends future sustainable management and policy interventions to produce climate-resilient coffee production. This chapter addresses aim (i) Farmers' perception of climate change and their adaptation strategies.

Authors contribution: The study was conceptualized by the first author and Bohdan L . with substantial support from Nikola T. and Mesele N. The first author prepared a questionnaire, conducted field data collection and data analysis, drafted the manuscript, and made necessary revisions.

The original article was published online on January 18, 2023.

Abstract

Recent studies suggest that smallholder farmers' perceptions rather than meteorological data strongly influence how they adapt to the changing climate. Therefore, we explored the climate change (CC) perceptions and adaptation strategies of coffee farmers in dependence on the meteorological data (1983 – 2020) along an elevation gradient (1,600–2,000 masl) in the Sidama region, Ethiopia. In total, 351 coffee farmers were randomly selected for household interviews and complemented with key informants (KIs), focus group discussions (FGDs, and field observations. Severity Index (SI) was computed to measure farmers' perception of CC, followed by a Mann-Kendall test to ascertain climate trends. Weighted Average Index (WAI) was also used to rank adaptation strategies. We detected an increasing temperature and annual rainfall trend. Nevertheless, while farmers agreed on rising temperatures, they perceived rainfall reduction, contradicting the meteorological data. The highest SI was recorded for the rising temperature, followed by the uncertainty of rainfall distribution, increasing number of hot days, late-onset, and reduced amount of rainfall. The SI results with KIs and FGDs confirmed that weather events seemed more variable than in the past two to three decades and affected coffee production. As the most important CC adaptation strategies, the respondents' practice agroforestry, application of compost, terrace construction, modification of farming calendar, and crop diversification. Our results also revealed that gender, education, farming experience, family size, access to agricultural and farmer-to-farmer extensions, and credit services affected adopting adaptation strategies. This study confirms that farmers' perception is more important in shaping the applied adaptation strategies.

keywords: Adaptation strategies**,** agroforestry, elevation gradient, farmers’ perception, severity index, Sidama

3.2.1 Introduction

East African countries including Ethiopia, Kenya, Uganda, and Rwanda, are among the leading producer-exporters of high-quality highland Arabica coffee (*Coffee arabica* L.) (Nzeyimana et al. 2013; Wang et al. 2015), which is a strategic commodity for these countries with significant contributions to foreign currency earnings. East African countries account for over 80% of Africa's total coffee production (UNCTAD 2018) and share 26% of the world's coffee market (Hoebink & Ruben 2015). The livelihoods of an estimated 30 million people in smallholder households in East Africa depend directly on coffee production (Hoebink & Ruben 2015). Coffee smallholders usually produce a wide variety of annual and perennial food crops and fruit species for household consumption or income in diverse farming systems called coffee-based farming systems. However, many studies predict a future drastic reduction of areas suitable for coffee growing (Zullo et al. 2011; Schroth et al. 2015; Grüter et al. 2022; Mulinde et al. 2022), mainly caused by an increase in the mean temperature or prolonged drought period, particularly at low latitudes and altitudes (Bunn et al. 2015; Ovalle-Rivera et al. 2015; Mulinde et al. 2022). Studies indicate that the average temperature will rise between 1.8^0C and 4^0C by the end of the century globally (IPCC 2007) and 2.7^0C to 3.4^0C by 2080 in Ethiopia (Tadege 2007). Such temperature changes will pose an enormous threat to coffee production and smallholder coffee-based farmers' livelihood. Thus, CC adaptation is of the utmost importance for most major coffee producing regions (Grüter et al. 2022), notably in Ethiopia, which is the origin of the worldwide arabica coffee gene pool (Stellmacher and Grote 2011).

Coffee is the main cash crop in Ethiopia, and about 95% is produced by smallholding farmers (Tefera 2020). Ethiopia is Africa's largest coffee producer and the world's fifth largest exporter of arabica coffee (ICO 2015). In 2014, the country produced 398,000 tons of coffee (ICO 2016; Hirons et al. 2018) with an export value of approximately 1 billion US$ (UNCOMTRAD 2014; Hirons et al. 2018) and contributed about 7% to 10% of total world coffee production (Tefera and Tefera 2013). Arabica coffee dominates the total export earnings contributing 25–30% (Worku 2019). Coffee production creates 25% of the employment opportunity and 4–5% of GDP in Ethiopia (Worku, 2019), supporting the livelihood of 15 million people (USAD 2014). Consequently, concerns about the impact of CC on coffee production are growing exponentially as CC will likely reduce coffee yields and quality and increase the occurrence of pests and diseases (Baca et al. 2014; Bunn et al. 2015). Grüter et al. (2022) and Mulinde et al. (2022) study revealed that CC will impact and shift growing regions of arabica coffee more than those of other plantation crops (banana, avocado, and cashew) because of the narrow ecological niche of arabica coffee. It becomes clear that the increasing climate variability and more frequent extreme weather events in the near future require immediate action. Understanding smallholder coffee-based farmers' perception of such changes and their adaptive capacity is a prerequisite for successfully implementing sustainable agricultural strategies.

Empirical studies in Africa (e.g. Bryan et al. 2009; Deressa et al. 2011; Shiferaw et al. 2014; Asare-Nuamah and Botchway 2019; Mulinde et al. 2019) confirmed that smallholding farmers have already perceived the impacts of changing climate and employed adaptation strategies to cope with harsher and more unpredictable weather events. Shade trees in the coffee-based agroforestry systems (AFS) ameliorate microclimatic fluctuations and protect coffee plants from extreme weather conditions (Lin 2007). Thus, agroforestry has been recognized as a promising way to sustain coffee production under CC scenarios (Lin 2007; IPCC 2014).

While some site-specific studies attempted to analyse how Ethiopian smallholder farmers integrating annual crop and livestock adapt to CC (e.g. Deressa et al. 2009; Tesfahunegn et al. 2016; Alemayehu and Bewket, 2017; Belay et al. 2017; Teklewold et al. 2019) and both perception of and adaptation strategies (e.g. Deressa et al. 2011; Ayal & Filho 2017; Berhe et al. 2017) but studies are very limited especially on perceptions of smallholding coffee producing farmers to CC and their adaptation strategies in Ethiopia. As coffee is the main cash crop in the region, the changing climate can significantly affect the income of those smallholder farmers; thus, it is crucial to know current CC perceptions and adaptation strategies. For instance, Eshetu et al. (2021) studied the determinants of smallholder coffee producers' adaptation options to CC in southwest Ethiopia but failed to explain explicitly farmers' perceived impact of CC and variability on coffee production. Moreover, in CC adaptation discourse, the concept of 'one size does not fit all, therefore, the need for conducting micro-level assessments (Asfaw et al. 2018). The study at the micro-level plays an immense role by providing empirical evidence of how smallholder farmers perceive and adapt to CC and variability. It also, helps in designing appropriate adaptation strategies and effective policy interventions to lessen the adverse impact of changing climate and enhance smallholder farmers' adaptative capacities. Therefore, the main objective of this study was to assess the CC perception and its relationship with applied adaptation strategies of smallholder coffee-based farmers along elevation gradients in Sidama National Regional State, Ethiopia, which is one of the main coffee-producing regions. More specifically, our objectives were: (i) to assess coffee farmers' perceptions of climate change and the impacts on coffee production, (ii) its comparison with long-term meteorological data, and (iii) identification of suitable adaptation strategies, their biophysical and socioeconomic determinates and barriers hindering their adoption.

3.2.2 Materials and methods

3.2.2.1 Description of study area

This study was conducted in Dale and Wesnho districts of Sidama National Regional State, Ethiopia (Figure 2-1). The general descriptions of the study areas were indicated in session 2.1.

3.2.2.2 Analytic framework of the study

The present study focuses on how different factors influence smallholder coffee-based farmers' adoption of adaptation strategies in the phase of CC (Figure 4-1). Climate change, which manifests as rising temperature, harsh weather events, uneven rainfall distribution, and increased pests and diseases, affects coffee production and agroecosystems. Hence, adaptation strategies implemented by the farmers reduce the adverse impact of CC on coffee production. Farmer adoptions of climate adaptation strategies are determined by farmers' perceptions of CC and socio-demographic and institutional characteristics. Demographic factors (gender, age, education, farming experience, family size), socioeconomic factors (annual family income, income from coffee production, the area under coffee production), and institutional factors (access to agricultural extensions and farmer-to-farmer extension, access to credit services (Figure 4-1). Finally, the framework illustrates barriers to adaptation (dot line) limit smallholder coffee-based farmers' adaptive capacity to CC and variability and challenge coffee production (Figure 4-1).

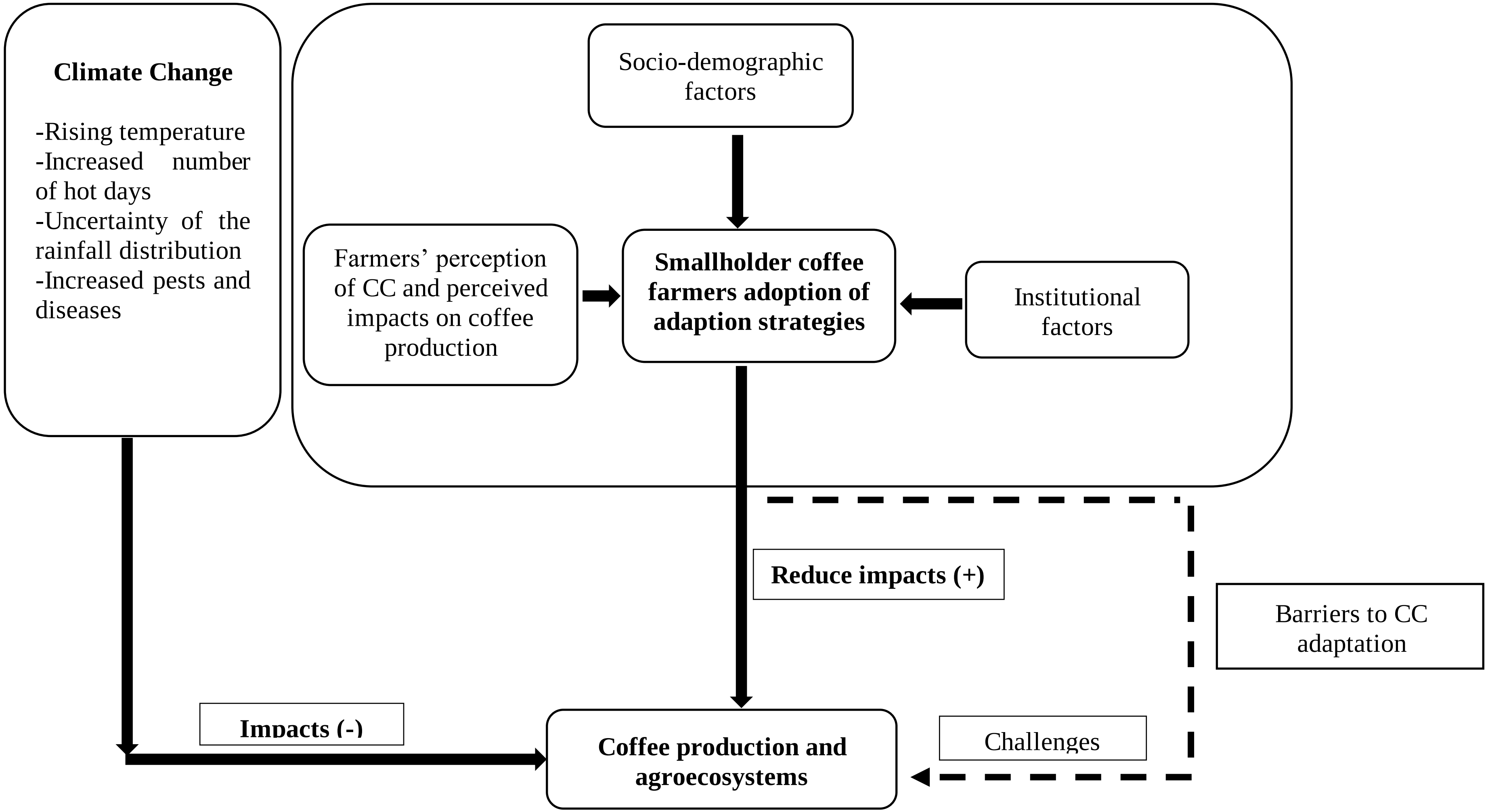

Figure 4- 1. Analytical framework of the study

3.2.2.3 Study design and sample size

This study employed a multistage sampling technique. First, Dale and Wensho districts were selected due to their well-defined elevational gradients covering low (Dale district), mid (Dale district), and high elevations (Wensho district), while having high coffee production in Sidama region (Table 4-1). Consequently, a purposive sampling method was employed to select representative from the lowest administrative units in Ethiopia, which is known as peasant association (PA) from each elevation. Altogether, nine representative PAs were randomly selected, six from Dale district and three from Wensho district, corresponding to two PAs from the low (1,600 to 1,750 masl), four PAs from the mid (1,750 to 1,850 masl), and three PAs from the high elevation (1,850 to 2,000 masl). In each elevation range, we randomly selected a representative number of households engaged in coffee production for farmers' survey. Geographical Information System (GPS) was used to ensure the interviewed households were located in each elevation range.

Table 4- 1. Districts and elevation gradients selected for the study in Sidama National Regional State, South-eastern Ethiopia

District	Elevation zone	Elevation (masl)	n
Dale	Low	1,600 to 1,750	86
	Mid	1,750 to 1,850	138
Wensho	High	1,850 to 2,000	127
Total			351

n: number of respondents

The number of respondents included in the study was determined using the methodology of Yamane (1967) as follows:

$$n = \frac{N}{1+N\,(e)^2} \qquad (1)$$

Where n represents the sample size (number of respondents), N represents the total number of households and e is the level of precision (allowable error, 8%). In total, 351 respondents were selected. The sample sizes from each of the three elevations were determined proportionally based on the total number of households. Further on, 10 KIs, who were knowledgeable farmers (n = 6) and/or coffee experts (n = 4), were also selected for the interview based on the length of their function in PAs, years of coffee farming experience, and basic knowledge of climate variability. Moreover, three FGDs (one organized in each elevation region), each encompassing 10 persons, were conducted. KIs and farmers involved in FGDs were selected by PAs administrative officials, development agents, and district coffee experts.

3.2.2.4 Data collection

3.2.2.4.1 Meteorological data

We used rainfall and temperature data (1983–2020) to evaluate their trends. Rainfall and temperature data from the nearby stations' observations of our study sites were inadequate due to incomplete temporal coverage and characterized by very too many missing data. Hence, owing to the limited availability of long-term field-based meteorological data in the study sites, we used Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) version 2.0 (Funk et al. 2015) and the maximum (Tmax) and minimum (Tmin) temperature from the observational reanalysis hybrid (Chaney et al. 2014). These are the most accurate data products for east Africa. The CHIRPS data is a 30^{+} year quasi-global rainfall dataset incorporating 0.05° resolution satellite imagery with *in-situ* station data. For the temperature, we used time-series temperature data from ERA5 monthly aggregates. Of these, the 2 m air temperature was used in this study. Both the rainfall and temperature data for the study area were extracted in the Google Earth Engine environment (Gorelick et al. 2017).

3.2.2.4.2 Farmers' survey

We used a mixed-method approach, comprising both quantitative and qualitative methods, allowing us to ask a wider range of research questions and collect the essential information (Creswell 2014). Primary data were collected using Participatory Rural Appraisal (PRA) tools, including KIs, FGDs, semi-structured questionnaires (Appendix A Table 1), and field observations. Checklist questions were prepared to ensure each KI had equal opportunities to provide consistent and accurate information. The major discussion topics for KIs were perception of CC, the impact of CC on coffee production and sources of weather information. FGDs were conducted to get in-depth information and insight about trends of CC and variability, the impact of CC on coffee production, major adaptation strategies, and factors hindering CC adaptation. FGDs were also used to complement the responses acquired using the questionnaire.

A detailed household survey was administered between September and December 2020 in the selected households (n = 351). Socio-demographic and biophysical characteristics (Appendix A Table 2), farm-related information, perception of CC, perceived impacts of CC and variability on coffee production, adaptation strategies, determinants of adaptation and adaptation barrier data were collected using a semi-structured questionnaire. Data from the selected respondent households were collected using 5-point Likert scale typology questions, applied similarly to Masud et al. (2017) and Hasan and Kuma (2019). To ensure the validity of the obtained information, field observations were conducted throughout the whole course of the research work.

3.2.2.4.3 Data analysis

3.2.2.4.3.1 Meteorological Data Analysis

Meteorological data was analysed using R-software. Mann–Kendall test was used to determine whether climate trend exists in time series data, using rainfall and temperature as proxies (Chepkoech et al. 2018). Mann–Kendall trend test is a non-parametric test used to identify trends in a series (Alemu and Dioha 2020) and is less affected by outliers (Salmi et al. 2002). It is also commonly employed to detect monotonic trends in a series of environmental or climate data (Alemu and Dioha 2020).

3.2.2.4.3.2 Severity index (SI) calculation

Severity Index was calculated following Al-Hammad and Assaff (1996), Longe et al. (2009) and Masud et al. (2017) to measure farmers' perceptions of climate change as follows:

Where:
a_i = the index of a class and a constant expressing the-weight given to the class
x_i = frequency of responses
i = 0, 1, 2, 3, 4 and described as: x_0, x_1, x_2, x_3, x_4, are the frequencies of response corresponding to $a_0 = 0$, $a_1 = 1$, $a_2 = 2$, $a_3 = 3$, $a_4 = 4$, respectively.
The rating classifications are described as:
a_0 = Strongly Disagree $0.0 < SI < 12.5$
a_1 = Disagree $12.5 < SI < 37.5$
a_2 = Neutral $37.5 < SI < 62.5$
a_3 = Agree $62.5 < SI < 87.5$
a_4 = Strongly Agree $87.5 < SI < 100$
Based on a 5-point Likert scale, the scores administered to the responses of surveyed households are: strongly disagree (0), disagree (1), neutral (2), agree (3), and strongly agree (4). To simplify the interpretation, each rating is given the following connotation: Strongly Disagree (SDA), Disagree (DSA), Neutral (N), Agree (A), and Strongly Agree (SA).

3.2.2.4.3.3 Weighted Average Index (WAI) calculation

Weighted Average Index (WAI) was used to rank farmers adaptation strategies and factors hindering CC adaptation**.** WAI was estimated using Eq. (3) as employed by other studies (Fagariba et al. 2018; Williams et al. 2019).

$$\text{Weighted Average Index}, (WAI) = \frac{\sum FiWi}{\sum Fi} \qquad (3)$$

Where F is the frequency of each assessed adaptation response/barriers variables, W is the weight of each score and i is the score.

3.2.2.4.4 Statistical analysis

One-way ANOVA was applied to evaluate the association and differences between the three elevations over different attributes. The 5-point Likert scale used to measure perception and adaptation strategies was aggregated into a continuous variable for the purpose of inferential analysis (ANOVA) (Asare-Nuamah and Botchway 2019). The perception of farmers' climate variability and its impact on coffee production were evaluated using aggregated mean scores of their response to multidimensional indicators of climate variability (Ayal and Filho 2017) (Table 4–3). A multiple regression analysis was also conducted to identify determinants of smallholding farmers' perception on CC and variability and their adaptation strategies. Finally, the qualitative data collected through KIs, FGDs and personal observation were analyzed through qualitative descriptions, narrations, and thematic analysis.

3.2.3 Results

3.2.3.1 Trends of rainfall and temperature

We observed an increasing trend of historical rainfall data (1983 – 2020) in all three studied elevations (Appendix A Figure 1). Likewise, an increasing trend was also detected in both Tmax and Tmin across the whole study sites (Table 4-2).

Table 4- 2. Mann–Kendall test for temperature and rainfall (1983 – 2020) in the study sites

Elevation zone	Variables	Year	Mann-Kendall test	
			Kendall's Tau	*p-value*
Low elevation	Annual rainfall	1983-2020	0.226	0.05
Mid elevation	Annual rainfall	1983-2020	0.314	0.006
High elevation	Annual rainfall	1983-2020	0.275	0.02
Low elevation	Tmax	1983-2020	0.447	<0.001
Mid elevation	Tmax	1983-2020	0.458	<0.001

High elevation	Tmax	1983-2020	0.376	0.001
Low elevation	Tmin	1983-2020	0.417	<0.001
Mid elevation	Tmin	1983-2020	0.438	<0.001
High elevation	Tmin	1983-2020	0.405	<0.001

The Kendall's Tau is a number between -1 and +1 with positive values indicating an increasing trend and negative values indicating a decreasing trend.

3.2.3.2 Farmers' perception of climate change and variability

In total, 97.7% of the respondent households perceived the impacts of CC in the last 30 years (Table 4-3). Based on the recorded SI and the aggregated mean scores, the five most strongly perceived features of CC indicators were as follows: rising temperature, the uncertainty of the rainfall distribution, an increasing number of hot days, late onset of the rainy season, and reduced amount of rainfall. The SI values of the majority of CC indicators ranged between 73.15% and 84.19% (Table 4-3).

The perception of smallholding farmers differed ($p < 0.05$) among the three elevation zones ($F_{2, 348} = 56.68$; $p < 0.001$) and decreased with increasing elevation. The SI results with KIs and FGDs confirmed that weather events seemed to be more variable and less predictable compared to the past two to three decades, particularly in low elevations. For instance, the SI value for rising temperature is higher for low elevation (SI = 93.02%), followed by mid (SI = 88.04%) and high (SI = 74.02%) elevations (Table 4-3). Of the surveyed households (n = 351), 50.7% agreed, and 44.5% strongly agreed with rising temperature. Also, the result showed that 54.7% agreed and 36.5% strongly agreed with the uncertainty of the rainfall distribution. Further FGDs on CC and variability revealed that farmers were concerned with the frequency and severity of extreme weather and significant changes that they perceived in weather patterns. Moreover, farmers emphasized the difficulties in recognizing the start of rainy seasons, which is critical for planting new coffee plants and other crops.

Table 4- 3. Responses of surveyed households on climate change and variability indicators along an elevation gradient in South-eastern Ethiopia (n=351)

Variables		Likert scale					Elevation zone (aggregated SI%)				Elevation zone (Mean on Likert scale)				F	*p*-value
		SDA (0)	DSA (1)	N (2)	A (3)	SA (4)	High (n=127)	Mid (n=138)	Low (n=86)	Total (n=351)	High (n=127)	Mid (n=138)	Low (n=86)	Total (n=351)		
Rising temperature	NRS	2	8	6	178	157	74.02	88.04	93.02	84.19	2.96	3.52	3.72	3.37	46.72	<0.001
	PRS	0.6	2.3	1.7	50.7	44.5										
Number of hot days increased	NRS	1	10	7	247	86	72.64	78.44	89.24	78.99	2.91	3.14	3.57	3.16	35.85	<0.001
	PRS	0.3	2.8	2.0	70.4	24.5										
Number of warm nights increased	NRS	30	63	27	206	25	54.92	60.33	64.83	59.47	2.20	2.41	2.59	2.38	3.36	0.036
	PRS	8.5	17.9	7.7	58.7	7.1										
Increased the coldness of cold seasons	NRS	102	186	60	3	0	17.52	21.38	31.40	22.44	0.70	0.86	1.26	0.90	18.30	<0.001
	PRS	29.1	53.0	17.1	0.9	0.0										
Increased rainfall	NRS	170	133	23	25	0	30.91	5.80	18.90	18.09	1.24	0.23	0.76	0.72	58.33	<0.001
	PRS	48.4	37.9	6.6	7.1	0.0										
Decreased rainfall	NRS	19	25	8	193	106	55.51	83.33	87.79	74.36	2.22	3.33	3.51	2.97	73.98	<0.001
	PRS	5.4	7.1	2.3	55.0	30.2										
Uncertainty of the rainfall distribution	NRS	5	20	5	192	129	71.46	84.42	85.17	79.91	2.86	3.38	3.41	3.20	17.84	<0.001
	PRS	1.4	5.7	1.4	54.7	36.8										
Cesation of rinafall becomes unpredictable	NRS	9	37	14	202	89	64.96	79.71	74.71	73.15	2.60	3.19	2.99	2.93	13.32	<0.001
	PRS	2.6	10.5	4.0	57.5	25.4										
Late onset of rainy season	NRS	11	46	8	156	130	54.92	87.50	83.72	74.79	2.20	3.50	3.35	2.99	75.05	<0.001
	PRS	3.1	13.1	2.3	44.4	37.0										
Total grand mean											2.21	2.62	2.80	2.51		
F statistics															56.68	<0.001

Notes: NRS, PRS, SDA, DSA, N, A, SA, and SI indicate the Number of Respondents, Percentage of Respondents, Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree, and Severity Index, respectively.

3.2.3.3 Perceived impacts of climate change and variability on coffee production

The perceived changing climate was reflected in the observed impacts on coffee production. Based on the mean scores and SI results, the five most reported impacts of CC on coffee production in the order of importance were loss of coffee berries (falling of coffee fruit), late-ripening, higher incidence of coffee pests and diseases, decreased coffee yield and death of coffee plants (planted young seedlings and saplings) (Table 4-4). The perceived impacts of CC on coffee production differed among farmers in different elevations ($F_{2, 348} = 346.76$; $p < 0.001$) and CC was perceived to have a more substantial impact on coffee production in low elevation, followed by mid, and, however nearly no impact in high elevation (Table 4–4). The aggregated SI values of climate indicators were higher for lower elevations, followed by mid and high elevations. Of the respondent households (n = 351), the farmers agreed with decreased coffee yield (27.6%), late ripening (44.2%), loss of berries (43.3%), and increased coffee pests and diseases (52.7%) (Table 4-4). The results of FGDs and KIs interviews corroborated findings obtained from the questionnaires. Farmers who participated in FGDs highlighted that the coffee producers in the three elevations already experienced the impacts of CC. The KIs confirmed that rising temperatures and erratic rainfall distribution affect coffee yield. Informants also stated that coffee production depends on optimal rainfall distribution. While the rising temperatures and rainfall uncertainty have already started to reduce coffee yields in the low elevation, the KIs from high elevation stated that the areas under coffee production were increasing but also shifting to higher elevation regions, where farmers did not grow coffee 30 years ago.

Table 4- 4. Responses of surveyed households on the perceived impact of climate change and variability on coffee production along an elevation gradient in South-eastern Ethiopia (n=351)

Items		Likert Scale					Elevation zone (aggregated SI%)				Elevation zone (Mean score on Likert Scale)					
		SDA (0)	DSA (1)	N (2)	A (3)	SA (4)	High (n=127)	Mid (n=138)	Low (n=86)	Total (n=351)	High (n=127)	Mid (n=138)	Low (n=86)	Total (n=351)	F	*p*-value
Decreased yield	NRS	35	130	21	97	68	27.76	62.86	71.80	52.35	1.11	2.51	2.87	2.09	79.43	<0.001
	PRS	10.0	37.0	6.0	27.6	19.4										
Late ripening	NRS	22	91	6	155	77	31.89	79.53	79.94	62.39	1.28	3.18	3.20	2.50	198.6 9	<0.001
	PRS	6.3	25.9	1.7	44.2	21.9										
Loss of berries	NRS	18	78	0	152	103	35.63	84.42	86.92	67.38	1.43	3.38	3.48	2.70	250.9 6	<0.001
	PRS	5.1	22.2	0.0	43.3	29.3										
Death of coffee tree	NRS	58	139	51	95	8	21.06	46.01	57.27	39.74	0.84	1.84	2.29	1.59	66.87	<0.001
	PRS	16.5	39.6	14.5	27.1	2.3										
Increased coffee pest and diseases	NRS	15	92	14	185	45	38.98	72.64	74.42	60.90	1.56	2.91	2.98	2.44	89.79	<0.001
	PRS	4.3	26.2	4.0	52.7	12.8										
Decreased coffee bush density	NRS	97	142	14	77	21	12.20	40.58	57.85	34.54	0.49	1.62	2.31	1.38	85.99	<0.001
	PRS	27.6	40.5	4.0	21.9	6.0										

Notes: NRS, PRS, SDA, DSA, N, A, SA, and SI indicate the Number of Respondents, Percentage of Respondents, Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree, and Severity Index, respectively.

3.2.3.4 Farmers' adaptation strategies

The adoption of agroforestry/tree planting (WAI = 3.30), application of organic manure/compost (WAI = 3.12), soil conservation (terrace construction) (WAI = 2.82), modification of farming calendar (WAI = 2.46), and crop diversification (WAI = 2.38) were the five most important adaptation practices implemented by the farmers to overcome the impacts of CC across the three studied elevations (Table 4-5). The households moderately practiced other adaptation practices such as changing crop varieties, growing drought-resistant crops, fodder tree planting, mulching, and water harvesting. Migration, application of inorganic fertilizer and insecticides, and irrigation were positioned as the least common adaptation practices employed by the farmers in the study region (Table 4-5). No difference was detected in the adaptation strategies applied by farmers in different elevations ($F_{2.84}$; $p = 0.07$) (Table 4–5). In the low and mid-elevations, organic manure/ compost application ranked in the second position (after AFS) while for high elevation area in the third place. In the low elevation, mulching and replacing coffee with growing drought-resistant crops such as Khat (*Catha edulis* Forsk) and eucalyptus species (*Eucalyptus* spp.) (Figure 4-2) were the main adaptation practices. Terrace construction is the most important adaptation practice reported for mid and high-elevations.

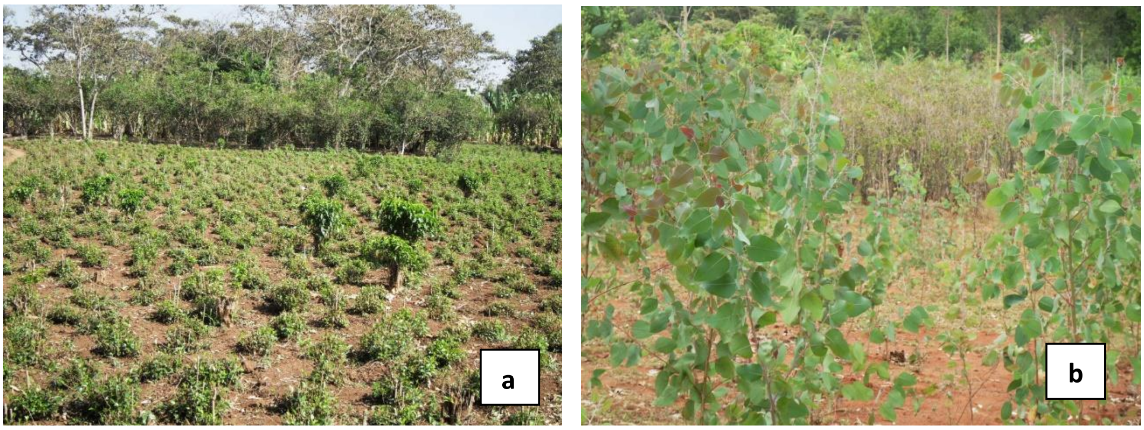

Figure 4- 2. The replacement of coffee with Khat (*Catha edulis* Forsk) (a) and *Eucalyptus* spp. (b) in low elevation areas.

Table 4- 5. Adaptation strategies to climate change adopted by surveyed households along an elevation gradient in South-eastern Ethiopia (n=351)

Adaptation strategies	Total (n = 351)		Elevation zone (WAI)					
			High (n = 127)		Mid (n = 138)		Low (n = 86)	
	WAI	Rank	WAI	Rank	WAI	Rank	WAI	Rank
Agroforestry/tree planting	3.30	1st	3.00	1st	3.46	1st	3.48	1st
Application of organic manure/compost	3.12	2nd	2.71	3rd	3.32	2nd	3.41	2nd
Soil conservation (terrace construction)	2.82	3rd	2.91	2nd	2.73	4th	2.85	7th
Modification of farming calendar	2.46	4th	1.76	7th	2.78	3rd	2.88	6th
Crop diversification	2.38	5th	1.89	5th	2.49	6th	2.93	5th
Change crop varieties	2.36	6th	2.22	4th	2.28	7th	2.71	8th
Growing drought resistant crop varieties	2.23	7th	1.32	9th	2.54	5th	3.08	4th
Fodder tree planting	2.11	8th	1.87	6th	2.01	9th	2.64	9th
Mulching	1.97	9th	1.45	8th	2.06	8th	3.31	3rd
Water harvesting	1.31	10th	1.29	11th	0.96	11th	1.90	10th
Selling of livestock	1.15	11th	0.54	12th	1.44	10th	1.57	12th
Migration	0.85	12th	0.40	15th	0.93	12th	1.41	13th
Application of inorganic fertilizer	0.77	13th	0.53	13th	0.28	15th	1.90	10th
Application insecticides	0.72	14th	0.44	14th	0.43	13th	1.60	11th
Use irrigation	0.69	15th	1.32	9th	0.35	14th	0.30	14th
F test statistics								
N	15							
Sum of Squares	5.196							
F statistics	2.84							
p-value	0.07							

WAI = Weighted Average Index

3.2.3.5 Determinants of perceptions and adaptation to climate change

The studied determinants altogether explained 50% and 67% of the variation of smallholding farmers' perceptions and adaptation strategies to CC, respectively (Table 4-6). The results revealed that elevation, education, farming experience, membership in the coffee cooperatives, radio ownership, access to agricultural extension, and access to weather information significantly and positively impacted perceptions ($p < 0.05$), while gender and family size significantly and negatively affected the perception of CC, respectively ($p < 0.05$).

The results revealed that elevation, gender, education, farming experience, family size, the area under coffee production, access to agricultural extension, access to farmer-to-farmer extension and access to credit services and sources ($p < 0.05$) significantly and positively affected the adoption of adaptation strategies. The average annual income from coffee production ($p = 0.02$) also affected the adoption of adaptation strategies in the study area.

Table 4- 6. Determinants affecting the farmers' perception of climate change and the adoption of adaptation strategies

Variables	Perception of CC		Adaptation strategies	
	Coefficient	*P*-value	Coefficient	*p*-value
Elevation	0.122	<0.001	0.251	<0.001
Gender	-0.154	<0.001	0.193	<0.001
Education	0.032	0.043	0.050	0.001
Farming experience	0.062	0.050	0.086	0.004
Family Size	-0.022	0.042	0.029	0.004
Household head age	0.000	0.994	0.022	0.590
Membership in coffee cooperatives	0.168	<0.001	-0.021	0.538
Radio ownership	0.139	0.001	0.063	0.094
Area under coffee production	-0.149	0.139	0.321	0.001
Average annual income	-1.685E-007	0.920	2.498E-006	0.113
Average annual income of coffee	-2.347E-007	0.293	-4.729E-006	0.024
Access to agricultural extension	0.221	<0.001	0.169	<0.001
Access to farmer-to-farmer extension	0.047	0.163	0.111	<0.001
Access to credit service and sources	-0.026	0.467	0.151	<0.001
Access to weather information	0.097	0.007	0.053	0.115
Constant	2.771	<0.001	1.171	<0.001
Adjusted R^2	0.50		0.67	
F statistics	22.670	<0.001	47.288	<0.001

3.2.3.6 Barriers of climate change adaptations

Based on the WAI, the top five recorded barriers to CC adaptation across the three studied elevations included poor soil fertility (WAI = 2.93), land shortage (WAI = 2.78), lack of weather information (WAI = 2.61), lack of credit (WAI = 2.60), and lack of water (WAI = 2.39) (Table 4-7). Lack of agricultural extension services and tree seedlings were reported as minor challenges in implementing adaptation strategies. There were common challenges, but slightly different levels of rankings were found across the three elevations (Table 4-7). In the low and mid-elevations, higher importance was placed on poor soil fertility, lack of weather information and credit services. In the high elevations, farmers stated mainly land shortage, poor soil fertility, and lack of agricultural labour (in decreasing order) were the significant challenges.

Table 4- 7. The barriers of climate change adaptation strategies adoption by surveyed households

Barriers	Total (n =351)		Elevation zone (WAI)					
			High (n =127)		Mid (n =138)		Low (n = 86)	
	WAI	Rank	WAI	Rank	WAI	Rank	WAI	Rank
Poor soil fertility	2.93	1st	2.43	2nd	3.21	1st	3.21	1st
Shortage of land	2.78	2nd	2.46	1st	3.01	4th	2.87	4th
Lack of weather information	2.61	3rd	1.77	6th	3.12	2nd	3.05	2nd
Lack of credit/money	2.60	4th	1.87	4th	3.08	3rd	2.94	3rd
Lack of water	2.39	5th	1.72	7th	2.50	5th	3.21	1st
Lack of agricultural labour	2.18	6th	2.02	3rd	2.25	6th	2.30	5th
Shortage of farm inputs	1.97	7th	1.86	5th	1.96	7th	2.15	6th
Education level	1.62	8th	1.42	8th	1.57	9th	1.90	7th
Lack of tree seedlings	1.46	9th	1.08	9th	1.59	8th	1.83	8th
Lack of agricultural extension services	1.04	10th	0.91	10th	0.68	10th	1.80	9th
F test statistics								
N	10							
Sum of squares	3.144							
F statistics	3.579							
p-value	0.04							

WAI = Weighted Average Index

3.2.4 Discussion

3.2.4.1 Smallholding farmers perception of climate change

The 37 years of meteorological data confirmed the rising temperatures and also increasing rainfall, which were partially perceived by the coffee farmers, who reported rising temperatures, but rainfall reduction. Our findings are in line with several studies in other parts of the tropics (Isa et al. 2005; Masud et al. 2017). Nearly all farmers agreed that rising temperatures, increased number of hot days, and decreased rainfall were the main manifestations of CC and variability. These are consistent with existing literature that reported rising trends in temperature (e.g. Deressa et al. 2011; Ayal & Filho 2017; Asfaw et al. 2018) and an increase in the number of hot days and warm nights (Ayal & Filho 2017) in Ethiopia. Similarly, our study coincided with other studies that reported a decrease in duration and amount (e.g. Zampaligré et al. 2014; Abid et al. 2015; Chepkoech et al. 2018), unpredictability (Berhe et al. 2017; Mulinde et al. 2019) and uneven distribution (Tesfahunegn et al. 2016) of rainfall in Ethiopia and elsewhere in the tropics. Similar results were also reported from other parts of Ethiopia (Meze-Hausken 2004; Bewket 2012), where the authors attributed the perception of declining rainfall to the increasing variability and unpredictability of extreme weather events. Thus, although the farmers' perception of rainfall trends is not associated with an overall rainfall reduction, it is likely based on the lack of rainfall during crucial periods of coffee berries development (Lin et al. 2008; Speranza 2010). The perception of lower rainfall could also be explained by higher evapotranspiration rates resulting from rising temperatures (Slegers 2008), which also explains why the impacts of changing climate were perceived more by the farmers in the lowlands in comparison to mid- and high-elevation farmers (Table 4–3). A similar assumption was also asserted by Belay et al. (2005), observing a higher frequency of drought periods in the lowlands than in other areas of Ethiopia.

The result from KIs and FGDs indicates that farmers were keenly concerned about rising temperature and erratic rainfall condition and their effects on farming activities and livelihoods. Recalling the start of the rainy season was one of the bottlenecks for the farmers in the study sites. This agrees with Johansson et al. (2019) and Asare-Nuamah and Botchway (2019) studies that rainfall variability was one of the most perceived impacts of CC who depend on subsistence rain-fed agriculture in East and West Africa, respectively. The KIs and farmers during FGDs also asserted that CC impacted coffee's sustainable production and lowered their incomes. Our field observation confirmed that the impacts of CC on coffee production and other agricultural activities were manifested more in the low elevation than in the mid and high elevations owing to high rainfall variability and loss of soil moisture in the former. Similarly, Tavares et al. (2018) noted that excessive heat in warmer areas makes it unsuitable for growing coffee and causes yield reduction.

On the other hand, the KIs in the higher elevation stated an increasing rainfall trend, which might be linked with the steep topographic nature of the areas and more intense rainfall events that often resulted in strong erosion and enhanced farmers' perception of rainfall (Deressa et al. 2011).

3.2.4.2 Climate change adaptation strategies

The adoption of agroforestry is the most common adaptation strategy among coffee-based farmers to cope with the changing climate (Ruiz-Meza 2015; Eshetu et al. 2021) due to the positive effect of shade trees on microclimate, soil fertility, and production of diversification, and likely because of its historical and cultural importance in the tropical areas. Farmers integrate commercial crop and fruit species such as banana or avocado or timber shade trees (e.g. *C africana*), similarly to farmers in Mexico (Ruiz-Meza 2015) or Guatemala (Jassogne et al. 2013). The KIs also confirmed that shade trees reduce the high intensity of direct sunlight, reduce day air temperature, maintain soil fertility, and help farmers to diversify their income. The tree species in the agroforestry system also increase the resilience of coffee farming systems and buffer risks arising from CC and variability. Besides the positive effect of shade trees on coffee production, shade tree leaves and litter (along with other organic materials) are commonly used by farmers in the study area for compost preparation. In soil, compost improves water retention capacity, increases soil fertility and crop resilience to drought (UNFCCC 2021), while enabling farmers to certify and market their coffee as organic, further increasing income. Similar practices have been observed among Ghanaian farmers where compost application is a common CC adaptation strategy in horticulture production (Fagariba et al. 2018).

Moreover, as a reaction to irregular distribution and often more intense rainfall, farmers in high elevations more frequently opt for terrace construction to reduce water runoff and erosion. Nevertheless, despite the enhanced water storage, the erratic nature of the rainfall has already forced the farmers to modify the farming calendar in the study area and elsewhere (Asfaw et al. 2018).

Mulching is another common CC adaptation strategy during high temperature and drought periods. In the study area, farmers use mulch materials such as cut grass, weed, crop residues, and tree leaves. Mulch reduces soil moisture evaporation (Jiménez et al. 2017) and improves the topsoil's soil structure and biological activity (Zhao et al. 2017), while reducing the labour requirements compared to compost preparation. Farmers also shift towards more drought and disease-resistant coffee varieties (Model – 71110 and 71112) with better performance under changing climate or even replace coffee with drought-resistant perennial crops such as khat. Khat is commonly grown in monoculture for its economically important leaves and tender twigs, which are chewed for their stimulating effect. Farmers claim to currently obtain better income from khat than coffee, especially in the lower elevations of the Sidama region (Mellisse et al. 2018), which is alarming given the Sidama region being one of the world's most important arabica coffee cultivation areas.

Moreover, the most important barriers hampering CC adaptation strategies by farmers in the study area are poor soil fertility, shortage of land especially in higher elevations, lack of weather information, lack of credit, and lack of water, which were reported to be the key barriers also elsewhere (Bryan et al. 2009). According to the farmers, poor soil fertility (or more precisely poor soil health) resulting from inadequate agricultural practices is related to the low capacity of soils to cope with changing climate. Healthy soils are capable of withstanding the increasing temperature because of their ability to hold water and regulate soil temperature (Lal 2016). However, inadequate farming practices have resulted in soil degradation linked with deterioration of soil fertility and crop performance. Compost application is often not sufficient to increase soil health due to the labour intensiveness.

Shortage of land is also one of the bottlenecks for smallholder farmers to adapt to CC. The average landholding (0.86 ha) in the study area supports the average family size of around seven people. Feeding the large family size forced the farmers to cultivate a small plot of land from year to year and thus, reduced land productivity. Hence, for such a large family size, land availability is an important agricultural asset to diversify more products and include improved crop varieties to minimise risks related to CC. Similar observations have also been made by Bryan et al. (2009) and Abid et al. (2015), reporting that rural farmers with a large land size could produce more and use improved crop varieties, which enhances their adaptation capacity to CC. Ultimately, farmers pointed out that they rely on their own perception to adapt to CC due to inaccessibility and less trust in weather forecasts. Thus, integrating farmers' knowledge in CC perception and developing trust among farmers about weather information from meteorological agencies could improve the likelihood of implementing different adaptation options. Eshetu et al. (2021) also stated that regular access to weather information is more likely to change cropping time to adapt to the changing climate. Additionally, lack of credit access clearly impedes farmers from getting the necessary technologies (irrigation, water harvesting technologies, and others) and resources to adapt to CC in the study area and elsewhere (Bryan et al. 2009; Asfaw et al. 2018; Williams et al. 2019).

3.2.4.3 Determinants of perception of climate change and variability

Our result indicated that female household heads perceived more the impact of CC than male household heads because they are more concerned about environmental issues that threaten their families and the surrounding communities. This study coincides with Safi et al. (2012) and Ayal & Filho (2017), who stated that female-headed households are perceived more than male-headed households because they are more affected by the changing environment. The result showed that educated farmers perceived the impact of CC more than less-educated farmers because they are more aware of and know the adverse effect of CC and variability on farming activities.

Our results also showed older people perceive the impact of CC more than younger people. This is in line with Maddison (2007) and Ayal & Filho (2017), who reported that older farmers perceived the impact of CC more because older farmers understand their environment in time horizon, and enabling them to perceive CC easily. On the contrary, studies argued that younger people are more insightful of CC and variability in their localities (Semenza et al. 2011). Farmers with more farming experience perceived the impact of CC more than low- experienced farmers. This is in line with Maddison (2007) and Mbwambo et al. (2021), who observed that farmers with more farming experience were more likely to have stronger perceptions of CC than farmers with lower farming experience. Moreover, those farmers who participated in the formal institutions, owning radio and access to agricultural extension, farmer-to-farmer extension, credit services, and weather information perceived more CC and variability than other farmers. This is a similar finding to Deressa et al. (2011) and Ayal and Filho (2017).

3.2.4.4 Determinants of climate change adaptations

The result revealed that biophysical and socio-demographic factors influence CC adaptation practices. More educated farmers adopt more adaptation strategies than less educated ones because they are more likely to accept new ideas and technologies to improve their farming systems. Our results concur with the findings of Abid et al. (2015) and Masud et al. (2017) from Pakistan and Malaysia, respectively. Similarly, farmers with longer farming experience have been observed to be more capable of identifying and reacting to fluctuations in climate and optimizing adaptation decisions (Arunrat et al. 2017). Our results also agree with Deressa et al. (2011), demonstrating that larger families are usually associated with a higher labour force allowing for the implementation of various adaptation practices. Likewise, the expansion of the coffee production area, participation in coffee cooperatives, access to agricultural and farmer-to-farmer extensions, and credit services positively influence the adaptation strategies similarly to other studies in Ethiopia (Asfaw et al. 2018).

3.2.4.5 Future sustainable management and policy interventions

For rainfed coffee-producing smallholder farmers, CC affects their coffee production and forces the farmers to replace coffee with other crops suited to the changing environment. In our study area, smallholder coffee producer farmers have attempted to shift traditional coffee-based agroforestry systems to cash crop khat-based farming systems, strongly relying on the input of inorganic fertilizers and pesticides. Studies in Ethiopia showed that coffee production is now being abandoned and replaced by drought-resistant cash crop khat, mostly grown as monocultures (Gebissa 2008). A study by Jara et al. (2017) also disclosed that coffee fields were abandoned and replaced by khat in the eastern and south-eastern parts of Ethiopia. The farmers in our study region have started reducing shade tree species and coffee bush density to plant khat. This concurs with Dessie & Kinlund (2008) finding that the expansion of khat on the farmlands has contributed to the removal of on-farm trees and the conservation of forestland to khat in Wondo Genet, Southern Ethiopia. The authors further stated that khat production contributed to forest decline.

Our field observation confirmed that the expansion of khat significantly reduces shade trees and coffee bush density. Jara et al. (2017) also revealed that the major shift from coffee to khat eroded much of the woody species' diversity since khat is usually grown FSCS. Also, land conversions reduce the genetic resources of Arabic coffee in the study region. Arabica coffee is grown in specific climatic and biophysical conditions coupled with narrow genetic diversity (Chemura et al. 2021). Hence, there is an urgent need to identify and develop appropriate adaptive interventions in the low-elevation areas of the study region. Policy-driven actions are crucial to facilitating farmers' long-term credit to implement improved water harvesting technologies and promoting irrigation to support farmers coping with CC. Also, the government should invest in and promote agricultural extension services and research in developing, testing, and using more drought-pest, and diseases-resistance coffee varieties and support planting shade tree species better suited to warmer and drier conditions.

On the other hand, our KIs and field observation results indicated that coffee migrates to higher elevation areas challenged the local ecosystem management and the production of food crops, such as barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.). This is in line with the finding of Chemura et al. (2016), who reported that expanding coffee plantations to higher elevation areas might increase pressure on local ecosystems and conflict with food crops. Hence, appropriate government policies are required to ensure that shifts in production locations will not affect local ecosystems and decrease food security for the local population. Moreover, as coffee planting, managing, and harvesting require knowledge and skill, the future policy aims to provide training and adequate agricultural extension services for farmers in higher-elevation areas. Furthermore, empirical research will be needed to identify and assess the synergies and trade-offs with the existing land use in the higher elevation areas.

3.2.5 Conclusion

We focused on farmers' perception of CC and the undertaken adaptation measures along Ethiopia's elevational gradient (1600 - 2000 masl). The farmers perceived the impacts of rising temperatures on coffee and the steps taken to adapt to CC. Most farmers adopt agroforestry practices, organic manure/compost, soil conservation, changing farming calendar, and crop diversification. Farmers also perceived a rainfall reduction, which is not supported by the meteorological data and is likely caused by irregular rainfall distribution. The farmers' perceptions differed among the three elevations, but no significant difference was observed in their adaptation strategies. Farmers in the low-elevation areas perceived the impact of CC more than in mid and high elevations because they experienced a higher frequency of drought periods. The results of KIs, FGDs, and field observations also confirmed that CC affected the coffee production systems of smallholder farmers. Moreover, it forced the farmers to replace coffee with drought-resistant crops, particularly in the low elevation areas. Education, farming experience, family size, and access to the extension are the most significant factors influencing farmers' perception of CC and their adaptation practices. Poor soil fertility, land shortage, lack of weather information, and lack of credit access have been identified as the key challenges to adapting to CC. Hence, policymakers should design and support appropriate adaptation strategies to lessen the adverse effect of CC, such as improved agroforestry practices, farm management, farmers' training, and increasing access to credit, market, and weather forecasting information.

3.3 Perennial species diversity, ecosystem carbon stocks and carbon income in coffee-based agroforestry systems along an elevation gradient in Sidama

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This chapter evaluates the perennial plant species diversity, ecosystem C stocks, and possible C income from CAFS to inform policymakers about promoting CAFS to enhance ecosystem services while improving the livelihood of smallholder coffee producers. Moreover, demonstrating and understanding the C accumulation in shade tree biomass and soil in AFS can be vital for developing climate change mitigation strategies at the national and global levels.

Authors contribution: The study was conceptualized by the first author and BL. with substantial support from MN. and NT. The first author prepared an inventory format, conducted field data collection and data analysis, drafted the manuscript, and made necessary revisions. This chapter addresses aims (ii and iii) the potential role of CAFS for shade species conservation, ecosystem C stocks, and possible C income through C credit schemes. Also addresses the relationship between perennial species diversity and biomass carbon stocks.

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Abstract

In the current context of deforestation, coffee-based agroforestry system (CAFS) is credited for climate change (CC) mitigation and biodiversity conservation while supporting local livelihoods. Despite integrating shade tree species in CAFS, empirical studies to support this assertion are inadequate in Eastern Africa, and hence, its ecosystem services provisions are less understood. We evaluated perennial species diversity, carbon (C) stocks in the biomass and soil organic C (SOC) along an elevation gradient of 72 plots of CAFS, while 36 plots were selected for FSCS within three elevations, namely, low (1600 – 1750 masl), mid (1750 – 1850 masl) and high (1850 – 2000 masl) elevations in Southeastern Ethiopia. The perennial species diversity and biomass, SOC, fine root and litter C stocks were evaluated. Perennial species Shannon diversity significantly differed among the studied elevations ($p < 0.001$). CAFS had significantly higher ecosystem C stocks than FSCS ($p < 0.05$). The highest C stocks were found in the soil in both coffee systems. However, we found a weak relationship between the Shannon diversity and biomass C. The C income in CAFS was 70% higher than FSCS. The present study showed that CAFS accumulates more C and provides additional benefits from C credits. Hence, CAFS deliver ecosystem services that enhance biodiversity conservation and CC mitigation while generating an additional C income for farmers. However, we learned that the impact of perennial plant diversity on C stock and C income is context and site-specific.

Keywords: Agroforestry, carbon income, carbon stocks, ecosystem services, elevation gradient, Ethiopia, shade trees

3.3.1 Introduction

The increasing evidence of CC and, consequently, the need to mitigate C emissions and biodiversity loss has heightened interest in quantifying C stocks in biomass, products, and soil, as well as in biodiversity conservation (Zaro et al. 2020) within terrestrial ecosystems. Tropical forest resources are a large reservoir of biodiversity and store high C stocks (Pan et al. 2011). However, deforestation and forest degradation ramp up a high loss of C owing to the expansion of commercial and subsistence agriculture, illegal logging and unwise utilisation of biomass fuel. This necessitates looking for alternative land use on the agricultural landscape, such as agroforestry systems (AFS) that mitigate C while supporting local livelihoods. One of the most frequently discussed options to provide a wide range of ecosystem services and maintain the livelihoods of local people is the adoption of the AFS, where agricultural production (crops and/or livestock) is combined with the presence of perennial woody vegetation serving productive and ecological function (Dinerstein et al. 2019). AFS are considerably more sustainable than conventional agriculture (Santiago-Freijanes et al. 2021). The systems are considered a nature-based solution for fostering the resilience of perennial crops sensitive to CC, such as coffee, through shading (Bunn et al. 2015; Koutouleas et al. 2022). The importance of AFS in adapting to CC has been acknowledged by several authors (e. Zaro et al. 2020; Niguse et al. 2022). It is also well-recognized in Ethiopia's climate-resilient green economy strategy that targets reducing GHG emissions significantly by 2030 (MEFCC 2016).

The ecosystem services provided by AFS are removing CO_2 from the atmosphere (e.g. Nair et al. 2009; Nair 2012; Negash & Starr 2015) and retaining a high number of plant species that contribute to biodiversity conservations (Tadesse et al. 2023). AFS enhances C stocks in biomass (Aalde et al. 2006) as well as in soil through organic matter turnover (Lorenz & Lal 2014). AFS in the tropics have higher C stock than mono-crop fields (Albrecht & Kandji 2003; Nair 2012). Studies indicated that AFS is estimated to be practised on 1,000 – 1,023 million ha globally. The system has the potential to sequester C at a rate ranging from 30 to 322 C Pg yr^{-1} (Jose & Bardhan 2012). In the tropics, more than 10.5 million ha of land are under coffee production (FAO, 2016). Traditionally, coffee is grown under native shade trees (Denu et al. 2016), forming typical AFS (Goncalves et al. 2021). Arabica coffee (*Coffea arabica* L.) is native to Ethiopia and primarily grown in agroforests, generating high-economic benefits for the farmers (Tadesse et al. 2014).

Numerous studies reported that farmers retained shade tree species in CAFS to provide shade for coffee and co-products (e.g. Oelbermann et al. 2007; Soto-Pinto et al. 2010; Chatterjee et al. 2020) such as fruits, fodder, timber and fuelwood. They also contribute to soil nutrient maintenance and protection through litterfall decomposition, recycling leached nutrients and mining nutrients from depths beyond the roots of coffee trees (Oelbermann et al. 2007; Soto-Pinto et al. 2010). Compelling evidence credits AFS, particularly diversified CAFS, for conserving biological diversity (e.g. Toledo & Moguel 2012; Pinard et al. 2014; Giudice Badari et al. 2020), by providing habitat for many organisms and mitigating CC by storing C (Tadesse et al. 2014; De Beenhouwer et al. 2016) both in plant biomass (Denu et al. 2016) and soil (Tumwebaze & Byakgaba 2016) compared to FSCS (Zaro et al. 2020). Several studies have documented CAFS as a major C storage pool elsewhere in the tropics (e.g. Soto-Pinto et al. 2010; Schmitt-Harsh et al. 2012). For instance, CAFS could store C up to 213.8 tons ha^{-1} in Mexico (Soto-Pinto et al. 2010) and 195.6 tons ha^{-1} in Brazil (Zaro et al. 2020) in plant biomass, leaf litter, and soil. Similar studies in East Africa by Negash & Starr (2015) and Toru & Kibret (2019) reported that CAFS in soil and biomass store C up to 256.3 and 277.5 ton ha^{-1}, respectively.

The potential of CAFS to store C comes from the high diversity of CAFS as it is greatly affected by the species composition, tree density and age (Rajab et al. 2016; Schroth et al. 2016; Silatsa et al. 2017). The global meta-analysis by Ma et al. (2020) revealed that regional climate strongly influences the potential of AFS to sequester C. The authors also reasoned that tree age, tree density, tree species diversity, and land use history are the important factors that affect the C sequestration of the system. Moreover, storing soil organic C in AFS depends on soil depth, litter inputs and farm management (Tumwebaze & Byakagaba 2016; Asigbaase et al. 2021). An elevation gradient also influences vegetation composition, structure and function as well as coffee production systems (Smith et al. 2012). These factors are all regulated by the management approach adopted by smallholder coffee-producing farmers (Asigbaase et al. 2021).

Several authors' reviews provided conceptual models and theoretical bases for the potential of AFS in sequestering C (e.g. Nair & Nair, 2003; Montagnini & Nair 2004). However, Takimoto et al. (2008) and (Thangata & Hildebrand 2012) argued that empirical field measurements to justify these concepts and hypotheses have not been undertaken to a significant level, particularly in CAFS of East Africa. Moreover, little has been reported concerning the potential C sequestration of AFS under smallholder management and its quantification (Thangata & Hildebrand 2012) and the relationship between shade species diversity and biomass C stocks (Asigbaase et al. 2021). Furthermore, previous studies on the relationship between perennial diversity and C stocks have produced inconsistent findings regarding their interactions in CAFS. For instance, Negash (2013) reported no significant relationship between perennial plant diversity and C stocks, whereas Saha et al. (2009) in India and Islam et al. (2015) in Bangladesh found a substantial relationship between plant diversity and C stocks in CAFS. Therefore, we aim to substantiate either argument. Additionally, evaluation of the amount of C sequestered under specific CAFS is scarce due to the complexity of AFS and the variability of soil (Nair et al. 2009) as well as coffee production systems (Tumwebaze & Byakagaba 2016). Moreover, the percentage share of coffee plants storing C in CAFS was less documented. Furthermore, there is limited empirical evidence on how coffee growers could benefit from C revenue and income from coffee cultivation.

Hence, we aimed to evaluate the perennial plant species diversity, ecosystem C stocks, and possible C income from CAFS to inform policymakers about promoting CAFS to enhance ecosystem services while improving the livelihood of smallholder coffee producers. Specifically, we address the following objectives: (i) to evaluate the perennial plant species composition and diversity of the CAFS production system along an elevation gradient, (ii) to quantify biomass and soil C stocks and sequestration in the CFAS and FSCS along an elevation gradient, (iii) to study the relationship between perennial species diversity and biomass C stock, (iv) to quantify the C income of both CAFS and FSCS along an elevation gradient.

We hypothesized that CAFS would store higher ecosystem C stock and generate more C income than FSCS and would be significantly varied along an elevation gradient. Results from this empirical study will improve our understanding of the links between perennial species diversity and C stocks in climate-smart coffee production systems, which might complement the proposed REDD+ mechanism, a critical strategy for mitigating global CC (Wertz-Kanounnikoff & Kongphan-apirak 2009). Additionally, demonstrating and understanding the C accumulation in shade tree biomass and soil in AFS can be vital for developing CC mitigation strategies at the national and global levels (Schmitt-Harsh et al. 2012; Ma et al. 2020).

3.3.2 Materials and methods

3.3.2.1 Description of the study area and study design

This study was conducted in Dale and Wesnho districts of Sidama National Regional State, Ethiopia (Figure 2-1). The general descriptions of the study areas were indicated in session 2.1. A multi-stage approach was used to select the study farms. First, Dale and Wensho districts were purposively selected based on an elevation gradient and their high coffee production in the Sidama region. The districts were selected in consultation with key informants, including regional and district coffee experts, who possess knowledge of coffee production and productivity in the region. This selection process was complemented and supported by intensive field observations. Secondly, identified districts were stratified into three elevations: low (1,600 to 1,750 masl), mid (1,750 to 1,850 masl), and high (1,850 to 2,000 masl) elevations to obtain homogenous sampling units (Table 5-1). Finally, representative coffee farms of CAFS and FSCS were randomly selected from each elevation. Elevations were used for stratification due to their influence on coffee and other perennial plants' composition, growth and biomass productivity. Accordingly, a total of 54 farms, comprising 18 farms from each elevation gradient, were selected randomly for the study. Among these, 36 farms had CAFS, while 18 farms were FSCS (Table 5-1). At each farm, two plots were randomly laid out for perennial plants inventory, including coffee plants, resulting in a total of 108 sample plots (= 72 CAFS and 36 FSCS). Additionally, soil, litter and fine root data were collected from 54 farms, with one plot sampled per farm.

Table 5- 1. The districts, elevation range and number of sample plots selected for the studied areas in Sidama, South-eastern Ethiopia

District	Elevation	Elevation range	Number of sample plots		
			CAFS	FSCS	Total
Dale	Low	1600 – 1750 masl	24	12	36
	Mid	1750 – 1850 masl	24	12	36
Wensho	High	1850 – 2000 masl	24	12	36
Total			72	36	108

3.3.2.2 Perennial species and biomass carbon stock assessment

A nested sample plot of 20 m x 20 m with the three subplots 5 m x 5 m across the diagonal of the main plot was established. At each plot, the total height (m) and diameter at breast height (DBH cm) of all trees and shrubs were measured. All species of trees and shrubs, both single and multi-stemmed, with DBH $\geq$ 2.5 cm were measured. This allowed for the calculation of their basal area, tree density and both above and belowground biomass C stocks. Identification of local names and use values of woody species was done with the help of key informants. The scientific names of species were identified using books of Flora of Ethiopia and Eritrea (Hedberg et al. 2003) as well as "Useful trees and shrubs for Ethiopia" by Tesemma (1993).

3.3.2.3 Soil, fine root and litter carbon stocks assessment

The soil samples were collected from randomly placed 1 m x 1 m subplots within the larger 5 m x 5 m subplots, which were located within the main 20 m x 20 m plot. Soil samples were collected from three soil depths (0 – 20 cm, 20 – 40 cm, and 40 – 60 cm). A total of 486 soil samples were collected (54 farms x 3 subplots x 3 soil depths). The soil samples were collected using a core sampler with dimensions of 7 cm in diameter and 10 cm in height, resulting in a volume of approximately 384.9 cm^3. The collected soil samples were air-dried at room temperature, milled and passed through a 2 mm sieve. SOC concentrations were determined using the Walkley and Black method (Walkley & Black 1934). Similarly, the same number of soil samples were collected separately for bulk density determination. These soil samples were oven-dried for 24 hours at 105^0C. The bulk density (Mg m^{-3}) was calculated using the core sampler's volume and the oven-dried sample's weight. From each sample, the stone contents were sorted out by hand and measured using a digital electronic balance.

Fine root samples (< 2 mm diameter) were collected from the soil samples for the three depths (0 – 20 cm, 20 – 40 cm and 40 – 60 cm) using a soil core sampler. The soil samples were drenched for 30 – 40 minutes to facilitate the breakdown of soil aggregates. Afterwards, they were washed, extracted by hand and passed through a 2 mm sieve. Then, the samples were oven-dried at room temperature (70°C) for 24 hours and measured using a digital electronic balance. The oven-dried fine roots were grinded and the C content was determined through the loss on ignition (LOI) method at 550^0C for 2 hours. The amount of organic C in the ignited fine root samples was determined by multiplying the burnt organic matter by 0.50 (Pearson et al. 2007).

The litter samples, including dead leaves, branches, twigs, flowers, and deadwood less than 10 cm in diameter, were collected using a 1 m x1 m wooden frame. These samples were collected from the same designed for soil data collection. A total of 162 litter samples (54 farms x 3 subplots) were collected. The fresh litter samples were collected and measured right on the field using a digital spring balance. Then, the samples were sun-dried for one day, taken to the laboratory, oven-dried at 65^0C for 24 hours and weighed to determine the dry-to-fresh weight ratios. While C contents of litter are estimated to be 37%, as demonstrated by IPCC (2006).

3.3.2.4 Data analysis

The basal area ($m^2 ha^{-1}$) and stem density (stems ha^{-1}) of trees and other perennial plants were calculated using the standard method. In the case of multi-stemmed shrubs, each stem was measured, and the diameter equivalent of the plant was calculated as the square root of the sum of the diameters of all stems per plant, following Snowdon et al. (2002). Each species' Importance Value Index (IVI) was estimated as the sum of the relative abundance, relative dominance, and relative frequency (Asigbaase et al. 2021). Species richness estimator (E (estimate), Chao 1, Jack 1, ICE, ACE) and diversity indices (Shannon, Simpson and Fisher's alpha) were computed using EstimateS software version 9 (Colwell 2013). The Jaccard and Sorensen similarity index was computed using the equation of Kent & Coker (1992).

Aboveground (AGB) and belowground biomass (BGB) C stocks of woody species, bananas (*Musa spp.*), and coffee were determined for individuals from a DBH of ≥ 2.5 cm and a tree height of ≥1.5 m. The AGB and BGB of woody species were estimated using allometric equations developed for trees grown on farmland (Table 5-2) (Kuyah et al. 2012a, b). While BGB was derived from the AGB by multiplying it by the root-shoot ratio for trees, shrubs and coffee, which is estimated to be 0.26 (Kuyah et al. 2012b; Negash et al. 2013b), and for the banana is 0.24 (Negash et al. 2013b). The basic wood density of indigenous and exotic tree species grown in Ethiopia was obtained from the report on the Forest Reference level of Ethiopia (EFRLS 2016).

Table 5- 2. Allometric equations used to estimate the biomass of woody species and other perennial plants grown in CAFS of Sidama, South-eastern Ethiopia

Species	Equation	R^2	% C	Reference
Wood species	$AGB = 0.225 \times d^{2.341} \times p^{0.73}$	0.98	48	Kuyah et al. (2012a)
	$BGB = 0.048 \times d^{2.303}$	0.95	48	Kuyah et al. (2012b)
	$BGB = 0.26 \times AGB$	-	48	Kuyah et al. (2012b)
Coffee (*Coffea arabica*)	$AGB = 0.147 \times d^2{}_{40}$	0.80	49	Negash et al. (2013a)
	$BGB = 0.26 \times AGB$	-	49	Kuyah et al. (2012b)
Banana (*Musa spp.*)	$ABG = -6.415 + 2.940 Ind$	0.82	48	Kamusingize et al. (2017)
	$BGB = 0.24 \times AGB$	-	48	Negash et al. (2013b)

AGB Aboveground biomass in kg dry matter/plant, BGB Belowground biomass in kg dry matter/plant, d diameter at breast height in cm; p wood density in g cm^{-3}.

Total ecosystem C stocks were determined by summing the biomass C stocks (AGC and BGC), litter, fine root and SOC. The total biomass C stock (TCS) of woody species and other perennial plants was calculated as the sum of AGC and BGC. The biomass C stock was converted to CO_2 equivalent by multiplying it by 3.7. Then, the C sequestration rate per year was calculated as follows: Sequestration rate = CO_2 equivalent/(1000×25) (Negash and Starr, 2015; Asigbaase et al. 2021). The SOC was estimated using the method proposed by Negash and Starr (2015), expressed as SOC = %C×BD×Z× (1 - frag/100) ×100, where SOC = soil organic C stock in ton ha^{-1}, C = C content in %, BD = soil bulk density in g cm^{-3}, Z = soil depth in cm and course frag = correction factor for coarse (> 2 mm) fraction content multiplying by (100% - volumetric content of coarse fraction, %) divided by100).

The gross monetary value (MV) of total standing biomass C stocks was estimated using the formula, MV = CE×P, where CE is the CO_2 equivalent of C stocks (CE = C stocks × 3.7), and P is the unit price (US $) of CE (Somarriba et al. 2013). As in other studies, a unit price of US$ 5 was used for Africa in the voluntary market, as stated by Asigbaase et al. (2021). We utilized farmers' feedback on the age of the farms and trees to estimate the age of each coffee system (A). The MV of the C sequestration rate (i.e. CE rate) was estimated as MV/A, assuming linear increment, as demonstrated by Somarriba et al. 2013. Additionally, the rate of CO_2 equivalent of C stocks was calculated as CE/A, following the methodology outlined by Asigbaase et al. (2021).

3.3.2.5 Statistical analysis

All statistical analyses were done using R-software and Statistical Package for Social Science (SPSS) software version 21. A one-way analysis of variance (ANOVA) was employed to test for significant sources of variation in terms of species richness estimate and diversity. Additionally, ANOVA was used to assess the variation in AGC, BGC and SOC stocks along an elevation gradient. The Least Significant Difference (LSD) post hoc test was used to examine the significant difference between the means across the elevation classes of the study areas. General Linear Model (GLM) was run to evaluate the interaction effects between Shannon diversity and stem density, biomass C and Shannon diversity, stem density and biomass C, and DBH and biomass C. Pearson correlation was also used to measure the strength of the relationship between perennial species diversity (Shannon diversity) and biomass C.

3.3.3 Results

3.3.3.1 Perennial plant species diversity

In total, 31 perennial plant species representing 27 genera and 20 families were identified and recorded in CAFS (Appendix A, Table 3). The highest species richness shade trees and other perennial species were recorded in mid-elevation (21 species), followed by high elevation (20 species) and low elevation (17 species). Perennial species Shannon diversity significantly differed among the studied elevations ($p < 0.001$). It was higher for the mid, followed by high and low elevations (Table 5-3). Sorensen's similarity Index was moderately similar between mid and low elevations (58%). The highest species similarity was observed between high and mid elevations (68%), followed by high and low (65%). Moreover, Jaccard's similarity index was estimated to be 41%, 48% and 52%, respectively, between mid and low, high and low, and high and mid-elevations.

M ferruginea in both mid and high elevations, whereas *C africana* in low elevation were the most familiar and preferred native shade tree species with the highest IVI values (Appendix A Table 4). Our result indicated that basal area (m^2ha^{-1}) differed significantly across an elevation gradient ($p < 0.05$) (Table 5- S3). The highest mean basal area (m^2ha^{-1}) was observed in the mid-elevation, followed by high and low elevations. Tree density varied from 330 stems ha^{-1} in low elevation to 415 stems ha^{-1} in mid-elevation, but no significant differences were observed among the three studied elevations (Appendix A Table 5).

Table 5- 3. Mean (± SD) perennial plant species richness estimators and diversity indices along an elevation gradient in the CAFS of Sidama, south-eastern Ethiopia

		Elevation				
Variables		High (n=24)	Mid (n=24)	Low (n=24)	*F-value*	*P-value*
Species richness estimators	Estimate(est)	14.80±1.08[a]	16.21±1.75[a]	13.34±2.00[b]	3.20	0.047
	ACE	16.50±1.83[a]	17.65±2.05[a]	16.98±3.88[a]	0.38	0.687
	ICE	21.48±4.86[a]	22.27±5.10[a]	19.07±5.20[b]	4.15	0.020
	Chao1	15.85±1.69[a]	17.66±2.04[a]	16.12±3.43[a]	1.42	0.249
	Jack 1	19.04±1.70[a]	20.22±1.97[b]	17.05±1.80[a]	3.11	0.051
Species diversity indices	Shannon diversity	1.98±0.08[a]	2.17±0.22[b]	1.74±0.15[c]	28.29	<0.001
	Fishers' alpha	4.19±0.69 [a]	4.54±0.71[a]	3.78±0.68[b]	24.27	<0.001
	Simpson (reverse)	4.89±0.40 [a]	6.29±0.73[b]	3.89±0.67[c]	109.43	<0.001

ACE Abundance coverage-based estimator, ICE Incidence coverage-based estimator, n number of sample plots. Similar letters show no significant differences, while different letters in a row show significant differences between elevations at a 5% significance level.

3.3.3.2 Biomass carbon, CO2 equivalent and sequestration rate

The biomass C stocks of AG (ton ha^{-1}) of shade trees were significantly varied along an elevation gradient ($p < 0.001$) (Table 5-4). The total biomass C stocks decreased in the ordered along an elevation gradient, Mid > High > Low elevations. The total CO_2 equivalent removal (ton ha^{-1}) and sequestration rate (ton $ha^{-1}yr^{-1}$) were also statistically significant across the three elevation classes ($p < 0.001$) (Table 5-4).

Our study showed that the mean (±SD) biomass C stocks, total CO_2 equivalent removal and sequestration rate of the coffee plant in FSCS was slightly higher than that of the coffee plant in CAFS (Appendix A Table 6). The C stocks in the coffee plant, both with CAFS and FSCS, significantly varied along an elevation gradient ($p < 0.001$).

In the CAFS, trees accounted for 80% of total biomass C, followed by coffee plants (20%), shrubs (0.4%) and non-wood plants (0.2%) of the total biomass C stocks. The ten top shade tree species contributed to 96% in high, 90% in mid, and 92% in low elevations of the total biomass C stocks in the studied areas (Appendix A Table 4).

Table 5- 4. Mean (± SD) of perennial plant species biomass C (ton ha^{-1}), CO_2 equivalent removal (ton ha^{-1}) and sequestration rate (ton $ha^{-1}yr^{-1}$) along an elevation gradient in the CAFS of Sidama, South-eastern Ethiopia

Coffee production systems	Elevation	n	Biomass C (ton ha^{-1})			CO_2 equivalent removal (ton ha^{-1})			Sequestration rate (ton^{-ha-yr})		
			AGC	BGC	TC	AG CO_2 eqv. removal (ton ha^{-1})	BG CO_2 eqv. removal (ton ha^{-1})	Total CO_2eqv. removal (ton ha^{-1})	AGC Seq. rate (ton ha^{-1} yr^{1})	BGC Seq. rate (ton $ha^{-1}yr^{-1}$)	Total Seq. rate (ton $ha^{-1}yr^{-1}$)
CAFS	High	24	24.68±4.73^{a}	6.42±1.23^{a}	31.10±5.97^{a}	91.31±17.52^{a}	23.74±4.55^{a}	115.05±22.08^{a}	8.85±2.22^{a}	2.30±0.58^{a}	11.14±2.80^{a}
	Mid	24	32.38±7.81^{b}	8.44±2.07^{b}	40.82±9.87^{b}	119.07±28.86^{b}	36.71±28.24^{b}	155.78±43.84^{b}	12.03±2.60^{b}	3.00±0.74^{b}	15.02±3.08^{b}
	Low	24	20.07±6.27^{c}	5.22±1.63^{c}	25.29±7.89^{c}	74.27±23.18^{c}	19.31±6.03^{a}	93.58±29.21^{c}	9.38±2.71^{a}	2.44±0.70^{a}	11.81±3.42^{a}
	Pooled mean	72	25.71±8.12	6.69±2.13	32.40±10.24	94.88±29.82	26.59±18.23	121.47±41.61	10.08±2.85	2.58±0.73	12.66±3.51
	F-value		22.72	22.54	22.68	21.94	6.89	22.03	10.96	7.13	10.65
	P – value		<0.001	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	0.002	<0.001

AGC Aboveground C, BGC Belowground C, eqv equivalent, ha hectare, Seq sequestration, TC total C. Similar letters show no significant differences, while different letters in a column show significant differences between elevations at a *5*% significance level.

3.3.3.3 Interaction effect between stand structure, species diversity and biomass carbon

The result of the General linear model showed that shade tree species' Shannon diversity index did not significantly interact with stem density (t = 1.13; $p = 0.259$) and biomass C (t = 0.46; $p = 0.649$) (Appendix A Figure 2). Additionally, our result confirmed a weak relation (r = 0.01; $p = 0.649$) between the Shannon diversity index and biomass C.

3.3.3.4 Soil, fine root and litter carbon stocks

In the CAFS system, the concentration of SOC stocks along an elevation gradient was statistically significant for the soil surface (F = 17.01; $p < 0.001$) and middle layers (F = 3.89; $p = 0.024$) whereas no variations were observed for the lower layer (F = 0.81; $p = 0.447$). On the other hand, SOC stocks did not differ along an elevation gradient in the FSCS. The topsoil layer accounted for 45% of the total SOC in CAFS, while 43% for FSCS.

Our results indicated that the fine root C stocks (ton ha^{-1}) along the soil layers were significantly varied for both CAFS and FSCS (Figure 5-1). Moreover, the fine roots C stocks across an elevation gradient were statistically significant only in the top layers for both coffee production systems. The litter C stocks (ton ha^{-1}) along an elevation gradient were varied in the CAFS and FSCS. The mean (±SD) litter C stock of CAFS and FSCS was the highest for the lower elevation, followed by mid and high elevations.

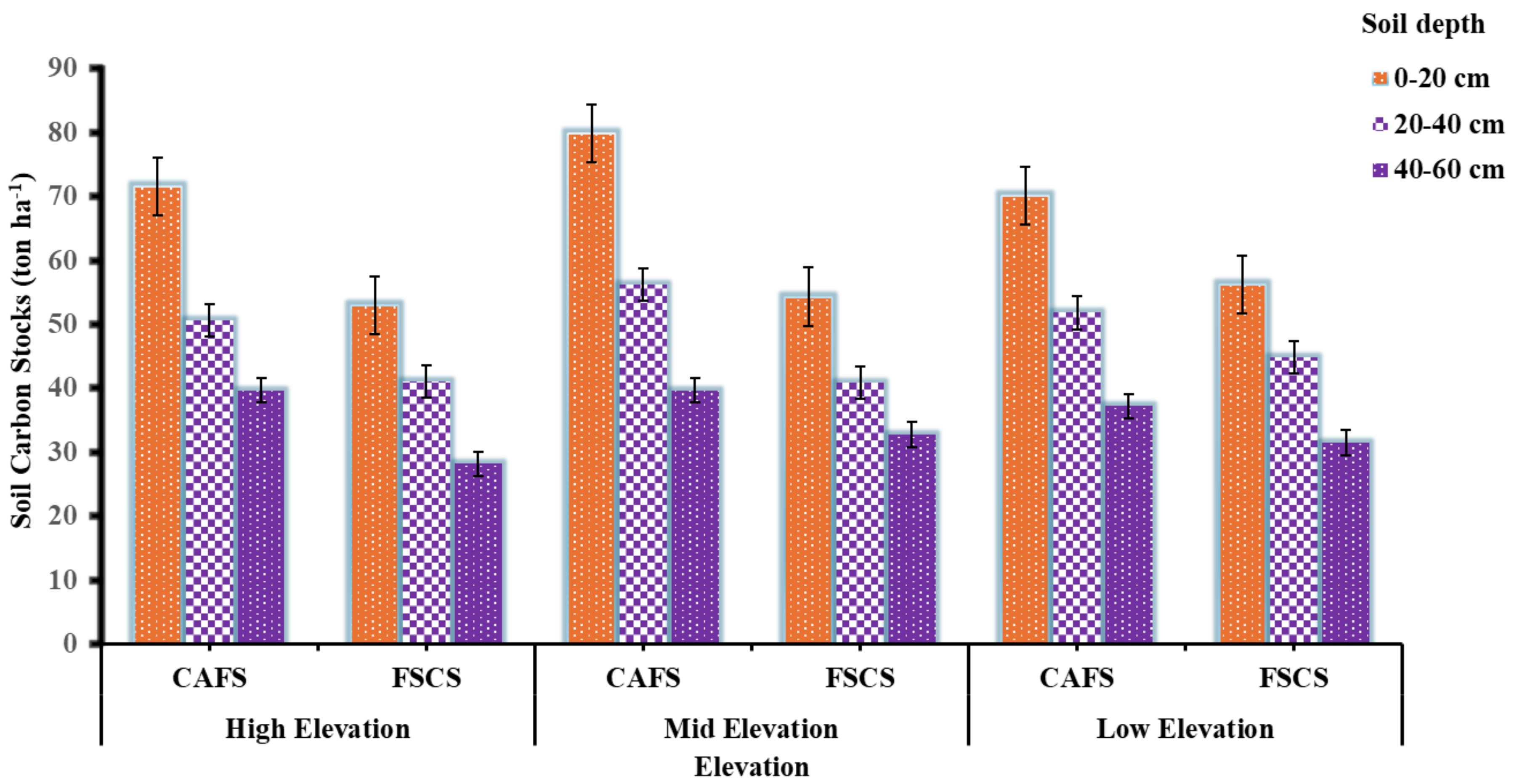

Figure 5- 1. Mean (± SD) of SOC (ton ha^{-1}) along an elevation gradient in the CAFS and FSCS of Sidama, South-eastern Ethiopia. CAFS Coffee Agroforestry System; FSCS Full Sun Coffee System

3.3.3.5 Ecosystem carbon stocks and carbon income

The ecosystem C stocks (sum of C in biomass, litter, fine root stocks and SOC (0 – 60 cm)) in CAFS ranged from 193.2 to 225.9 ton ha^{-1} (Figure 5-2A), while for FSCS ranged from 131.9 to 142.6 ton ha^{-1} (Figure 5-2B). The SOC in the CAFS production system accounted for 80%, while in the FSCS, it accounted for 92% of the ecosystem C stocks. The ecosystem C stock of CAFS was 20% higher than FSCS; it was statistically significant (Figure 5-2).

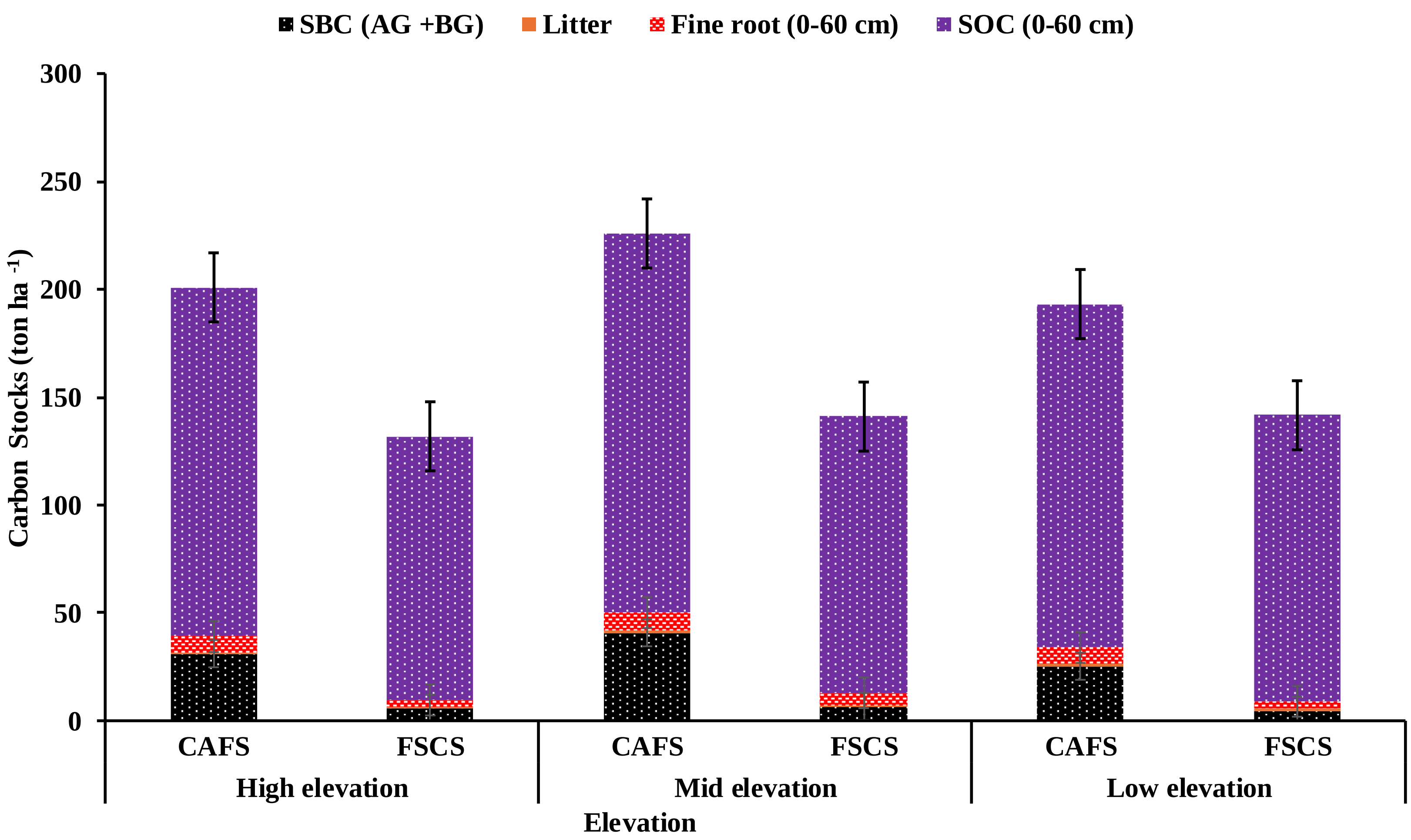

Figure 5- 2. Ecosystem C stock (ton ha^{-1}) along an elevation gradient in CAFS and FSCS of Sidama, South-eastern Ethiopia. AB above ground C; BG belowground C; CAFS Coffee Agroforestry System; FSCS Full Sun Coffee System; SBC standing biomass C; SOC soil organic C

Our result also indicated that the C income of the CAFS was higher by 70% than FSCS. The gross C income was significantly varied along an elevation gradient (Table 5-5). The value of CO_2 equivalent and sequestration rate used to calculate C income were indicated in Table 5-4 and Appendix A Table 6.

Table 5- 5. Monetary value of CO_2 equivalent of biomass C and accumulation rate in CAFS and FSCS along an elevation gradient of Sidama, South-eastern Ethiopia

Farm type	Elevation	Value of CO_2 equiv. of C stocks (US $ ha^{-1})	Value of CO_2 equiv. of C stocks (US $ ha^{-1} yr^{-1})
CAFS	High	575.25	33.42
	Mid	778.90	75.10
	Low	467.90	59.05
	Mean	605.35	63.30
FSCS	High	108.00	13.8
	Mid	125.10	19.35
	Low	87.80	10.65
	Mean	106.30	14.6

Price (US$) = 5 US$ [ton CO_2]$^{-1}$

3.3.4 Discussion

3.3.4.1 Perennial species composition and diversity

Our result indicated that CAFS in the study region maintained higher perennial species diversity than the study reported by Muleta et al. (2007) in the CAFS of southwest part of Ethiopia. However, we observed variation in species diversity along an elevation gradient. Variations in species composition and diversity between regions could be due to the differences in farmers' preference for tree species, farm size, socioeconomic issues, management approach of farmers and agroclimatic variation (Wade et al. 2010). This is also confirmed in our previous study, we observed decreasing land suitability for coffee due to increasing temperature and erratic rainfall in the low elevation of our study region (Jawo et al. 2023). This has resulted in land use change, which reduced the composition and diversity of shade tree species. Increasing temperature and rainfall variability influences farmers' preference in the selection of tree species which has a significant impact on tree species diversity. In areas with low rainfall and dry areas, decreasing tree density and diversity could be associated with limited moisture in the soil (Cerda et al.2017). Schroth & Harvey (2007) also reported that location, farm management, and farm history affect the floristic composition and diversity of AFS in the tropics.

The native shade species such as *C africana, M ferruginea, and A gummifera* were highly preferred by farmers for soil fertility management. This is owing to their leaves decomposing quickly, improving soil fertility and shedding their leaves during the active growing season of coffee shoots and fruits (Negash & Starr 2021). The shedding of the leaves also benefits the coffee plant by providing direct sunlight for photosynthesis, thus maximising energy capture (Negash et al. 2012a). Several studies documented farmers in coffee growing areas select shade trees based on their compatibility with coffee production by assessing traits such as shape of crown, shade production, deciduous nature, foliage density, root system attributes, and allelopathic effects (e.g. Souza et al. 2012; Anglaaere et al. 2011; Cerda et al. 2017).

The integration of timber species (*C africana* and *Afrocarpus falcatus)* and fruit species (*M paradisiaca* and *P americana*) in the CAFS of the study region would provide additional income for the farmers. Integrating shade trees in coffee production systems also plays a central role in conserving tree and food crop species (Negawo & Beyene 2016), helping farmers diversify their income. The farmers could harvest the shade trees for consumption or sale, particularly during low coffee production or low prices (Rice 2008). Besides, shade tree species in CAFS provide various benefits such as fuelwood, medicine, livestock feeds, suppression of weeds and pests, and hosts for beneficial insects such as pollinators.

3.3.4.2 Biomass carbon stocks, CO2 equivalent and carbon income

Our result of biomass C stocks in CAFS (AG, BG, litter and fine root) ranged from 39.7 – 49.6-ton ha^{-1} was within the global range of tropical agroforestry biomass C (12 and 228-ton ha^{-1}) (Albrecht & Kandji 2003) and the study conducted in agroforestry of south-central Ethiopia (Tadesse & Negash 2023). Our result indicated that CAFS had higher biomass C stock than FSCS. This is mainly attributed to the availability of deciduous shade tree species in the system, contributing up to 80% of the total biomass C stocks. Several studies documented that deciduous tree species such as *Cordia africana and Erythrina brucei* contain high nitrogen in their leaves, larger specific leaf areas, and a higher rate of photosynthesis (e.g. Medina & Francisco 1994; Asigbaase et al. 2019). For instance, Negash & Starr (2013) reported that the annual inputs of Nitrogen from *C africana*, *E brucei* and *M ferruginea* through litterfall in coffee-enset-based agroforestry system were 92.7, 13.8 and 60.5 kg per ha, respectively.

Many literatures revealed that AFS stores more C in AG than mono-culture agriculture. For instance, converting agricultural lands to AFS with 10% tree cover globally can store 12.3

billion Mg C in AG tree biomass (Ma et al. 2020). A study in Costa Rica by Cerda et al. (2017) reported that CAFS had more than twice the amount of AGC than coffee in the FSCS. This is attributed to their more diverse and denser shade canopies. Similar to our finding, other studies in different parts of the tropics also confirmed that CAFS store more C in AG biomass than conventional farms. This was evidenced from other studies in Togo, 67 MG ha^{-1} (Dossa et al. 2008), Indonesia, 43 MG ha^{-1} (van Noordwijke et al. 2002) and Mexico, 40 MG ha^{-1} (Rahn et al. 2014). Cerda et al. (2017) also asserted that establishing and managing tall and coarse-trunk trees could enhance the sequestration potential of CAFS. However, the biomass C storage potential of AFS depends on system management, biophysical conditions, tree structure and composition, which are determined by social, cultural, economic and environmental factors (Nadège et al. 2019).

Moreover, our study indicated that an elevation gradient affect biomass C accumulation. The low elevation in the present study accumulated lower biomass C stock than the mid and high elevations. This could be ascribed to the impact of CC on coffee production in the study region. Our previous study (Jawo et al. 2023) based on meteorological data also confirmed an increased temperature in the same study areas for the last three decades. This resulted in land use change from CAFS to drought-resistant crops such as khat (*Catha edulis* Forsk, a stimulant plant) and eucalyptus species (*Eucalyptus* spp.) (Jawo et al. 2023). The change in land use affects the species richness and composition of shade trees, which can, in turn, reduce the biomass C storage capacity of AFS (Tadesse et al. 2014). A study in India by Singh et al. (2023) stated that the land use system influenced the AG, BG and annual C sequestration potential. Yadava (2011) also reported that the management and selection of coffee shade and integration of appropriate annual or perennial crops to the coffee farm affect the biomass C in CAFS. Moreover, with increasing temperatures, rainfed coffee production declined at the lower elevation (Bunn et al. 2015), affecting the biomass productivity of coffee plants and shade trees, which in turn impacts biomass C stocks (Tadesse et al. 2014).

The leaf litter and root biomass C stock of CAFS was higher than FSCS. This is attributed to the availability of shade tree species producing high litterfall (Negash & Starr 2021) and a significant volume of root biomass (Jose & Bardhan 2012). Our result showed that the biomass C stocks of coffee plants grown in FSCS are slightly higher than those grown under shade. Our result agrees with those reported in the literature. For instance, Dossa et al. (2008) observed low biomass C stocks in coffee plants of CAFS due to less biomass production. The authors further explained that light competition under tree canopies caused the reduction of biomass and C stock of the coffee plants in CAFS. Coffee plants that grow in the FSCS contain higher biomass from greater light absorption (Dossa et al. 2008).

The presence of shade tree species greatly enhances biomass C accumulation and its associated C income compared to FSCS. The potential of C storage is assumed to co-occur with the availability of shade trees (Venter 2014). Studies indicated that shade species are the main drivers of biomass C stocks (Schroth et al. 2015), making agroforestry a viable REDD + strategy (Minang et al. 2014). The REDD+ C crediting scheme ensures additional benefits for the farmers, helping them overcome declines in coffee productivity and, consequently, income due to climate change and variability as well as damage from pests and diseases (Singh et al. 2023). The value of C credit is determined by higher biomass production and the C sequestration potential of the AFS (Goswami et al. 2014). The higher C income for CAFS incentivizes the local communities to manage shade trees (Asigbaase et al. 2021) and motivates them to integrate and maintain more native trees into the farms.

3.3.4.3 Soil carbon stocks

CAFS had significantly higher SOC than FSCS. Our findings concur with those of Hergoualc'h et al. (2012) in Costa Rica and Tumwebaze & Byakgaba (2016) in Uganda. This is due to shade trees and the coffee plants providing continuous leaves and acceptable root litter inputs. The C input to the soil emerged from the litter (quantity and quality) and fine root mortality and exudation, enhancing soil C stocks. A similar study reported that CAFS facilitate soil C sequestration and conservation due to the establishment of trees that produce ample litter (Schmitt-Harsh et al. 2012; Oelbermann & Voroney 2007). Montagnini & Nair (2004) also reported that SOC in AFS is enhanced by organic inputs such as pruned biomass, litter, root decay, and exudation of trees. A study in multi-strata AFS in south-eastern Ethiopia showed that the annual litter production for the Fruit-Coffee system averaged 12,938 kg ha^{-1}, 10,187 for the Enset-Coffee system and 7,430 Enset systems. The yearly associated C fluxes (kg ha^{-1}) were 5,145 (Fruit-Coffee system), 3,928 (Enset-Coffee system) and 2,803 (Enset system) (Negash & Starr 2013). The high litter inputs improve the SOC and maintain the soil fertility of CAFS systems, which in turn enhance the productivity of coffee. The high SOC stocks in CAFS are not limited to maintaining soil productivity and quality but are also credited for permanently storing SOC more than biomass (Negash &Starr 2015). In coffee grown in FSCS, much smaller C inputs from the litter fall, and the loss cannot be compensated via mineralization (Hergoualc'h et al. 2012; Xiao et al. 2020).

We observed variation in SOC along an elevation gradient in our study region. Studies also documented that the amount of C stored in the soil depends on local climatic conditions (Gama-Rodrigues et al. 2010) and altitude (Cerda et al. 2017). Desie et al. (2020) also reported that the composition of tree species in AFS selected by the farmers affects the system's SOC sequestration and soil fertility status. In our study region, farm management practices (use of manure and compost), tree species selection and composition differ from farmer to farmer and along an elevation gradient. The mid-elevation in the present study accumulated higher SOC stock than high and low elevations. The variations of SOC stocks along an elevation gradient were likely attributed to the difference in rainfall, soil temperature, tree species management and land-use history (Nair et al. 2009) and rate of mineralization by soil microorganisms and local climate (Soto-Pinto et al. 2010). For instance, high soil temperature in the low elevation enhances the activity of soil macrofauna, which could result in faster litterfall decomposition. Human activities stimulate soil C losses through SOC mineralization by reducing shade, which, in turn, increases soil temperature and heterotrophic respiration (Davidson & Janssens 2006). A meta-analysis by Ma et al. (2020) shows a variation in plant biomass increment and soil C inputs in wet and dry seasons. Dry climates resulting in higher temperatures facilitate the decomposition rates and reduced soil C storage (e.g. Naiman et al. 2010; Sutfin et al. 2016). In contrast, the low soil temperature in the high elevation reduces these organisms' activities and limits organic matter release. Finally, SOC was high in both coffee production systems on the top layer (0 – 20 cm) and decreased along the soil depths. This is owing to the high organic matter inputs from trees and shrubs via litterfall on the surface soil.

While our study offers valuable insights into the contribution of SOC to the ecosystem C stock within the AFS under investigation, it is important to acknowledge a certain limitation. Conventional laboratory-based C estimation methods, such as the Walkley-Black method, may underestimate C levels due to incomplete digestion of SOC, while methods like LOI (Loss-On-Ignition) could overestimate C levels due to the loss of inorganic fractions, such as carbonates, resulting from high ignition temperatures (El-Hussieny 2017). Hence, there is a need to explore more rapid, accurate, robust, precise, and cost-effective methodologies for detecting soil organic matter (SOM). Techniques such as spectroscopy for SOM detection, laser-induced breakdown spectroscopy, and inelastic neutron scattering for SOM analysis have garnered attention in recent literature (Cambou et al. 2016; Viscarra Rossel et al. 2016; Mir et al. 2023).

3.3.4.4 Ecosystem carbon stocks

Our result showed that ecosystem C stock of CAFS was 20% higher than FSCS. Cerda et al. (2017) reported that CAFS stores more C and provides multiple ecosystem services while improving the livelihood of small farmers. The SOC stocks in CAFS accounted for 80% of our studied region's total ecosystem C stocks. Similarly, results were also reported by several studies elsewhere in the tropics (e.g. Häger 2012; Schmitt-Harsh et al. 2012). The shade trees enhanced the sequestration of C both in plant biomass and soil. The C fixed in the shade trees transports through the litter to fine roots and deposits in soil (Beedy et al. 2010), thus improving the system's soil fertility and biomass productivity (Albrecht & Kandji 2003).

In our study area, the native shade tree species are deciduous, shading their leaves during the dry period, enhancing the C ecosystem stocks, and improving soil fertility. Asigbaase et al. (2019) study also reported that integrating deciduous shade species in cocoa AFS enhanced the C sequestration potential of the systems. A similar study showed that planting of N-fixing leguminous in CAFS systems increases litter decomposition (Mulumba & Lal 2008), reduces run-off (Ruiz Meza 2015), and increases nutrient cycling, which resulted in the sequestration of more C in the biomass and soil. Hence, the integration of native shade species in CAFS could be a strategy to enhance the ecological resilience and ecosystem services of the systems. Shade species contribute to soil nutrient recycling through litter fall, which further increases the potential of CAFS to capture and store more C in the system (Asigbaase et al. 2019). Moreover, an elevation gradient influenced the ecosystem C stocks in our study region. Our study concurs with other studies that reported climate, topography, soil-forming substrates and management of AFS by smallholder farmers significantly affect the ecosystem C stock (Zaro et al. 2020). Moreover, the density and distribution of shade trees in CAFS with different decomposing litter and retaining of the litter as a mulch or compost preparation and management impact the ecosystem of the CAFS system. Negash et al. (2022b), in their study of the AFS in Ethiopia, also concluded that there is a high potential to manage C and N stocks and their persistence, as well as soil productivity, by managing the duration of agroforestry, the density of large trees, the proportion of legumes, and the main crops (enset and coffee) in the multistrata agroforestry.

The CAFS systems deliver multiple ecosystem services that can increase the economic value of the land (Dale & Polasky 2007) while mitigating climate change, which is vital for both current and future generations. The systems also create a conducive microclimate by reducing the incidence of solar radiation while improving gas exchange and water use efficiency (Mbow et al. 2014) of the understorey plants (Bayala et al. 2015). The availability of organic matter in the system via litterfall and decomposition also regulates water and soil temperature and improves soil structure and porosity. Litterfalls from the trees used as mulch increase soil fertility and health (Jassogne et al. 2013) and thus promote organic production. This, in turn, increases the quality of coffee and further increases income (Jawo et al. 2023).

Our result of a negative relation between biomass C and Shannon diversity was in line with other studies reported in the tropics (Mandal et al. 2013). Richards & Mendez (2014) asserted that biomass C is not associated with species diversity because farmers manage agricultural landscapes, which disturbs the system. Moreover, biomass C stock not only relies on diversity but is also dependent on the size of the tree, implying that the impact of plant diversity on C stocks and the consequent income is context and site-specific.

3.3.5 Conclusion

Our study demonstrates the significance of maintaining native shade tree species to foster the ecosystem function of C sequestration. Additionally, our results indicate that CAFS plays a vital role in C accumulation in soil and biomass compared to the FSCS. However, we observed variations in ecosystem C stocks along elevation gradients due to the local climate. Also, there was no relationship between shade species diversity and biomass C stocks. Our study highlights that coffee production with shade trees generates more income for smallholder farmers through C crediting schemes, incentivizing coffee growers to foster and manage shade trees to enhance C and biodiversity conservation. This, in turn, benefits the smallholder farmers from C financing schemes on the agricultural landscape, such as REDD+. Hence, the conservation of shade tree species in the coffee production system should consider farmers' preferences in tree species selection and weigh ecological and economic benefits. Moreover, the international community should recognize the AFS role in CC mitigation in the tropics while simultaneously supporting local livelihoods and conserving biodiversity.

3.4 The effect of shade species on soil macrofauna diversity and coffee yield in the coffee-based agroforestry system along an elevation gradient

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This chapter evaluates the effect of shade tree species on soil macrofauna diversity and coffee yield in the CAFS. This finding contributes to the knowledge and literature on shade species and soil macrofauna diversity in CAFS, which might help develop strategies for managing soil macrofauna and improving coffee productivity in the study region.

Authors contribution: The study was conceptualized by TO. and BL. with substantial support from MN. The first author prepared an inventory format, conducted field data collection and data analysis, drafted the manuscript and final writings. This chapter addresses the hypothesis that the shade species in CAFS with high plant diversity promote the soil macrofauna, contributing to the system's resilience.

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Abstract

Native shade tree species protect crops from extreme weather conditions and improve their growth through enhanced soil fertility. Agroforestry systems practised by smallholder farmers enhance the abundance and diversity of soil macrofauna compared to mono-culture agriculture. Soil macrofauna are critical indicators for the sustainable management of agricultural ecosystems through soil fertility management and maintenance. The overall objective of this study was to evaluate shade tree species' effect on soil macrofauna diversity and coffee growth and yield in the CAFS along elevation gradient of Southeastern, Sidama, Ethiopia. To achieve the study's objective, soil macrofauna data were collected, and coffee growth and yield were measured in both CAFS and FSCS. The soil macrofauna diversity was evaluated using the Shannon diversity indexs. The bright red color (fully ripened) coffee yield was harvested, sundried, and grinded, and thus, the coffee beans were measured using a digital measuring balance. In both CAFS and FSCS, the highest amount of soil macrofauna data was collected during the wet season compared with the dry season. Soil macrofauna diversity was high in CAFS and significantly differed among the studied elevations in the rainy season. In contrast, no statistical significance ($p > 0.05$) of soil macro-fauna diversity was observed in the FSCS in both seasons. The soil macrofauna diversity was highest for mid-elevation and lowest for high elevation. The mean (±SD) of coffee yield was slightly higher for coffee grown in FSCS than in CAFS. Our result indicated a strong relationship ($r = 0.90$; $p < 0.001$) between the Shannon diversity of shade trees and soil macrofauna. Also, soil macrofauna diversity positively affects coffee yield ($r = 0.28$; $p = 0.05$). The present study indicated that the CAFS promotes the abundance and diversity of soil macrofauna and helps smallholder farmers produce climate-resilient coffee and high production stability in the face of climate change and variability.

Keywords: climate-resilient, agroforestry, coffee yield, elevation gradient, Ethiopia, soil macrofauna, Sidama

3.4.1 Introduction

Soil biota plays an indispensable role in ecosystem functioning (Korboulewsky et al. 2016) and productivity (Chapman et al. 1988). They are critical indicators for the sustainable management of agricultural ecosystems through soil fertility management and maintenance (Okigbo 2020). Soil macrofauna are animals visible to the naked eye and inhabit different soil layers (Masebo et al. 2024). Zulu et al. (2022) explained that soil macrofauna has an average body width greater than 2 mm and consists of many different organisms. Soil macrofauna is a significant biological component in soil processing and formation (Brussaard 1998). Soil macrofauna is an 'ecosystem engineer' for their role in decomposing and distributing organic matter and affecting soil structure (Jones et al. 1994; Lavelle et al. 1997; Asfaw & Zewudie 2021). A growing number of studies from various continents confirm that soil macrofauna is a good indicator of soil quality and land productivity; e.g. in Ethiopia (Asfaw & Zewudie 2021), Kenya (Murage et al. 2000), West Africa (Black & Okwakol 1997) and Nicaragua (Rousseau et al. 2013). Soil macrofauna influences soil's chemical and physical properties, for instance, through borrowing, casting and mixing plant litter (Edwards & Bohlen 1996; Decaens et al. 2004). Such a role has an essential effect on plant productivity and community structure (Eisenhauer et al. 2009). Studies indicated that soil macrofauna directly interacts with vegetation through root herbivory (Wardle et al. 2004) or indirectly by transporting the propagules of fungal that affect the soil nutrient availability (Lussenhop 1992) and releasing nutrients (Verhoef & Brussaard 1990; Filser 2002) through organic decomposition.

Studies documented the effect of vegetation on soil macrofauna abundance and diversity (Pauli et al. 2011; Kamau et al. 2017). The diversity of canopy trees can shelter different species by promoting the emergence of different microhabitats (Cavard et al. 2011). For instance, the integration of different legume trees in AFS enhances the diversity and abundance of soil macrofauna (Kamau et al. 2017). Moreover, studies documented the effect of native shade tree species on soil macrofauna and thus on soil properties and quality (eg. Joshi et al. 2004; Oberthür et al. 2004; WinklerPrins & Barrios 2007; Asfaw & Zewudie 2021). Shade trees, in so called agroforestry systems (AFS), influence soil macrofauna by providing energy and matter via living and dead plant products such as leaf and root litter, dead wood, and rhizodeposition (Ganault et al. 2021).

Studies credited the importance AFS for increasing soil macrofauna abundance and diversity (e.g. Kamau et al. 2017; Asfaw & Zewudie 2021). AFS influences the activity, abundance, and diversity of soil microfauna through the availability of plant litter and modification of the microclimate of the system (Singh et al. 2012; Martin-Chave et al. 2019). Moreover, trees in AFS modify the local microclimate, reducing day air temperature (Moat et al. 2017) and light intensity (Muschler 1998), intercepting the rainfall (Vaast et al. 2015) and increasing crop productivity. Trees and soil macrofauna play a critical role in increasing the resilience and adaptation of the coffee farming system to climate change and variability (Coltri et al. 2019). However, soil macrofauna activities are influenced by elevation, soil characteristics, plant litter fall (Castro-Huerta et al. 2015), and land use practices (Asfaw & Zewudie 2021).

In general, several studies have shown the importance of shade trees in protecting crops from extreme weather conditions and improving their growth. For instance, shade trees protect coffee plants from rising temperatures (Hirons et al. 2018), increase nutrient cycling and soil organic matter and increase coffee quality (Perfecto et al. 2007; Lunz et al. 2005). Campanha et al. (2004) indicated that shade trees also impact coffee quality because of more uniform maturation under shade. DaMatta (2004) further explained that as a consequence of fewer flowers under the shade tree, enlarged coffee bean size, and fewer fruits exist per plant.

Ethiopia is the home of shade-demanding Arabica coffee with high genetic diversity (Daba et al. 2023), mainly produced by smallholder farmers in the home garden or AFS (Jawo et al. 2023). In 2019/2020, the country's coffee production covered 538,000 ha of land with a total production of 447,000 tons (USDA 2020), with an estimated average yield of 0.64 ton per ha (Daba et al. 2023), which is lower compared to coffee yield 1.3 ton per ha in Brazil (Gomes et al. 2020). The low production in Ethiopia is attributed to a lack of infrastructure, an absence of improved coffee variety, and a lack of extension services (Daba et al. 2023).

Previous empirical studies documented the role of AFS in tree species diversity, soil fertility improvement and contributions to household livelihood improvement in Ethiopia (e.g. Birhane et al. 2020; Tadesse et al. 2021) and elsewhere in the tropics (De Beenhouwer et al. 2016; Asigbaase et al. 2021) but limited scientific evidence available on the significant effect of CAFS on soil macrofauna diversity and coffee yield. Asfaw & Zewudie (2021) also pointed out that few scientific studies investigated the effect of AFS on soil macrofauna diversity and abundance in east Africa. The diversities of soil macrofauna in CAFS compared to FSCS were less studied. Hence, the main objective of this study was to evaluate shade tree species' effect on soil macrofauna diversity and coffee yield in the CAFS of Southeastern, Sidama, Ethiopia.

Specifically, our objectives were to (i) assess soil macrofauna abundance and diversity along an elevation gradient, (ii) evaluate coffee yield and growth in different coffee production systems (CAFS and FSCS), (iii) evaluate the relationship between shade tree species diversity and soil macrofauna diversity. We hypothesized that CAFS could enhance the abundance and diversity of soil macrofauna. Moreover, season affects the diversity of soil macrofauna in the study region. Our finding can contribute to the knowledge and literature on shade species and soil macrofauna diversity in CAFS, which might help develop strategies for managing soil macrofauna and improving coffee productivity in the study region and elsewhere in East Africa.

3.4.2 Materials and methods

3.4.2.1 Study design

This study was conducted in Dale and Wensho districts in the Sidama region (Figure 2-1). The data were collected from three elevations: low (1,600 to 1,750 masl), mid (1,750 to 1,850 masl), and high (1,850 to 2,000 masl) elevations. The data were collected from both CAFS and FSCS. Accordingly, a total of 54 farms (18 farms from each elevation gradient) with an age of 10 to 12 years were selected randomly for the study, constituting 36 and 18 farms with CAFS and FSCS, respectively (Table 1). At each farm (20 m x 20 m), two plots (total 108 plots = 72 CAFS and 36 FSCS) were randomly laid down to conduct woody perennial plants (including coffee) and soil macrofauna inventory.

3.4.2.2 Data collection

At each sample plot, all woody perennials were identified and measured (total height, DBH). For soil macro-fauna data collection, a metal frame (25 x 25 cm x 10 cm depth) was placed in the soil, and the soil monolith was extracted and immediately placed in the bag. The data were collected from three samples per plot. The soil was hand-sorted, and macro-invertebrates (> 2mm) were extracted by tweezers, placed in a flask with ethanol (70 %) and labelled, where they can be stored until laboratory analysis. After sorting, the soil was returned to the sampling sites to minimize site degradation. Most of the tree species identified on the site using species keys such as Bekele & Tengnas (2007) and Ethiopia and Eritrea Flora (Hedberg & Edwards 1995; Hedberg & Edwards 2003). For those shade trees that could not be identified on the sites were taken to herbarium of Wondo Genet College of Forestry and Natural Resources, Hawassa University, Ethiopia, for species identification. Additionally, soil samples were taken for taxonomic identification of soil microfauna at the family level in the pathology laboratory of the same institution.

Coffee yield and growth parameters were measured in three 5x5 m subplots across the diagonal of the tree/shrub plot for a period of two years, 2020 and 2021. From each subplot, three coffee trees were randomly selected. From those, three branches (upper, middle, and lower part of the bush) were marked to measure different parameters, such as the branch per coffee plant, the number of leaves per coffee branch, the number of nodes per coffee branch, the coffee fruit per node, and an increment of the branch, stem length, and height. The sampled branches were counted, and the number of fruits per node per branch was identified. Bright red color (fully ripened) coffee was harvested and sun-dried until a constant weight (12%) was reached. Accordingly, the sundried coffee beans were weighed and grinded. Finally, the number of coffee yields harvested per plot (20 m x 20 m) was converted to ha to estimate coffee yield per ha.

3.4.2.3 Data analysis

Diversity indices (Shannon, Simpson and Fisher's alpha) were computed with EstimateS software version 9 (Colwell, 2013) to evaluate soil macrofauna species diversity. Relative abundance (RA) and relative frequency (RF) of soil macrofauna were calculated. The mean of two years was used to analyse coffee yield and growth under both coffee production systems (CAFS and FSCS).

All statistical analyses were done using Statistical Package for Social Science (SPSS) software version 21. A one-way analysis of variance (ANOVA) was used to test for significant sources of variation in shade and soil macrofauna species richness estimate and diversity along an elevation gradient. A General Linear Model (GLM) was run to evaluate the interaction effects between shade species and soil macrofauna Shannon diversity, and coffee yield, and stem density and coffee yield. The Pearson correlation coefficient was also used to measure the relationship between the Shannon diversity of shade trees and soil macrofauna. Least Significant Difference (LSD) post hoc was used to test the significant difference between the means across the elevations of the study regions.

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3.4.3 Results

3.4.3.1 Composition and abundance of soil macrofauna

The study indicated that the soil macrofauna community in the study area was dominated by Pontoscolex, Centipede, and Millipede, followed by beetle larvae and beetle adult families. We identified eight families in the CAFS of Sidama. The families Crowsoniellidae, Glossoscolecidae, Lithobiidae, Scarabaeidae, Spirostreptidae were represented by 14.26%, while Formicidae and Platyarthridae were represented by 9.52% families each. In the study, a total of 459 and 240 individuals of soil macrofauna, respectively, were identified in CAFS and FSCS during the rainy season. On the other hand, 116 and 53 individuals, respectively, were identified in the CAFS and FSCS during the dry season (Table 6-1). Pontoscolex is highly abundant in the high (50.38%) and mid-elevation (36.90%), whereas Centipede is in the low elevation (48.10%) (Table 6-1).

Table 6- 1. Relative abundance (RA) and relative frequency (RF) of soil macrofauna families sampled in rainy and dry seasons from CAFS (n=72) and FSCS (n=36) of Sidama, south-eastern Ethiopia

			CAFS				FSCS			
			Rainy season		Dry season		Rainy season		Dry season	
Elevations	Common name	Family name	RA (%)	RF (%)	RA (%)	RF (%)	RA (%)	RF (%)	RA (%)	RF (%)
High	Beetle adult	Scarabaeidae	1.50	4.08	14.29	17.65	0.00	0.00	0.00	0.00
	Beetle larvae	Crowsoniellidae	8.27	12.24	22.45	20.59	32.93	24.32	12.50	17.65
	Earthworm	Lumbricidae	1.50	4.08	4.08	5.88	7.32	10.81	4.17	5.88
	Centipede	Lithobiidae	17.29	18.37	24.49	26.47	17.07	18.92	25.00	23.53
	Millipede	Spirostreptidae	21.05	20.41	10.20	11.76	13.41	18.92	8.33	11.76
	Pontoscolex	Glossoscolecidae	50.38	40.82	24.49	17.65	29.27	27.03	33.33	23.53
Mid	Ants	Formicidae	2.98	6.94	2.56	2.86	4.62	7.69	6.25	6.25
	Beetle adult	Scarabaeidae	0.60	1.39	7.69	8.57	1.54	2.56	18.75	18.75
	Beetle larvae	Crowsoniellidae	10.12	13.89	15.38	14.29	18.46	20.51	12.5	12.5
	Centipede	Lithobiidae	27.98	25.00	10.26	11.43	13.85	15.38	18.75	18.75
	Millipede	Spirostreptidae	19.64	18.06	20.51	20.00	26.15	20.51	25.00	25.00
	Platyarthrus	Platyarthridae	1.79	2.78	23.08	22.86	0.00	0.00	0.00	0.00
	Pontoscolex	Glossoscolecidae	36.90	31.94	20.51	20.00	35.38	33.33	18.75	18.75
	Termites	Rhinotermitidae	0.78	1.83	0.00	0.00	0.00	0.00	0.00	0.00
Low	Ants	Formicidae	3.80	4.76	17.86	12.00	18.28	20.00	7.69	9.09
	Beetle adult	Scarabaeidae	3.16	4.76	14.29	16.00	11.83	11.11	15.38	18.18
	Beetle larvae	Crowsoniellidae	8.23	11.11	10.71	12.00	13.98	17.78	23.08	27.27
	Platyarthrus	Platyarthridae	1.27	3.17	10.71	12.00	6.45	8.89	15.38	18.18
	Centipede	Lithobiidae	48.10	36.51	10.71	12.00	31.18	24.44	15.38	9.09
	Millipede	Spirostreptidae	10.13	12.70	0.00	0.00	0.00	0.00	0.00	0.00
	Pontoscolex	Glossoscolecidae	24.05	23.81	10.71	12.00	18.28	17.78	23.08	18.18

3.4.3.2 Soil macrofauna diversity

The mean (mean (±SD) of soil macrofauna Shannon diversity was higher for the rainy season than the dry season in both coffee production systems (Table 6-2). Soil Macrofauna Shannon diversity, Fisher Alpha, and Simpson (reverse) indices significantly differed among the studied elevations ($p < 0.001$) in the rainy season for the CAFS. No statistical significance ($p > 0.05$) was observed for coffee grown in FSCS in both seasons. The mean of soil macrofauna Shannon diversity of CAFS was higher than FSCS in the study area. Shannon diversity's mean (±SD) was slightly higher for the mid, followed by low and high elevations for both coffee production systems (Table 6-2).

Table 6- 2. Mean (± SD) soil macrofauna species diversity indices across an elevation gradient in CAFS and FSCS of Sidama, south-eastern Ethiopia

Coffee production systems	Sampling seasons	variables	Elevation			*F- value*	*P-value*
			High	Mid	Low		
CAFS (n=72)	Rainy season	Shannon diversity	1.44±0.13[a]	1.67±0.09[b]	1.61±0.10[b]	15.886	0.000
		Fishers' alpha	1.38±0.36[a]	1.63±0.37[b]	1.90±0.41[c]	76.681	0.000
		Simpson (reverse)	3.27±0.45[a]	4.35±0.37[b]	4.18±0.41[b]	40.841	0.000
	Dry season	Shannon diversity	1.34±0.15[a]	1.57±0.17 [b]	1.57±0.19 [b]	1.113	0.335
		Fishers' alpha	2.49±1.09 [a]	3.45±1.43 [b]	4.34±1.93 [a]	41.210	0.000
		Simpson (reverse)	4.08±0.55 [a]	4.69±0.66 [b]	4.84±0.74 [c]	3.120	0.050
FSCS (n=36)	Rainy season	Shannon diversity	1.36±0.14[a]	1.37±0.15[a]	1.50±0.15[b]	2.685	0.075
		Fishers' alpha	1.49±0.46[a]	1.90±0.58[b]	1.79±0.50[c]	20.693	0.000
		Simpson (reverse)	3.76±0.48[a]	3.67±0.47[a]	4.17±0.61[a]	5.809	0.005
	Dry Season	Shannon diversity	1.30±0.22[a]	1.35±0.26[a]	1.30±0.30[a]	0.238	0.790
		Fishers' alpha	3.20±1.36[a]	4.65±2.45[a]	5.61±3.37[a]	1.342	0.275
		Simpson (reverse)	3.56±0.69[a]	4.22±0.77[b]	3.83±0.88[c]	35.271	0.000

n number of sample plots. Similar letters show no significant differences, while different letters in a row show significant differences between elevations at a *5*% significance level.

3.4.3.3 Coffee yields and growth

The coffee yield (ton ha^{-1}) significantly varied along an elevation gradient in both growing systems, with CAFS (F= 5.83; *p* = 0.05) and FSCS (F = 7.94; *p* = 0.001). We found the highest mean coffee yield in the mid-elevation (0.43 ton/ha), followed by high (0.38 ton/ha) and low (0.37 ton/ha) elevations. The mean (±SD) of coffee yield was slightly higher for coffee grown in FSCS than CAFS (Table 6-3), but not statistically significant (*p* > 0.05). The mean (±SD) of most of the parameters determining the coffee growth was higher for coffee grows in FSCS (Table 6-3). A higher Dbh (cm) was observed in coffee growing in CAFS, but the height was slightly high for the coffee plant growing in FSCS.

Table 6- 3. Mean (± SD) of coffee yield and growth parameters in CAFS and FSCS of Sidama, south-eastern Ethiopia

Variables	Coffee production systems	
	CAFS	FSCS
Number of leaves per coffee branch	14.03±5.25	15.40±12.49
Number of nodes per coffee branch	17.19±6.97	19.05±12.00
Number of nodes having coffee fruit	7.11±3.40	7.93±6.63
Number of coffee fruit per nodes	34.43±20.93	27.44±21.62
Number of branches per coffee plant	28.61±9.19	32.78±12.07
Branch length (cm)	72.51±18.95	66.44±26.20
Dbh (cm)	3.53±1.69	3.11±1.06
Height of coffee plant (m)	2.86±0.83	2.92±0.98
Coffee yields (ton/ha)	0.39±0.06	0.4±0.07

3.4.3.4 The relationship between shade diversity, soil microfauna diversity and coffee yield

General linear model results showed that the Shannon index of shade tree species diversity significantly interacts with soil macrofauna diversity (t = 304.77; *p* < 0.001) and coffee yield (t = 10.35; *p* < 0.001) (Figure 6-1). The GLM result also indicated that there is a good interaction effect of soil macrofauna diversity on coffee yield (t = 5.39; *p* = 0.02). Our result also indicated that stem density has not significantly interacted with coffee yield (t = 0.06; *p* = 0.81). The Pearson correlation coefficient result also showed a strong relationship (r = 0.90; *p* < 0.001) between the Shannon shade diversity and soil macrofauna (Table 6-4). Also, there is a positive relationship (r = 0.36; p = 0.002) between Shannon shade species diversity and coffee yield (ton^{-1}) in CAFS. Our result indicated a moderate relationship (r = 0.28; *p* = 0.023) between coffee yield (ton^{-1}) and Shannon soil macrofauna diversity. Stem density (ha^{-1}) had a weak relationship with coffee yield (r = -0.03; *p* = 0.806).

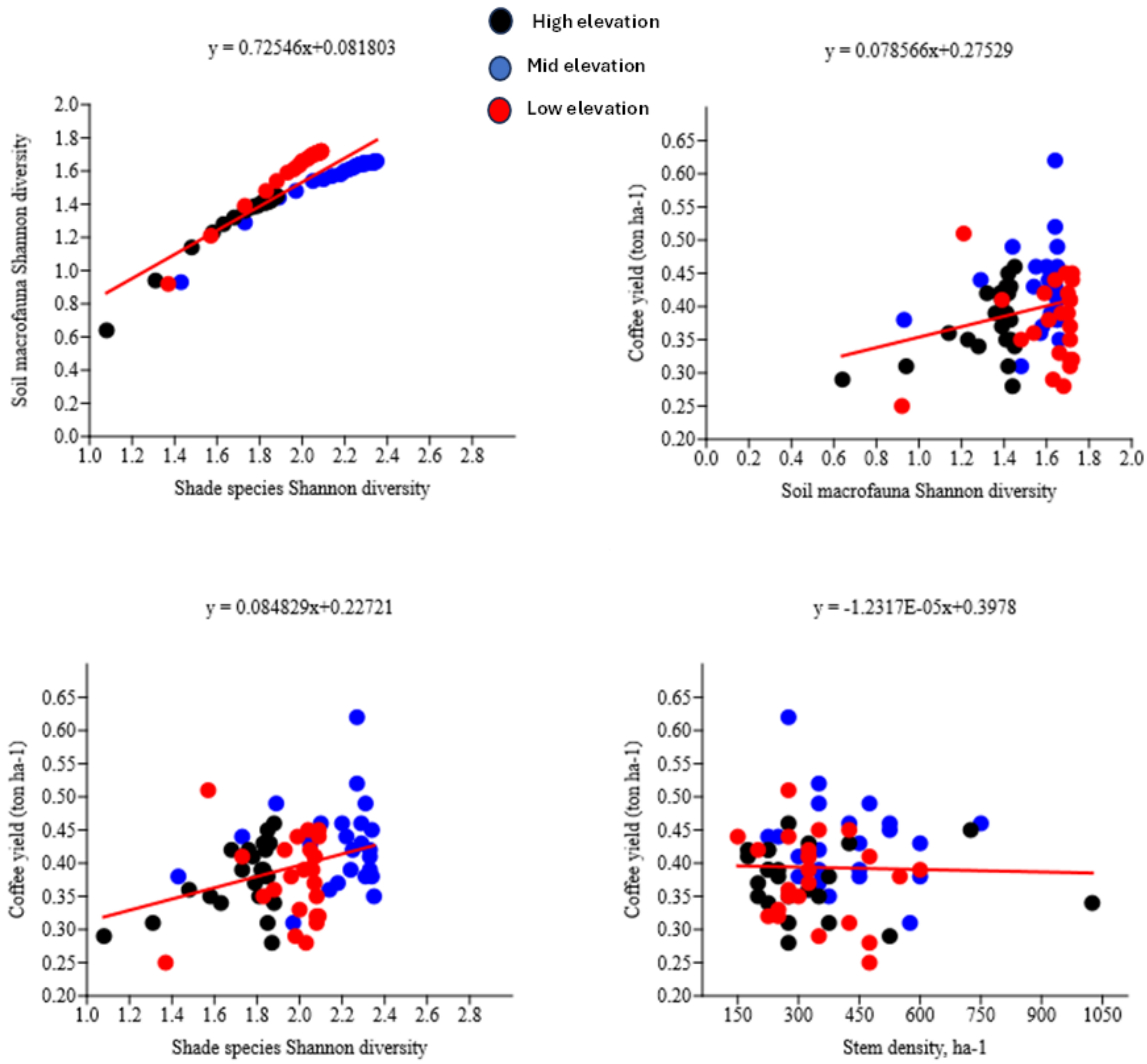

Figure 6- 1. The General Liner Model results on the interaction effect between shade Shannon diversity, soil macrofauna diversity and coffee across an elevation gradient in CAFS of Sidama, South-eastern Ethiopia

Table 6- 4. The relationship between shade species diversity, soil macrofauna species diversity and coffee yield in CAFS of Sidama, south-eastern Ethiopia

				Species diversity indices						
				Soil Macrofauna			Shade tree species			
	Species diversity indices		Elevation	Shannon diversity	Simpson (reverse	Fisher Alpha	Shannon diversity	Simpson (reverse	Fisher Alpha	Coffee yield (ton $^{-1}$)
Soil Macrofauna	Shannon Diversity	Pearson Correlation	.518**	1						
		P-value	.000							
		Sum of Squares and Cross-products	6.510	3.289						
		Covariance	.092	.046						
	Simpson (reverse)	Pearson Correlation	.576**	.947**	1					
		P-value	.000	.000						
		Sum of Squares and Cross-products	21.710	9.350	29.636					
		Covariance	.306	.132	.417					
	Fisher Alpha	Pearson Correlation	.830**	.201	.254*	1				
		P-value	.000	.090	.031					
		Sum of Squares and Cross-products	12.450	.789	2.990	4.684				
		Covariance	.175	.011	.042	.066				
Shade tree species	Shannon diversity	Pearson Correlation	.351**	.902**	.958**	.018	1			
		P-value	.003	.000	.000	.878				
		Sum of Squares and Cross-products	5.480	3.687	11.760	.090	5.082			
		Covariance	.077	.052	.166	.001	.072			
	Simpson (reverse)	Pearson Correlation	.362**	.711**	.882**	.096	.925**	1		
		P-value	.002	.000	.000	.423	.000			
		Sum of Squares and Cross-products	24.120	12.388	46.141	1.996	20.030	92.278		
		Covariance	.340	.174	.650	.028	.282	1.300		
	Fisher Alpha	Pearson Correlation	.341**	.866**	.919**	.072	.929**	.849**	1	
		P-value	.003	.000	.000	.547	.000	.000		
		Sum of Squares and Cross-products	9.760	6.480	20.642	.644	8.642	33.662	17.027	
		Covariance	.137	.091	.291	.009	.122	.474	.240	
	Coffee yield (ton $^{-1}$)	Pearson Correlation	.008	.267*	.313**	-.009	.359**	.381**	.320**	
		P-value	.946	.023	.008	.937	.002	.002	.006	
		Sum of Squares and Cross-products	.030	.258	.907	-.011	.431	.431	..704	.284
		Covariance	.000	0.004	.013	.000	.006	.006	.010	.004

3.4.4 Discussion

3.4.4.1 Composition and diversity of soil macrofauna

Land management systems affect soil macrofauna composition and diversity. For instance, the studies by Farska et al. (2014) show that managing forest ecosystems influences the composition and diversity of soil macrofauna through litter fall. Similar studies by Manhaes et al. (2013) support the argument that the distribution and composition of soil macrofauna are influenced by small farmers' land management systems and input resources such as litter and dead roots (Mutema et al. 2013; Asfaw & Zewudie 2021; Masebo et al. 2024), environmental condition and soil type (Lavelle et al. 2004).

Our results indicated a higher diversity and abundance of soil macrofauna in CAFS than in FSCS, similar to the studies of Masebo et al. (2024) and Asfaw & Zewudie (2021). Kamau et al. (2017) reported that the availability of legume trees and other tree species in AFS increases soil macrofauna abundance and diversity by providing shelter for them. Studies also documented that AFS promotes the abundance and diversity of soil macrofauna more than mono-culture agriculture (Pauli et al. 2011; Asfaw & Zewudie 2021), which could be attributed to the quality of litter on the surface (Manhaes et al. 2013) and the availability of organic fertilizers (Eyasu 2016). Several studies reported the mutual relationship between floristic diversity and soil macrofauna diversity (e.g. Manhaes et al. 2013; Eyasu 2016; De Valenca et al. 2017; Bufebo et al. 2021). Our result of the soil macrofauna diversity study was similar to several studies in the tropics (e.g. Ayuke et al. 2011; De Valenca et al. 2017; Zhou et al. 2022; Masebo et al. 2024), who reported that land practices with better vegetable cover associated with litter production influence composition and distribution of soil macrofauna. Several studies also credited that AFS influences the abundance and diversity of soil macrofauna (e.g. Singh et al. 2012; Martin-Chave et al. 2019).

Our study indicated that seasons and local climate influence soil macrofauna abundance and diversity. This is attributed to the availability of food, climatic factors, and soil physicochemical properties (Asfaw & Zewudie 2021). Studies documented that high soil moisture favors the diversity and composition of soil invertebrates (Pauli et al. 2011). The wet season is characterized by high soil moisture, which may have contributed positively to increasing the abundance and biomass of either earthworms and/or litter-dwelling microarthropods (Asfaw & Zewudie, 2021). Fernandes et al. (2013) highlight that the mobility of soil fauna is high in coffee farms during the rainy season. Wiwatwitaya & Takeda (2005) described that changes in season, temperature, rainfall amount, and elevation affect the population of soil invertebrates.

3.4.4.2 Effect of shade species on coffee yield and growth

Our result indicated that most of the parameters (Table 6-3) determining the coffee growth and yield were slightly higher for coffee grows in the FSCS. This is attributed to the competition between shade trees and coffee plants. Studies reported that integrating shade species in coffee farms leads to some degree of competition for light, water, and nutrients (Lin et al. 2010; Sebuliba et al. 2022) due to variations in canopy and root architectures. Studies also reported that shade species consume the available nutrients for their growth and development (Schnabel et al. 2018), and trees compete with coffee plants for soil nutrients and moisture (Sileshi et al. 2020; Sebuliba et al. 2022). This reduced coffee yield and growth under shade trees compared to those FSCS. Studies also reported that Arabica coffee grown in CAFS produces a lower yield than those grown in FSCS (e.g. Kufa & Burkhardt 2013, Cerda et al. 2017). High shade levels reduce coffee fruit loads, reducing yield because of longer internodes, fewer nodes, lower flower induction, and larger bean size (Jawo 2022). Under a shaded tree, the initiation of flora depends on light conditions and fewer flowers are developed. Several studies reported significant differences in coffee bean size between coffee grown in CAFS and FSCS (eg. Muschler 2001; Vaast et al. 2006). With increasing shade levels, the coffee bean size consistently increases even with increasing shade levels (Muschler 2001).

However, shade trees in the coffee farm have potential benefits, such as reducing air, soil, and leaf surface temperature (Ricci et al. 2013). Shade trees significantly increase coffee production stability by protecting coffee plants from strong wind and rain (Alvarenga et al. 2004) and increase soil organic matter and nutrient cycling (Campanha et al. 2007). A review by Jawo et al. (2023) pointed out that the shade tree species positively and negatively impact coffee growth and yield. For instance, the positive effects are managing local microclimate by reducing temperature and light intensity and increasing humidity and plant organ wetness. On the other hand, the authors found that shade species decrease coffee yield due to competition with light, water and soil nutrients. Jawo et al. (2023) concluded that while shade species complement coffee plants, they help smallholder farmers produce climate-resilient coffee and high production stability in the face of CC and variability. Moreover, shade trees help smallholder coffee producers to diversify products and gain financial incentives from REDD+

(Rahn et al. 2014) during low coffee prices and yield failure due to climate change and pest and disease occurrences (Jawo et al. 2023).

In our study area, coffee yield was more affected by elevation gradients. The increasing temperature and shortage of rainfall decrease coffee yield and growth in the low elevation of our study area. Jawo et al. (2023) studies indicated that the small farmers in the study area have started to reduce coffee bush density and shade trees to plant drought-resistant crops, like khat (*Catha edulis*). (Moat et al. 2017) conclude that CC results in increasing temperature and erratic rainfall, decreasing coffee yield and growth in the low elevation areas.

3.4.4.3 Effect of shade species diversity on soil macrofauna and coffee yield

Our study indicated a strong relationship between shade species and soil macrofauna diversity. Our study is consistent with (Cavard et al. 2011), who reported that the diversity of tree species promotes different macrofauna that can provide shelter for different species. Similarly, Scheu et al. (2003) and Salamon et al. (2008) studies described a higher diversity of soil organisms in mixed stands than in the monoculture plantation. Korboulewsky et al. (2016) stated that high plant diversity increases litter mixtures that enhance the diversity of soil macrofauna more than mono-specific litter. Hansen & Coleman (1998) reported that the availability of litter diversity in mixed stands favors the heterogeneity of soil microhabitats. A review by Korboulewsky et al. (2016) described that mixed stands positively affect microarthropod diversity due to the diversity of plant litter with more varied microhabitats. The author further explained that tree richness in mixed stands increases the abundance of earthworms than in monoculture stands. A similar study by Rodríguez & Salazar (2021) described that AFS with high plant diversity promoted the soil macrofauna to a greater extent, contributing to the system's resilience.

Our result indicated that soil macrofauna diversity positively affects coffee yield and growth. Soil macrofauna enhances soil fertility and increases crop yield in AFS. Several studies documented the importance of soil macrofauna in improving soil fertility and maintenance, increasing crop yield (e.g Oberthür et al. 2004; Asfaw & Zewudie 2021). Soil macrofauna provides valuable services, increases soil aeration and root plant penetration and increases water infiltration (Gilibert et al. 2022), improves cation exchange, mineralization, organic matter and nutrient cycling (Ofenberg 2015), which further increases crop yield and growth. Studies concluded that soil macrofauna like earthworms improve the chemical and physical conditions of plant growth and are involved in driving the process of ecosystems and enhancing the performance of the ecosystem (Lavelle et al. 2016).

3.4.5 Conclusion

We focused on the effect of shade species on soil macrofauna diversity and coffee yield along elevation gradients (1600–2000 masl). Our results have shown a higher diversity and abundance of soil macrofauna at the family level in CAFS than in FSCS, particularly in the wet season, implying that soil moisture determines the seasonal dynamics of soil macrofauna. The coffee grown under shade species yields less than coffee grown in FSCS due to the competition for resources (light, water and nutrients) between shade trees and coffee plants. We found a strong relationship between shade species and soil macrofauna diversity because shade species promote macrofauna by providing food and shelter for different species. Soil macrofauna in CAFS also improves the soil's fertility status by decomposing organic matter, which in turn enhances the system's sustainability. Shade species in CAFS with high plant diversity promote the soil macrofauna, contributing to the system's resilience. Hence, policymakers should support smallholder farmers in maintaining native shade species in coffee farms to adapt and mitigate the effects of CC, however the proper management of those shade trees has to be also establish to minimize their competition with coffee plants.

4 Discussion and concluding remarks

Coffee production attains high yield and quality at optimal temperature and rainfall. The narrow bio-climatic nature of Arabica coffee makes it sensitive to increasing temperature and drought. It also further reduces the land suitability of Arabic coffee and causes yield losses (Killeen & Harper 2016). Moreover, it resulted in the extinction of its wild population in East Africa, particularly in Ethiopia (Davis et al. 2012), which is the origin of the Arabica coffee gene pool and center of diversity (Aerts et al. 2017). Moreover, green coffee beans grown in Ethiopia are one of the best natural qualities in the world. However, deforestation, forest fragmentation and land degradation threaten the genetic diversity of coffee (Aerts et al. 2017), and CC shrinks the land suitability for coffee if adaptation measures are not taken. Consequently, failure to implement adaptation strategies in the coming decades will threaten millions of hectares of coffee farms, affecting the livelihoods of millions of smallholder farmers. Hence, adaptation is a valuable option for smallholder farmers to minimize the adverse impact of CC and conserve the genetic resources of coffee, particularly in low-elevation areas. Due to prolonged drought and erratic rainfall in the lower elevation areas, coffee production is abandoned and replaced by drought-resistant crops (like *Catha edulis*) grown in monocultures. The expansion of monoculture crops in the low-elevation areas challenges biodiversity conservation and reduces the genetic resources of Arabica coffee.

Managing and conserving the genetic resources of Arabic coffee is critical to advancing variety development, particularly concerning maintaining quality in drought-tolerant varieties that perform well under variable environments. Hence, CAFS or tree-based coffee production is one of the viable options for adapting coffee to increasing temperatures, erratic rainfall and extensive drought. The management of CAFS for biodiversity conservation needs huge efforts. It should be supported by technical knowledge and extension services that use participatory methods to teach farmers how to implement and manage AFS that are compatible with conserving biodiversity and the genetic resources of coffee.

4.1 Key findings and their linkages

This study focuses on the impact of CC on coffee production, farmers' perception of CC and their adaptation strategies, and the potential of the coffee production system in biodiversity conservation and sequestering carbon in the above and belowground biomass. Moreover, it highlighted the opportunity for additional carbon benefits for coffee-growing smallholder farmers from C crediting schemes. It also attempted to link shade species diversity, soil macrofauna and coffee yield. Thus, this study hypothesized that CAFS could enhance local people's adaptive capacity to CC and mitigate CC by sequestering carbon in the above and below ground while conserving biodiversity. The main empirical findings and future research prospects are proposed to enhance the productivity and benefits of CAFS, improving smallholder farmers' livelihoods in the face of climate change and variability.

Smallholder farmers who own small land areas and depend on agriculture for income and food security are more vulnerable to CC due to low agricultural productivity, capital, and adaptive capacity. Climate changes have increased temperature and rainfall variability, resulting in shrinking areas suitable for coffee growing and increasing the prevalence of pests and diseases. Our review paper showed that 90% of coffee-growing areas in the study region would become unsuitable for coffee by 2080. Hence, incorporating shade trees into coffee production is the main adaptation strategy implemented by smallholder farmers to reduce the impact of CC and variability on coffee.

Our findings confirm the hypothesis that the farmers perceived the features of CC indicators (such as rising temperature and erratic rainfall) and the impacts of CC on coffee production and practised different adaptation strategies. Smallholder coffee producer farmers were keenly concerned about rising temperature and erratic rainfall and their effects on coffee production. Our meteorological data also confirmed an increasing temperature and erratic rainfall trend for the last three decades. Farmers' perceptions of CC differed among the three elevations. Low-elevation farmers perceived the effects of CC more than mid- and high-elevation farmers because they experienced a higher frequency of drought periods and erratic rainfall. In the low-elevation areas, the coffee suitability areas and coffee yields decreased, forcing the farmers to replace coffee with other drought-resistant crops to adapt to CC, which is impacting shade tree cover and, consequently, reducing biodiversity at the farm. As we hypothesized, the farmers in the study areas use different strategies to adapt to the impacts of CC on coffee yields, such as agroforestry practices, organic manure/compost, soil conservation, changing farming calendar, and crop diversification. Our studies indicated that no difference was detected in the adaptation strategies applied by farmers in different elevations. The most significant factors influencing farmers' perception of CC and their adaptation practices are education, farming experiences, family size and access to extension services. Poor soil fertility, land shortage, lack of weather information, and lack of credit access have been identified as the key challenges to adapting to CC. Also, farmers rely only on traditional knowledge to adapt to CC. Hence, policymakers should design and support farmers' efforts by intensifying the existing agroforestry system, motivating farmers to integrate and maintain native shade tree species, building farmers' capacity via training, and increasing access to credit and the market.

As hypothesized, CAFS in the study region maintained higher perennial species diversity and C stocks. The perennial species Shannon diversity index significantly differed among the studied elevations and was higher for the mid, followed by high and low elevations. Variations in species composition and diversity between regions could be due to the differences in farmers' preference for tree species, farm size, socioeconomic issues, farmers' management approach, and agroclimatic variation. Moreover, mid-elevation maintained high species diversity because of farmers' farm management, farm history and large-scale coffee production. CAFS had significantly higher ecosystem C stocks than FSCS. The shade tree species in CAFS in the study area are deciduous, shedding their leaves during the dry period, increasing litter decomposition and nutrient cycling. This resulted in sequestering more C in plant biomass and soil. C stocks in the biomass (above and below) and soil in CAFS significantly varied along an elevation gradient. In both types of growing systems, the highest C stocks were found in the soil, followed by biomass, fine root and litter. However, a weak relationship between the Shannon diversity index and biomass C was observed, which is against to our hypothesis. The ecosystem C stocks in CAFS were higher than those in FSCS. CAFS has a greater potential to accumulate C, conserve biodiversity, and provide additional benefits from C crediting schemes than FSCS.

Moreover, as hypothesized, we found higher diversity and abundance of soil macrofauna in the CAFS than in the FSCS. CAFS promotes the abundance and diversity of soil macrofauna more than FSCS. This could be attributed to the quality of litter on the surface and the availability of organic fertilizers. Soil macrofauna abundance and diversity vary between seasons. The high abundance and diversity of soil macrofauna in the wet season imply that soil moisture determines the seasonal dynamics of soil macrofauna. There was also a strong relationship between shade species and soil macrofauna diversity. However, the coffee yield was lower, but not significantly, under shade species compared to FSCS. The integration of shade species in coffee farms leads to competition for light, water, and nutrients due to variations in canopy and root architectures. Shade species consume the available nutrients for their growth and development and trees compete with coffee plants for soil nutrients and moisture. High shade levels reduce fruit loads, resulting in lower yield because of longer internodes, fewer fruiting nodes and lower flower induction.

In general, our present scientific study evidence leads to the expectation that AFS has an indispensable role in climate mitigation and adaptation, particularly for smallholder coffee producers. Smith & Olesen (2010) described the win-win option of mitigation and adaptation, as mitigation measures enhance soil organic matter, which further improves soil health and quality. So, it enhances crop yield in AFS and also plays a crucial role in enhancing the adaptive capacity of the soil. Agroforestry generates multiple environmental, and livelihood benefits and helps farmers adapt to variable and extreme weather. CAFS is an innovative practice to increase coffee productivity and income diversification in a way that often contributes to CC mitigation through enhanced carbon sequestration in both plant biomass and soil, and that can also strengthen the ability of the system to cope with the adverse impacts of CC and variability. CAFS plays an essential role in the conservation of native plant species that are compatible with coffee plants, mitigating increasing CO_2 concentration, improving and maintaining soil fertility and providing habitat for biodiversity. Shade can reduce coffee crops against microclimatic extremes that will likely become more prevalent in a changing climate and reduce drought stress. Organic matter inputs from trees, shrubs and crops in CAFS improve soil fertility and microbial diversity. The microbial diversity in CAFS enhances the soil fertility of status of the systems by decomposing organic matter. Hence, CAFS provides broader ecosystem services, which, in turn, help the farmers produce climate-resilient coffee to sustain the system that increases income in the face of CC and variability. Also, the management of shade trees in CAFS systems helps farmers diversify their incomes and benefit from C financing. Hence, establishing CAFS for biodiversity conservation, income diversification, climate adaptation, and mitigation requires huge efforts. It requires support from specialized extension services that use participatory methods to teach farmers how to implement and manage shade species that are compatible with conserving biodiversity and increasing coffee production.

4.2 Recommendations and future research perspectives

In the current CC context, CAFS systems managed by smallholder farmers play a pivotal role in biodiversity, CC mitigation, and adaptation. Hence, empirical research is needed to determine the optimal shade level for coffee production in each elevation. To mitigate the impact of CC on coffee production in low-elevation areas, more research and extension services are needed to reduce the impact of CC on coffee production and develop drought-resistant coffee varieties. Also, enhancing the capacity of farmers with CC change adaptation strategies and facilitating credit for farmers to use water harvesting technologies and promoting irrigation. Moreover, more research will be needed to evaluate the reduction of coffee land suitability for the study region using remote sensing. On the other hand, coffee will migrate to higher-elevation areas to compensate for the increased temperature and shortage of rainfall in the lower elevations. The migration of coffee to higher-elevation areas challenged the local ecosystem management and the production of food crops. Consequently, empirical research will be needed to identify and assess the synergies and trade-offs with the existing land use in the higher elevation areas. Owing to smallholder farmers' contribution to biodiversity conservation and CC mitigation on the agricultural landscape in the study region, their efforts should be incentivized through payment for ecosystem services and C crediting schemes. The government should encourage the farmers to boost production, for instance, through technical advice on shade trees, pests and diseases and soil management. Moreover, rewarding groups of farmers by introducing certification schemes will contribute to the conservation of shade tree species, increasing coffee productivity. Finally, policymakers should support smallholder farmers in maintaining native shade species in coffee farms to sustain coffee production while adapting and mitigating CC.

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6 Appendices A

Appendix A Table 1: Household survey questionnaires

Appendix Table 1 (a): Farmers' perceptions of climate change

S/N	Variables	Rating				
		0	1	2	3	4
1	Rising temperature					
2	Number of hot days increased					
3	Number of warm nights increased					
4	Increased the coldness of cold seasons					
5	Increased rainfall intensity					
6	Decreased rainfall					
7	Uncertainty of the rainfall distribution					
8	Cesation of rinfall become unpredictable					
9	Late onset of rainy season					

0 = Strongly disagree, 1 = Disagree, 2 = Neutral, 3 = Agree, 4 = Strongly agree

Appendix A Table 1 (b): Perceived impact of climate variables on coffee production

S/N	Items	Rating				
		0	1	2	3	4
1	Decreased yield					
2	Late ripening					
3	Loss of coffee berries					
4	Death of coffee plant					
5	Increased coffee pest and diseases					
6	Decreased coffee bush density					

0 = Strongly disagree, 1 = Disagree, 2 = Neutral, 3 = Agree, 4 = Strongly agree

Appendix A Table 1 (c): Farmers' adaptation strategies to climate change

S/N	Adaptation strategies	Rating				
		0	1	2	3	4
1	Agroforestry/planting trees					
2	Mulching					
3	Change farming calendar					
4	Change crop varieties					
5	Crop diversification					
6	Planting resistance variety					
7	Application of organic compost/manure					
8	Application of inorganic fertilizer					
9	Application of herbicides/insecticides					
10	Fodder tree planting					
11	Soil conservation					
12	Water harvesting					
13	Use irrigation					
14	Selling of livestock					
15	Migration					

0 = Strongly disagree, 1= Disagree, 2 = Neutral, 3 = Agree 4 = Strongly agree

Appendix A Table 1 (d): Farmers' adaptation barriers to climate change

S/N	Barriers to adaptation	Rating				
		0	1	2	3	4
1	Education level					
2	Shortage of land					
3	Poor soil fertility					
4	Shortage of farm inputs					
5	Lack of weather information					
6	Lack of agricultural extension services					
7	Lack of credit/money					
8	Lack of tree seedlings					
9	Lack of water					
10	Lack of agricultural labor					

0 = Strongly disagree, 1= Disagree, 2 = Neutral, 3 = Agree 4 = Strongly agree

Appendix A Table 2: Respondents' socioeconomic and demographic characteristics

		Frequency	Percent
Gender			
	Female	78	22.2
	Male	273	77.8
Age			
	30-40	98	27.9
	41-60	231	65.8
	>60	22	6.3
Education			
	No education	156	44.4
	Primary school (Grade 1-4)	110	31.3
	Elementary school (Grade 5-8)	50	14.2
	High school (Grade 9-10)	23	6.6
	Preparatory (Grade 11-12)	12	3.4
Farming experience			
	0-10 years	17	4.8
	11-20 years	91	25.9
	21-30 years	148	42.2
	>30 years	95	27.1
Membership in formal institutions			
	No	131	37.3
	Yes	220	62.7
Radio ownership			
	No	120	34.2
	Yes	231	65.8
Access to agricultural extension			
	No	53	15.1
	Yes	298	84.9
Access to farmer to farmer extension			
	No	178	50.7
	Yes	173	49.3
Access to credit service and sources			
	No	212	60.4
	Yes	139	39.6
Access to weather information			

	No	219	62.4
	Yes	132	37.6
Average family size	6.33		
Average age of the respondents	46.36		
Average land holding size (ha)	0.86		
Average area under coffee production (ha)	0.47		
Average annual income (US$)	595.29 US$		
Average Annual income from coffee production (US$)	412 US$		

Appendix A Table 3: List of the shade tree species and other perennial plant species relative abundance (R.A), relative dominance (R.D), relative frequency (R.F) and importance value indices (IVIs) along an elevation gradient in the CAFS of South-eastern Ethiopia (n=72)

Elevation	Species	Family name	Local name	origin	Form	Source	Product	N	RA (%)	R.D (%)	R.F (%)	IVI
High	Albizzia gummifera (Gmel.) C.A.Sm	Fabaceae	Matticho	I	T	Reg	SH, SF, M	3	0.95	0.36	3.19	4.50
	Cordia africana Lam	Boraginaceae	Wadicho	I	T	Reg	SH, SF, T, LF, BF, M	28	8.83	7.84	10.64	27.31
	Erythrina abyssinica Lam. Ex	Fabaceae	Welako	I	T	Pln	SH, M, LF	2	0.63	0.27	2.13	3.03
	Euphorbia abyssinica Gmel	Euphorbiaceae	Charichu	I	T	Pln	LF, M	2	0.63	0.39	2.13	3.15
	Fagaropsis angolensis (Engl.) Del	Rutaceae	Godicho	I	T	Reg	FW, T, M	1	0.32	0.21	1.06	1.59
	Ficus sur Forrsk	Moraceae	Odako	I	T	Reg	SH,	11	3.47	6.80	6.38	16.65
	Ficus vasta Forrsk	Moraceae	Odao	I	T	Reg	SH, FW, T, LF	16	4.86	9.64	8.00	22.5
	Grevillea robusta A. Cunn	Protaceae	Gravila	E	T	Pln	SH, T	6	1.89	1.97	4.26	8.12
	Millettia ferruginea (Hochst.)	Fabaceae	Hengedich	I	T	Reg	SH, SF, LF, BF, M	124	39.12	27.20	21.28	87.59
	Musa paradisiaca L	Muzaceae	Muze	I	NWP	Pln	F	78	24.61	17.01	11.70	53.32
	Persea americana	Lauraceae	Abukato	E	T	Pln	FT	13	4.10	12.95	8.51	25.56
	Podocarpus falcatus (Thunb.)	Podocarpaceae	Dagucho	I	T	Reg	SH, T, FW, M	23	7.26	14.33	9.57	31.16
	Polyscias fulva (Hiern.) Harms	Araliaceae	Kobre	I	T	Reg	FW, T, M	10	3.15	0.89	4.26	8.30
	Prunus africana (Hook.f.)	Rosaceae	Garbicho	I	T	Reg	SH, FW, T, M	5	1.58	0.71	4.26	6.55
	Ocotea kenyensis Kosterm	Lauraceae	Shoicho	I	T	Reg	FW, T, M	4	1.26	5.34	4.26	10.86
	Sapium ellipticum (Hochst.) Pax	Euphorbiaceae	Gancho	I	T	Reg	FW	5	1.58	3.36	4.26	9.19
	Sesbania sesban L. Merr	Papilionoidaea	Suspania	E	SH	Pln	SH, SF, FW, F	4	1.22	0.04	1.00	2.26
	Syzigumm guineense (Wild.) DC	Myrtaceae	Duwancho	I	T	Reg	SH, M	1	0.32	0.33	1.06	1.71
	Vernonia amygdalina Del	Asteraceae	Hecho	I	T	Reg	FW, LF, SF, LF, M	1	0.32	0.03	1.06	1.41
	Vernonia auriculifera Hierm	Asteraceae	Rejicha	I	SH	Reg	FW, M	5	1.25	0.05	1.38	2.68
Mid	*Albizzia gummifera* (Gmel.) C.A.Sm	Fabaceae	Matticho	I	T	Reg	SH, SF, M	32	8.04	18.06	10.32	36.41
	Azadirachta indica	Meliaceae	Gudacho	E	T	Pln	SH, FW, M, T	1	0.25	0.05	0.79	1.10
	Bersama abyssinica Fresen	Melianthaceae	Xewerako	I	SH	Reg	FW, F	13	3.27	2.15	7.14	12.56
	Cordia africana Lam	Boraginaceae	*Wadicho*	I	T	Reg	SH, SF, T, F	84	21.11	32.47	14.29	67.86
	Croton macrostachys Hochst	Euphorbiaceae	Mesincho	I	T	Reg	FW, SF	6	1.51	0.03	3.17	4.71
	Ekebergia capensis Sparrman	Meliaceae	Olonchoo	I	T	Reg	SH, FW, T, SF, BF	10	2.51	0.06	1.59	4.16
	Euphorbia abyssinica Gmel	Euphorbiaceae	Charichu	I	T	Pln	FW, F	13	3.27	1.80	3.17	8.24
	Fagaropsis angolensis (Engl.) Del	Rutaceae	Godicho	I	T	Reg	FW, T	4	1.01	0.45	3.17	4.63
	Ficus sur Forrsk	Moraceae	Odako	I	T	Reg	SH, T	1	0.25	0.12	0.79	1.16
	Grevillea robusta A. Cunn	Protaceae	Gravila	E	T	Pln	SH, T, FW, BF	9	2.26	0.55	3.17	5.99
	Leucaena leucocephala (Lam.)	Mimosoideae	Lucinea	E	SH	Pln	SF, F, BF, FW	4	1.01	0.08	2.38	3.46
	Mangifera indica	Anacardiaceae	Mango	E	T	Pln	F, FW, BF, SH	6	1.51	0.27	2.38	4.15
	Millettia ferruginea	Fabaceae	Hengedich	I	T	Pln	SH, FW, T	104	26.13	26.83	18.25	71.21
	Musa paradisiaca L	Muzaceae	Muze	I	NWP	Pln	F	44	11.06	4.34	5.56	20.95
	Persea americana	Lauraceae	Abukato	E	T	Pln	F, SH	7	1.76	3.68	3.17	8.61
	Phoenix reclinata Jack	Arecaceae	Saticho	I	NWP	Pln	T (local doors)	4	1.01	0.14	0.79	1.93
	Afrocarpus falcatus (Thunb.)	Podocarpaceae	Dagucho	I	T	Reg	SH, FW, T	23	5.78	8.57	7.94	22.29
	Sesbania sesban L. Merr	Fabaceae	Suspania	E	SH	Pln	SH, SF, FW, F	13	3.27	0.70	3.97	7.94
	Vernonia amygdalina Del	Asteraceae	Hecho	I	T	Reg	SF, LF, FW, M, F	14	3.52	0.30	4.76	8.58

	Vernonia auriculifera Hierm	Asteraceae	Rejicha	I	SH	Reg	FW, M	5	1.26	0.06	2.38	3.69
	Fagaropsis angolensis (Engl.) Del	Rutaceae	Gobicho	I	T	Reg	FW	1	0.25	0.01	0.79	1.06
Low	*Acacia seyal* Del	Febaceae	Wacho	I	T	Reg	SH, SF, F, FW	1	0.30	0.45	1.00	1.75
	Albizzia gummifera (Gmel.) .CA.Sm	Fabaceae	Matticho	I	T	Reg	SH, SF, M	6	1.82	0.65	3.00	5.47
	Cordia African	Boraginaceae	Wadicho	I	T	Reg	SH, SF, T, F	121	36.78	50.47	24.00	111.25
	Croton macrostachys Hochst	Euphorbiaceae	Mesincho	I	T	Reg	FW, SF	4	1.22	0.99	3.00	5.21
	Ehretia cymosa Thonn	Boraginaceae	Gidincho	I	SH	Reg	FW, T, F	4	1.22	0.05	2.00	3.27
	Ekebergia capensis Sparrman	Meliaceae	Olonchoo	I	T	Reg	SH, FW, SF, T	1	0.30	0.27	1.00	1.57
	Euphorbia abyssinica Gmel	Euphorbiaceae	Charichu	I	T	Pln	FW, F	9	2.74	1.16	4.00	7.9
	Fagaropsis angolensis (Engl.) Del	Rutaceae	Godicho	I	T	Reg	FW, T	1	0.30	0.04	1.00	1.34
	Ficus sur Forrsk	Moraceae	Odako	I	T	Reg	SH, T	5	1.52	0.63	3.00	5.15
	Ficus thonningii BI.	Moraceae	Dinbicho	I	T	Reg	LF, M	5	1.52	0.90	3.00	6.66
	Grevillea robusta A. Cunn	Protaceae	Gravila	E	T	Pln	SH, T, FW, BF	13	3.95	2.92	7.00	13.87
	Millettia ferruginea	Fabaceae	Hengedich	I	T	Pln	SH, FW, T	57	17.33	9.05	15.00	41.38
	Musa paradisiaca L	Muzaceae	Muze	I	NWP	Pln	F	45	13.68	14.22	4.00	31.9
	Persea americana	Lauraceae	Abukato	E	T	Pln	F, SH	12	3.65	7.62	8.00	19.27
	Sesbania sesban L. *Merr*	Febaceae	Suspania	E	SH	Pln	SH, SF, FW, F	4	1.22	0.04	2.00	3.26
	Sapium ellipticum (Hochst.) Pax	Euphorbiaceae	Gancho	I	T	Reg	FW	1	0.30	0.02	1.00	1.32
	syzygium guineense (Wild.) DC	Myrtaceae	Duwancho	I	T	Reg	Fw, T, BF, M	2	0.61	0.22	2.00	2.83

Note: I Indigenous; T Tree; Reg Regnerated; Pln Planted; N Number of individuals; SH Shade; SR Soil Fertility; T Timber; M Medicine; LF Livestock Feed; BF Bee Forage; LF Live Fence; FW Firewood; NWP Non-wood product; F Firut Tree

Appendix A Table 4: The top 10 shade trees and other perennial plant species and their relative abundance (R.A), relative dominance (R.D), relative frequency (R.F), importance value indices (IVI) and their relative share of C stocks in each elevation category of CAFS of Sidama, South-eastern Ethiopia (n=72)

Elevation	Species	Family name	Local name	R.A (%)	R.D (%)	R.F (%)	IVI	C stocks %
High	*Millettia ferruginea* (Hochst.)	Fabaceae	Hengedich	39.12	27.20	21.28	87.59	34.61
	Persea americana	Lauraceae	Abukato	4.10	12.95	8.51	25.56	10.59
	Ocoteakenyensis Kosterm	Lauraceae	Shoicho	1.26	5.34	4.26	10.86	8.79
	Afrocarpus falcatus (Thunb.)	Podocarpaceae	Dagucho	7.26	14.33	9.57	31.16	8.49
	Ficus sur Forrsk	Moraceae	Odako	3.47	6.80	6.38	16.65	7.80
	Cordia africana Lam	Boraginaceae	Wadicho	8.83	7.84	10.64	27.31	6.29
	*Grevillea robusta*A. Cunn	Protaceae	Gravila	1.89	1.97	4.26	8.12	6.10
	Sapium ellipticum (Hochst.) Pax	Euphorbiaceae	Gancho	1.58	3.36	4.26	9.19	5.95
	Albizzia gummifera (Gmel.) C.A.Sm	Lauraceae	Shoicho	1.58	0.71	4.26	4.50	4.54
	Prunus African	Rosaceae	Garbicho	1.26	5.34	4.26	6.55	2.77
	Proportion of total C							**95.93%**
Mid	*Millettia ferruginea* (Hochst.)	Fabaceae	Hengedich	26.13	26.83	18.25	71.21	22.04
	Cordia africana Lam	Boraginaceae	*Wadicho*	21.11	32.47	14.29	67.86	16.38
	Persea americana Lam	Lauraceae	Abukato	1.76	3.68	3.17	8.61	11.13
	Albizzia gummifera (Gmel.) C.A.Sm	Fabaceae	Matticho	8.04	18.06	10.32	36.41	10.11
	Afrocarpus falcatus (Thunb.)	Podocarpaceae	Dagucho	5.78	8.57	7.94	22.29	8.76
	Ekebergia capensis Sparrman	Meliaceae	Olonchoo	2.51	0.06	1.59	4.16	7.06
	Euphorbia abyssinica Gmel	Euphorbiaceae	Charichu	3.27	1.80	3.17	8.24	4.84
	Croton macrostachys Hochst	Euphorbiaceae	Mesincho	1.51	0.03	3.17	4.71	3.76
	Mangifera indica	Anacardiaceae	Mango	1.51	0.27	2.38	4.15	3.44
	Grevillea robusta A. Cunn	Protaceae	Gravila	2.26	0.55	3.17	5.99	2.62
	Proportion of total C							**90.14%**
Low	*Cordia africana* Lam	Boraginaceae	Wadicho	36.78	50.47	24.00	111.25	21.32
	Millettia ferruginea (Hochst.)	Fabaceae	Hengedich	17.33	9.05	15.00	41.38	13.66
	Persea americana	Lauraceae	Abukato	3.65	7.62	8.00	19.27	12.34
	Ficus vasta Forrsk	Moraceae	Odao	4.86	9.64	8.00	22.5	10.16
	Ficus thonningii BI.	Moraceae	Dinbicho	1.52	0.90	3.00	5.42	6.66
	Croton macrostachys Hochst	Euphorbiaceae	Mesincho	1.22	0.99	3.00	5.21	6.45
	Euphorbia abyssinica Gmel	Euphorbiaceae	Charichu	2.74	1.16	4.00	7.90	6.36

Albizzia gummifera (Gmel.) .CA.Sm	Fabaceae	Matticho	1.82	0.65	3.00	5.47	6.09
Grevillea robusta A. Cunn	Protaceae	Gravila	3.95	2.92	7.00	13.87	4.66
Ficus sur Forrsk	Moraceae	Odako	1.52	0.63	3.00	5.15	3.82
Proportion of total C							**91.52%**

Appendix A Table 5: Mean (± SD) of DBH, height, basal area and stem density of perennial plants species across an elevation gradient in CAFS of Sidama, South-eastern Ethiopia

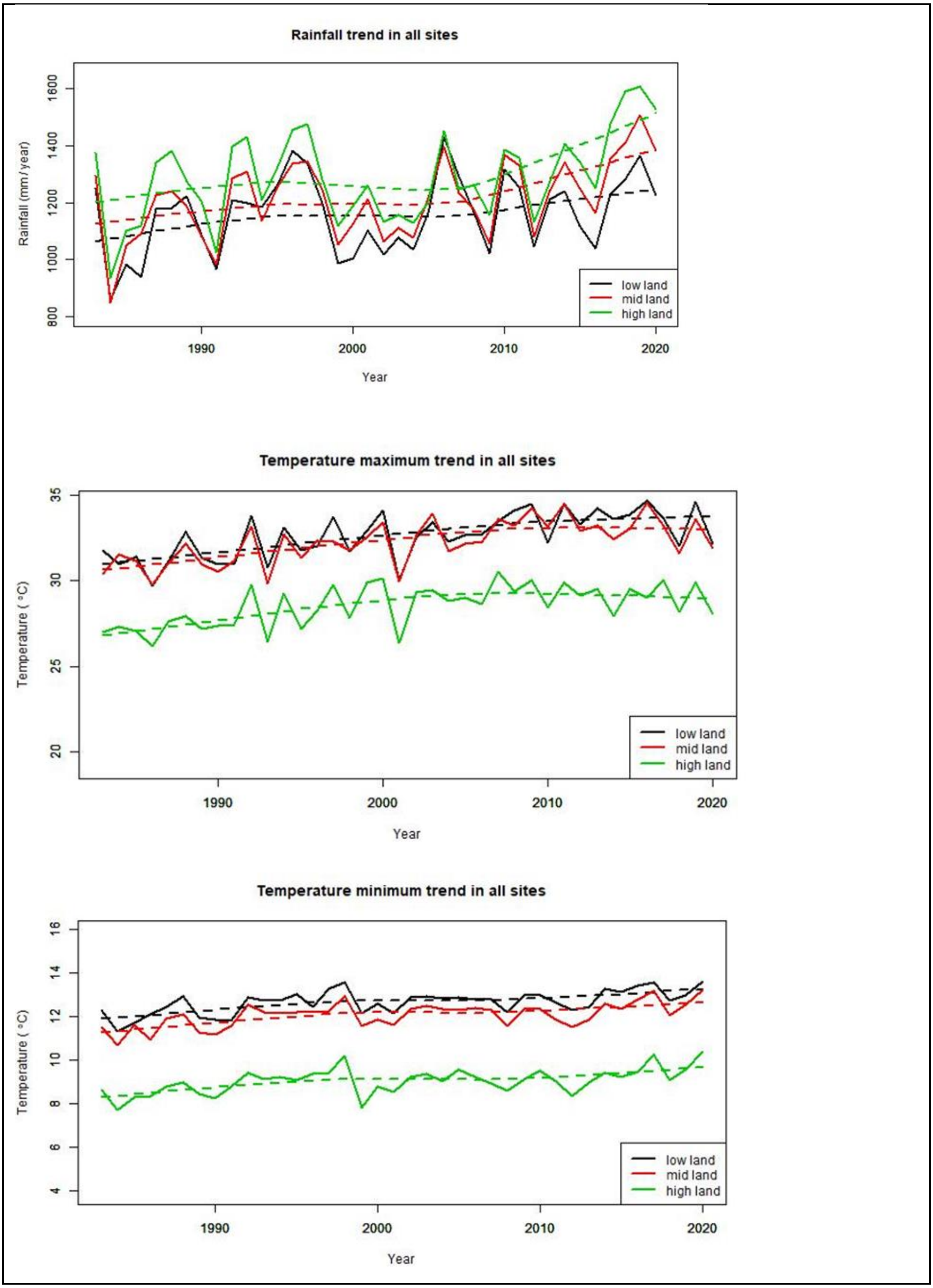
Variables	Elevation			F	P-value
	High (n=24)	Mid (n=24)	Low (n=24)		
DBH (cm)	15.96±2.26[a]	16.60±2.57[a]	14.49±3.18[b]	3.882	0.025
Height (m)	10.84±3.04[a]	11.43±2.15[a]	9.48±2.26[b]	3.794	0.027
Basal area (m^2ha^{-1})	6.59±2.31[a]	9.61±2.53[b]	6.54±2.98[a]	13.677	0.000
Stem density (ha^{-1})	342.71±111.43[a]	414.58±129.57[a]	330.21±192.52[a]	2.253	0.113

Similar letters show no significant differences while different letters show significant differences between elevations at 5% level of significance.

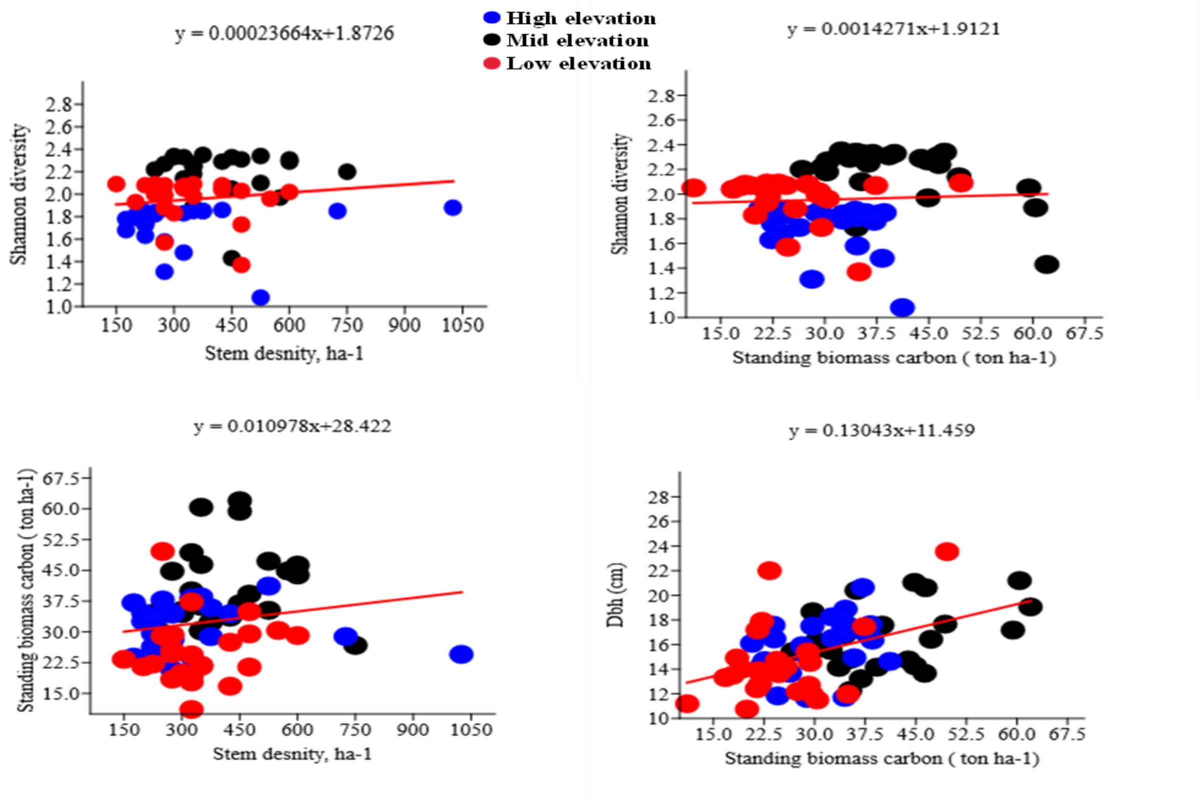
Appendix A Table 6: Mean (± SD) of biomass carbon (ton ha^{-1}), CO_2 equivalent removal (ton^{-ha}) and Sequestration rate (ton $ha^{-1}yr^{-1}$) of coffee plants in CAFS and FSCS across an elevation gradient in Sidama, south-eastern Ethiopia

Coffee production systems	Elevations	n	Standing biomass carbon (ton ha^{-1})			CO_2 equivalent removal (ton ha^{-1})			Sequestration rate (ton^{-ha-yr})		
			AGC	BGC	TC	AG CO_2 eqv. removal (ton ha^{-1})	BG CO_2 eqv. removal (ton ha^{-1})	Total CO_2eqv. removal (ton ha^{-1})	AGC Seq. rate (ton ha^{-1} yr^{-1})	BGC Seq. rate (ton $ha^{-1}yr^{-1}$)	Total Seq. rate (ton $ha^{-1}yr^{-1}$)
Coffee plants in CAFS	High	24	4.8±0.89^{a}	1.26±0.23^{a}	6.09±1.12^{a}	17.88±3.27^{a}	4.65±0.85^{a}	22.53±4.14^{a}	2.14±0.50^{a}	0.50±0.13^{a}	2.69±0.64^{a}
	Mid	24	4.81±1.11^{a}	1.25±0.29^{a}	6.06±1.39^{a}	17.05±4.93^{a}	4.43±1.28^{a}	21.49±6.21^{a}	2.57±0.80^{b}	0.65±0.22^{a}	3.22±1.01^{b}
	Low	24	3.42±0.90^{b}	0.89±0.23^{b}	4.31±1.14^{b}	12.66±3.34^{b}	3.29±0.87^{b}	15.95±4.21^{b}	1.75±0.50^{c}	0.46±0.13^{b}	2.21±0.64^{c}
	Pooled mean	72	4.35±1.17	1.13±0.30	5.48±1.47	15.86±4.51	4.13±1.17	19.99±5.68	2.15±0.70	0.55±0.19	2.71±0.88
	F-value		16.66	16.71	16.68	12.26	12.23	12.26	10.44	7.55	10.05
	P – value		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Coffee plants in FSCS	High	12	4.64±1.19^{a}	1.21±0.31^{a}	5.84±1.50^{a}	17.15±4.39^{a}	4.46±1.14^{a}	21.60±5.54^{a}	2.19±0.52^{a}	0.57±0.14^{a}	2.76±0.66^{a}
	Mid	12	5.28±0.90^{b}	1.37±0.24^{b}	6.65±1.13^{b}	19.54±3.34^{b}	5.08±0.87^{b}	24.62±4.20^{b}	3.11±0.50^{b}	0.76±0.25^{b}	3.87±0.70^{b}
	Low	12	3.77±1.46^{a}	0.98±0.38^{a}	4.75±1.84^{a}	13.93±5.40^{a}	3.63±1.40^{a}	17.56±6.80^{a}	1.95±0.66^{c}	0.55±0.31^{a}	2.13±0.79^{c}
	Pooled mean	36	4.56±1.33	1.19±0.35	5.74±1.67	16.87±4.91	4.39±1.28	21.26±6.19	2.42±0.75	0.63±0.25	2.92±1.01
	F-value		4.77	4.75	4.79	4.78	4.76	4.79	13.96	2.60	17.84
	P – value		0.015	0.015	0.015	0.015	0.015	0.016	0.000	0.089	0.000

AGC Aboveground carbon; BGC Belowground carbon; eqv equivalent; ha hectare; Seq sequestration; TC total carbon. Similar letters show no significant differences while different letters in a column shows significant differences between elevations at *5*% level of significance.



Appendix A Figure 1: Trends of annual rainfall, maximum and minimum temperatures of study sites (1983-2020)



Appendix A Figure 2: The General Liner Model results on the interaction effect between stand structure (DBH and stem density), Shannon diversity and biomass carbon across an elevation gradient in CAFS of Sidama, South-eastern Ethiopia

7 Appendices B

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Jawo TO. 2021.The Role of Women in Beekeeping Activities and the Contribution of Bee-wax and Honey Production for Livelihood Improvement. Tropentag 2021, 15 - 17 September 2021, University of Hohenheim, Germany.

Jawo TO. 2020. Value Chain Analysis of Pineapple (Ananas Comosus) Production and Marketing from Agroforestry System, Southern Ethiopia. Tropentag 2020, 9-11 September 2022, ATSAF e.V . Germany.

Jawo TO, Zerihun YZ. 2022 Empirical analysis of fuelwood consumptions and its environmental implications in rural sub-city, southern Ethiopia''.Tropentag 2022, 14 - 16 September 2022, Czech University of Life Science, Prague.

Jawo TO. 2014 Organic Honey-bee Farm Enterprise for Natural Resource Conservation and Climate Change Mitigation, 3 – 4 February 2014, Witzenhausen, Germany.

Jawo TO. 2013. Protective values and attitudes towards sacred forests or trees the case of *gurage*, Ethiopia. Paper presented Rural Development Beyond Agriculture: Perspectives and Potentials: 8 – 16 September 2013, Rottetnburg, Germany.

Jawo TO. 2010. The Role of Agroforestry as a Functional tool in Climate Change Mitigation. Paper presented Climate Change and Environmental Sustainability, 4 – 5 November 2010, Dresden, Germany

Jawo TO. 2010. The role of community forestry for sustainable natural resource management. DAAD annual meeting/conference, March 2010, Berlin, Germany.

EDUCATIONAL TRAININGS

Advance Academic Writing, Czech University of Life Sciences Prague, Czech Republic, 17- 28 January 2022.

Project and Financial Management, Czech University of Life Sciences Prague, Czech Republic, 25 October – 29 November 2021.

Higher Diploma License, Certified professional teacher, Hawassa University, Ethiopia, December 2017 – December 2018.

Socio-ecological Interactions in a Dynamic World, Global Environments Summer Academy, Bern Switzerland, 26 July – 15 August 2014.

Quality management along organic agri-value chains in developing countries, Kassel University, Germany, 11 February 2014.

Rural Development Beyond Agriculture: Perspectives and Potentials, Rottetnburg University of Applied Forest Science, Germany, 8 – 16 September 2013.

RESEARCH PROJECT

Publication and Research Activities Development for Education in Life Sciences at Hawassa University, Ethiopia." Funded by Czech government, 2019 – 2023.

Potentials of climate smart smallholders' coffee-based agroforestry system: linking adaptation, mitigation, biodiversity conservation and household level renewable energy production in selected districts of Sidama National Regional State, Ethiopia. Funded by Hawassa University, 2019 – 2021.

Climate smart agricultural practices adjacent to forest frontiers and their roles for resilience of local livelihoods and climate change mitigation in Guji zone, Oromia Region, Ethiopia. Funded by MRV project, Hawassa University, 2017 – 2019.

Biomass Energy Consumption and their Effects on the Environment and Human health: A Case of Hawassa City, Southern Ethiopia. Funded by Hawassa University, 2015 – 2018.

Assessing indigenous knowledge of farmers in identification honey bee flora and flowering time in Wondo Genet, Southern Ethiopia. Funded by Hawassa University, 2015 – 2016.

Community Based Ecotourism for balancing the trade-off between livelihood improvement and natural resource conservation. The case of Adaba-Dodola Community Based Ecotourism, South-east part of Ethiopia. Funded by Hawassa university, 2013 – 2014.