COST-BENEFIT ANALYSIS OF PRIORITIZED CLIMATE-SMART AGRICULTURAL PRACTICES AND INNOVATIONS AMONG SMALLHOLDER FARMERS: A CASE OF SELECTED VALUE-CHAINS IN SUB-SAHARAN AFRICA

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A Thesis Submitted to the Graduate School in Partial Fulfilment of the Requirements for the Master of Science Degree in Agricultural and Applied Economics of Egerton University

EGERTON UNIVERSITY

DECEMBER, 2022

DECLARATION AND RECOMMENDATION

Declaration:

This thesis is my original work and it has not been presented in this university or any other for the award of a Degree or a Diploma.

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DEDICATION

This thesis is dedicated to my mother Gladys Adongo Samo, my father Willis Oula Atie, my siblings Ronney Isaiah Odhiambo, Valency Felix Otieno, Reinhardt Carl Onyango, Imarh Otieno, Hazel Anam, and friends.

ACKNOWLEDGEMENTS

I wish to thank the German Academic Exchange Program (DAAD) and the African Economic Research Consortium (AERC) for funding my MSc studies and allowing me to specialize in Environmental Valuation and Policy Analysis at the University of Pretoria (UP). I wish to thank the Climate Action lever of the Alliance Bioversity International and the International Centre for Tropical Agriculture (CIAT) for the opportunity of developing this research thesis under the GIZ project. I wish to thank the staff at the Department of Agricultural Economics and Agribusiness Management (AGEC/AGBM) of Egerton University and my colleagues for their continuous guidance and assistance

My sincere gratitude goes to Our Almighty God, for leading me this far and for giving me strength and confidence throughout my academic journey. I would like to express my deepest appreciation to my supervisors Prof. Margret Ngigi, Dr. Mary Mathenge, and Dr. Stanley Karanja Ng’ang’a of The Alliance Bioversity International and International Center for Tropical Agriculture (CIAT), who have mentored and offered me guidance during the development of this thesis. Without your supervision and constant assistance, this project would not have been possible. I also wish to thank my dear mum and my entire family for their continued support.

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ABSTRACT

Current climate shocks are already affecting agricultural productivity, especially in the Least Developed Countries reducing the resilience of most vulnerable populations to deal with the negative effects. Smallholder farmers who depend on rain-fed agriculture are the most affected owing to the uncertainty of climate projections and limited capacity to adopt economically viable climate adaptation strategies. More so, they are constrained in both land and financial resources for the implementation of these agricultural innovations. Using a sample of 306 respondents, the Climate-Smart Agriculture-Prioritization Framework was used to assess the prioritized innovations for selected agricultural value chains in seven countries within the sub-Saharan Africa region; Kenya, Ethiopia, Zambia, Malawi, Togo, Nigeria, and Ivory Coast. Also, the study makes an economic case for investing in the prioritized innovations through a Cost-Benefit Analysis with a sample of 153 representative farmers. Four economic indicators comprising the Net Present Value, Internal Rate of Return, Benefit-Cost ratio, and payback period were computed. Data were collected via online interviews with the representative farmers by use of digitized questionnaires. The data was analyzed using the Cost-Benefit Analysis tool and the STATA software. The results indicated that most smallholder farmers in SSA prioritized the use of improved seed varieties, conservation agriculture, and good agricultural practices due to their ability to increase productivity and improve their resilience to climate change. The Net Present Value and the Internal Rate of Return for all the practices indicated the profitability of all the practices. In the sweet potato value chain in Kenya, good agricultural practices were viable with an NPV of US$ 28,044, an IRR of 328%, and a one-year payback period. This is in comparison to the improved seed varieties (US$ 8,738, 111%, and two years payback period) respectively. In Nigeria, the most viable option was the improved seed in the potato value chain and good agricultural practices in the rice value chain. In Malawi, Ethiopia, and Zambia, the most viable practices were improved seed, and conservation agriculture in the soybean, faba beans, and peanut value chains respectively. The NPV was highly sensitive to changes in the discount rate, moderately to price, yield, and practice lifecycle, and least to changes in annual labour costs. Policies should, therefore, be geared toward the development of low-cost strategies. These strategies should also present the ability to reduce the potential trade-offs and synergies as well as be in line with the objectives of increasing productivity, resilience, mitigation, and sustainability.

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LIST OF ACRONYMS AND ABBREVIATIONS

AD-DICE	Adaptation in Dynamic Integrated model of Climate and the Economy
AD-WITCH	Adaptation-World Induced Technical Change Hybrid Model
ART	Alemayehu Row-seed Technology
ASDS	Agricultural Sector Development Strategy
B/C	Benefit-Cost ratio
BAU	Business As Usual
BMZ	German Federal Ministry for Economic Cooperation and Development
CA	Conservation Agriculture
CATIE	The Tropical Agricultural Research and Higher Education Centre
CBA	Cost-Benefit Analysis
CCAFS	Research Program on Climate Change, Agriculture, and Food Security
CGIAR	Consultative Group for International Agricultural Research
CIAT	International Centre for Tropical Agriculture
CMD	Cassava Mosaic Virus Disease
COMACO	Community Markets for Conservation
CSA	Climate-Smart Agriculture
CSA-PF	Climate-Smart Agriculture Prioritization Framework
CSA-RA	Climate-Smart Agriculture Rapid Appraisal
CSI	Climate-Smart Innovation
CSV	Comma Separated Values
CVM	Contingent Valuation Methodology
FAO	Food and Agricultural Organization of the United Nations
FGD	Focus Group Discussion
GAP	Good Agricultural Practices
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIC	Green Innovation Centres
GIZ	The German Society for International Cooperation and Development
IAM	Integrated Assessment Models

ICT	Information and Communication Technology
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ITCZ	Inter-Tropical Convergence Zone
KCSAS	Kenya Climate-Smart Agricultural Strategy
MCA	Multi-Criteria Analysis
NAP	National Adaptation Plan
NAPA	National Adaptation Programmes of Actions
NGO	Non-Governmental Organization
NPV	Net Present Value
OFT	On-Farm Trials
PP	Payback Period
PRA	Participatory Rural Appraisals
PRISMA	Preferred Reporting Items for Systematic Review and Meta-Analysis
RAP	Robust Adaptation Planning
RRA	Rapid Rural Appraisal
ScML	Microsoft Word Structural Character Modelling Language
SME	Small Medium Enterprises
SSA	sub-Saharan Africa
TOA-MD	Trade-Off Analysis of Multi-Dimension Impact Assessment
UN	United Nations
UNFCC	United Nations Framework Convention on Climate Change
WTP	Willingness to Pay

CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Sub-Saharan Africa (SSA) region has undergone massive transformations in terms of economic developments, trade liberalization, technological advancements, and population growth (FAO, 2018). These changes have continued to take place and, as human, agricultural and ecological systems evolve, negative impacts are being felt and are further worsened by climate change (Onyeagocha *et al*., 2018). The Food and Agriculture Organization of the United Nations (FAO) reports that the increase in population and economic growth in most developing countries has increased the demand for food and other agricultural products which in turn exerts more pressure on scarce water and land resources. To meet this demand by the year 2050, the production of crops and livestock needs to increase by at least 60% (FAO, 2018).

Agricultural production in SSA is highly dependent on rainfall and temperature making it susceptible to climate change. Yields for certain crops in rain-fed systems may reduce by about 50% in 2020 (Apata, 2011). Adaptation is therefore key to ensuring the sustainability of agricultural systems. Depending on the objectives to be achieved, if there is no proper development of innovative and climate-smart strategies, extreme climate variability can impede the growth of agricultural systems, economies, and the welfare of rural communities (Rhodes *et al*., 2014). According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), temperature projections for most countries in the region will exceed 2^{o}C by the 2080s while rainfall projections are uncertain. This uncertainty is because rainfall events in the region are highly influenced by the Inter-Tropical Convergence Zone (ITCZ) which is in turn caused by the El Nino southern and northern oscillations (IPCC, 2014).

Current autonomous climate adaptation strategies implemented by smallholder farmers in SSA including Kenya, Malawi, Zambia, Togo, Nigeria, Ivory Coast, and Ethiopia among others, may prove to be ineffective in the long run given the uncertainty of future climate projections. Furthermore, the future climate, as predicted by Global Climate Models (GCMs), is likely to shift agricultural production areas, especially for high-value crops such as coffee and cocoa while at the same time favouring the cultivation of small grain and cereal crops such as pigeon peas, groundnuts, soybeans among others (Bunn *et al*., 2019; Läderach *et al.*, 2013; Seo *et al*., 2009). As climate change progresses in the coming decades, smallholder farmers in SSA will experience great challenges in their effort to sustain their livelihood and agricultural productivity. Several opportunities such as Sustainable Land and Water Management, Integrated Pest and Weed Management, and Soil water, fertility, and carbon enhancing practices are available to smallholder farmers to adapt to the changing climate (Westermann *et al*., 2018).

Smallholder farmers experience climate shocks such as droughts, floods, strong winds, extreme rainfall events, and tropical cyclones. To reduce vulnerability to these shocks, the governments of most SSA countries have developed policies and strategies that promote sustainable agricultural production practices. For example, practices under Sustainable Land and Water Management include but are not limited to; minimum or no-tillage practices, construction of terraces, soil bunds, stone or vegetation bunds, Half-moons[1], and Zai pits[2], mulching, on-farm storage facilities, irrigation, System of Rice Intensification (SRI), and alternate wetting and drying in rice production (Cai *et al*., 2019; Oremo *et al*., 2020). Practices aimed at pest and weed management include the use of pesticides, new crop varieties or cultivars, and crop diversification through intercropping or crop rotation (Agula *et al*., 2019). Other practices include agroforestry and cover cropping, changing planting dates, index-based insurance, and use of organic manure among others. These are aimed at income diversification, risk management, and enhancing soil carbon, fertility, and infiltration capacities (Hansen *et al*., 2019).

The strategies further provide an opportunity for the assessment of triple wins (synergies) and tradeoffs among the three objectives of Climate-Smart Agriculture (CSA) productivity, adaptation, and mitigation. National policies on climate change in various SSA countries include the Intended Nationally Determined Contributions (INDCs), and the National Adaptation Programmes of Action (NAPAs) which are a requirement for Least Developed Countries (LDCs) to develop and submit to the United Nations Framework Convention on Climate Change (UNFCCC) according to the COP-21 Paris Agreement (UNFCCC, 2016). Despite efforts placed by various governments, international research organizations, and Non-Governmental

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[1] A planting pit of about two meters in diameter

[2] A planting pit about 20-40 centimeters in diameter and 10-15 centimeters in depth

Organizations (NGOs) on the value and importance of implementing adaptation strategies, the adoption rate among smallholder farmers in SSA is still low (Kabubo-Mariara & Mulwa, 2019). Barriers such as huge initial costs of investments, poverty, low levels of understanding of climate change, the time needed before the benefits of an innovation are realized, and the fact that smallholder farmers are constrained in land and financial resources could be some of the reasons behind the low adoption rates of these practices (Bunn & Castro, 2018).

It is therefore important to make an economic case for investing in these Climate-Smart Innovations (CSI). Economic indicators such as the return on investment (ROI) and the net present value (NPV) could prove useful in increasing the rates of adoption and ensuring effective implementation. Cost-Benefit Analysis (CBA) as a decision-making tool requires that the costs, benefits, and externalities resulting from a policy action to invest in innovation or technology are evaluated in monetary terms. From an economic point of view, Tietenberg and Lewis (2012) opine that, if the benefits exceed the costs, then the innovation or technology is deemed desirable but if the costs exceed the benefits then it is not desirable. CBA, being applied especially to climate adaptation will help contribute towards achieving developmental goals given the different climate change scenarios and future projections. It explicitly weighs all the costs and benefits of each innovation and facilitates a systematic consideration of factors that influence choices.

This study focused on seven SSA countries including Ethiopia, Ivory Coast Kenya, Nigeria, Malawi, Togo, and Zambia. The value chains selected for this study were based on those prioritized by Green Innovation Centers (GICs) under the German Agency for International Cooperation (GIZ). These are milk and sweet potatoes (in Kenya); cassava, potatoes, corn, and rice (in Nigeria); soybeans, cassava, and peanuts (in Malawi); soybeans, milk, and peanuts (in Zambia); soybeans, cashew, and peanuts (in Togo); cassava and plantain (in Ivory Coast) and broad beans and wheat (in Ethiopia). The selected value chains were deemed important for each country since they contribute toward increasing and stabilizing the livelihoods of vulnerable communities and increasing food and nutrition security in the regions.

1.2 Statement of the problem.

Farmers and agricultural sector stakeholders are faced with multiple choices and options as it relates to climate change adaptation decisions. The decision-making process is often complex and involves making certain trade-offs.

It is, therefore, necessary and important to know which, from amongst the vast climate change adaptation options, is more feasible and economically viable, that is, in terms of their costs and benefits. There is a paucity of comprehensive information and data in this area, especially for the SSA region. This study, therefore, fills this knowledge gap by making an economic case for investing in climate change adaptation innovations. A private CBA is computed to establish if the investments are worth making or not. Further, the study undertakes a systematic review of the current literature to assess the potential trade-offs and synergies of climate adaptation strategies.

1.3 General Objective

To contribute towards the reduction of agricultural risks by assessing the potential trade-offs and synergies of climate adaptation strategies and development of a portfolio of priority agricultural innovations and risk management strategies among smallholder farmers in selected agricultural value chains for seven SSA countries.

1.3.1 Specific Objectives

i. To identify the trade-offs and synergies of climate adaptation innovations adopted among smallholder farmers in SSA.

ii. To evaluate the adaptation innovations adopted among smallholder farmers for selected value chains in seven SSA countries.

iii. To assess the prioritized adaptation innovations among smallholder farmers for the selected value chains in seven SSA countries.

iv. To conduct a CBA of the prioritized adaptation innovations for the selected value chains in seven SSA countries.

1.3.2 Research Questions

i. What are the trade-offs and synergies of climate adaptation strategies adopted among smallholder farmers in SSA?

ii. What are the adaptation innovations adopted among smallholder farmers for the selected value chains in the seven SSA countries?

iii. What are the prioritized innovations among smallholder farmers for the selected value chains in the seven SSA countries?

iv. What are the costs and benefits associated with each prioritized adaptation innovation in each value chain in the seven SSA countries and what are the values of their economic indicators of NPV, IRR, BCR, and payback period?

1.4 Justification

This study is in line with the achievement of 5 of the 17 sustainable development goals (SDGs). These are SDG 1 which is to end poverty in all its forms everywhere, SDG 2 which aims to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture, SDG 8 which promotes decent work and economic growth, SDG 9 which aims at fostering innovations, and SDG 13 which aims to decisively address the threat posed by climate change and environmental degradation (United Nations, 2019). With the uncertainty posed by future climate projections, a selected adaptation innovation may be relevant in the very short run but prove irrelevant in the medium to long term. This will warrant a farmer to adopt a different strategy to strengthen their resilience to climate shocks. This is costly, especially for smallholder farmers in SSA operating on the margins of poverty. This study will, therefore, provide information on the most feasible innovations and strategies to invest in and their respective payback period to enable informed and rational decisions.

This study is also in line with Africa's Agenda 2063 and more specifically the aspirations to promote modern agriculture for increased production and value addition. Furthermore, the study aligns well with the targets of ensuring sustainable environments and climate-resilient economies and communities (The African Union, 2015). The focus of this study was on adaptation as the best bet option since the SSA region plays a minor role in the emission of GHGs yet is greatly affected by the risks posed by climate change.

Each country is characterized by differences in climate, political, technological progress, and institutional, and social-economic dynamics. These differences could prove useful in conducting a comparative analysis of how varied policy options are impacting key agricultural value chains. Understanding how different countries in SSA develop and adopt various adaptation strategies to suit their needs is important to provide knowledge and decision options to policymakers on how well to incorporate these processes in their national adaptation planning agenda.

1.5 Scope and limitations of the study

There were a few limitations in the methodologies applied in this study. Firstly, no Focus Group Discussions (FGDs) were conducted in any of the countries. This was justified due to the period within which the research project was conducted (June to July 2020) where all the study areas were locked down and movement restricted due to the COVID-19 pandemic. Also, the interviews were conducted using online surveys only. This resulted in having minimal data and in some cases no responses. As a result, Togo and Ivory Coast were dropped while computing the CBA. Nigeria was the only representative country left for the West Africa region. The main implication of this is that the results may not be generalized or deemed representative of the region. To mitigate this limitation, the discussion was supplemented with information from similar studies within the region. Finally, the study only considered the private profitability of the adaptation strategies. No methodology was applied to evaluate the social or environmental effects (externalities). However, these externalities were explained by considering the findings from the literature on similar studies. These include the effects on biodiversity, water quality, availability, and social welfare (increase or decrease in labour required for each practice).

This study also restricted the choice of value chains to only those specified under the GIZ project in the seven countries. This was to ensure ease of reaching the respondents via the online surveys. Each of the countries has varied climate conditions which provided a basis for comparative analysis. The CBA was limited to private costs and benefits. However, the social costs and benefits were not considered in the analysis. The main limitation of the study was that the timeframe only allowed for use of a few representative farmers for the online interviews. This limitation was mitigated by supplementing the information from the online survey and interviews with secondary data sources and literature.

1.6 Operational definitions

Business-as-Usual (BAU) practice refers to the initial practice that a farmer was using to adapt to climate change before the introduction of the innovation.

Cost-Benefit Analysis refers to an assessment of the economic profitability or viability of the innovation with the incremental benefits measured by the increased productivity (yield multiplied by the output price) compared to the BAU practice. The incremental costs on the other hand are measured by multiplying the changes in the units of machinery/inputs/services/labour by their corresponding unit costs.

Climate-Smart Innovations refer to adaptation strategies, practices, and technologies that enable smallholder farmers to sustainably increase their productivity and build a strong resilience against risks posed by climate change**.**

The discount rate in the context of this study refers to the interest rate used by commercial banks on investment loans. It is expressed as a percentage and will vary from one country to another.

Good Agricultural Practices in the context of this study refers to a set of practices that are safe and sustainable for agricultural production to increase farmers' resilience to climate change and improve production.

Implementation costs refer to machinery and equipment, inputs, service, and labour costs incurred at the beginning of introducing a new adaptation innovation or practice. Includes both the once-off costs and costs incurred yearly.

Improved seed varieties refer to seeds obtained from a scientific process of selection and breeding to develop traits to increase resilience to climate risks or tolerance to pests and diseases.

Innovation in the context of this study refers to both the tangible (technology) and the intangible approaches and strategies used by smallholder farmers to adapt to climate change.

Internal Rate of Return (IRR) refers to the discount rate that equates the NPV to zero. If the IRR is greater than the discount rate then the adaptation innovation is deemed desirable.

Key representative farmers in the context of this study refer to farmers who have been identified with the help of experts within the GICs and have knowledge of the costs and benefits of the selected innovations.

Maintenance costs in this study refer to machinery and equipment, inputs, services, and labour costs incurred every other year after implementation of the practice or innovation to ensure a sustained good performance, and are computed every year.

Net Present Value refers to the value of discounted future net benefits. If the NPV of the innovation is greater than zero, then it is acceptable.

Operations costs refer to the costs associated with the introduction of the innovation or the practices that exclusively affect the output. For example costs of harvesting, machinery, and equipment used for harvesting or storage, threshing, dusting, bags for storage, etc.

The payback period refers to the time taken in years, for the costs of the innovation or practice to be completely paid off by the benefits realized.

Practice lifecycle refers to the period in years when the smallholder farmer implements the practice or innovation to when they stop using it or implement a new practice or innovation.

Prioritized innovation in this study refers to innovations selected based on scoring and ranking criteria depending on the objective and importance to the farmer.

Smallholder farmers in this study refer to individuals who own a piece of land less than a hectare.

Synergies in the context of this study occur when the combined effect of implementing two or more innovations is greater than the sum of their effects if they were implemented separately.

Trade-off refers to when the outcomes or benefits of implementing or adopting innovation result in less of another outcome.

CHAPTER TWO

LITERATURE REVIEW

2.1 Climate-change adaptation innovations and practices in SSA

The vulnerability of the SSA region to the negative impacts of climate change provides an incentive to assess the best possible way to achieve increased productivity and at the same time improve the adaptive capacity of vulnerable communities (Millner & Dietz, 2015). The IPCC projected with minimum confidence that, the mean surface temperature changes for the period 2016-2035 are likely to be in the range of 0.3^{o}C and 0.7^{o}C relative to the period 1986-2005. It further predicted with high confidence that the surface temperature at the end of the 21st century; 2081-2100 is likely to exceed 1.5^{o}C (IPCC, 2014b). The increase in temperature poses severe consequences to ecological, agricultural, and human systems resulting in negative impacts on livelihoods. Precipitation events are highly influenced by the increased surface temperatures as reported and these will vary across regions since it is significantly dependent on latitude.

Challinor *et al*. (2014) evaluated the yield impact of climate change and adaptation and further simulated impacts on wheat, rice, and maize crops for both the tropical and temperate regions using a meta-analysis approach based on data sets from the fourth assessment report (AR4) of the IPCC. Their study reported an eight percent (i.e., 7-15%) increase in yields as a result of the adoption of adaptation strategies, also a function of temperature and rainfall. However, there was a reduction in yield responses without adaptation for all three crops in the two regions. Given future climate projections, it is evident that adaptation could potentially reduce the risks of climate change. The constraints, limits, and the potential to adapt varies between sectors, ecosystems, communities, and regions (IPCC, 2014c). The climate of the region has been changing progressively over the decades. Smallholders alike have been changing and shifting their cultivation practices with the changing climate. For example, Kurukulasuriya and Mendelsohn (2008) opine that the choice of crop is highly sensitive to both temperature and precipitation and farmers will more often than not match future crops to future climates.

Farming households and communities have implemented mechanisms and innovations to deal with the severe negative effects of climate change on agricultural production (Bryan *et al*., 2011). The success of their implementation varies from one region to another (IPCC, 2014a). Mechanisms such as the use of Information and Communication Technology (ICT), the weather early warning systems, uptake of insurance, and extension services (Hudson *et al*., 2017). Other practices adopted at the household level include the use of good agricultural practices such as alteration of cropping patterns, mulching, crop diversification through intercropping, crop rotations, and using improved seeds (Debaeke *et al*., 2017). Practices that involve huge investments such as water storage facilities and irrigation management, commercial forage production, and integrated soil, weed, and pest management (Notenbaert *et al*., 2017; Oremo *et al*., 2019) among others, are adopted at the community level. The process of coming up with strategies that suit the different agro-ecological zones in SSA is complex and dynamic. Implementation of any CSA practice or innovation is successful if the emphasis is placed on continued research and development of low-cost innovations. This coupled with stakeholder participation and capacity building will enhance the up-scaling of these innovations (Kalungu *et al*., 2013).

There is an increase in literature on adaptation strategies implemented among smallholder farmers across the region. However, much of the literature is limited in the mention of which innovation is more economically viable, especially at the farm level. For example, in their assessment of how the risks posed by climate change and desertification are being managed in Malawi, Stringer *et al*. (2010) observed that many of the adaptation strategies relate to food security, water management, agriculture, and livelihood resilience. Chidanti-Malunga (2011) assessed various adaptive mechanisms to climate change that have been adopted by smallholder farmers in the Shire Valley area of Southern Malawi. The study determined that a majority of farmers own multiple farm plots in both the upper region which is prone to drought and the lower wetland region which is prone to flooding as a way of diversifying their livelihoods. The main adaptive strategies as evaluated include techniques that improve moisture retention such as mulching, the use of deep planting holes, and raised ridges to drain any excess moisture.

Apata (2011) assessed farmers' perceptions of climate change and the choice of adaptation mechanisms adopted by smallholder farmers in Nigeria. The study showed that about 65% of the respondents surveyed adopted either one or more of the adaptation strategies identified. Thus, mixed cropping, changing planting dates, planting trees, soil conservation practices, and, the use of different crop varieties. One of the main barriers identified that affects the ability of a farmer to adopt a particular strategy was the lack of money or credit to finance the adaptation activity. This implies that in most SSA countries, the assessment of costs of adaptation is vital to provide smallholder farmers with information on which mechanisms are suitable. Also because the main priorities for most smallholder farmers are income and yield (Tuan *et al*., 2016).

2.2 Review of the agricultural value chains in the selected study areas

2.2.1 Sweet potato value chain in Kenya

In Kenya, sweet potatoes are cultivated in almost all regions including the Western, Nyanza, Rift Valley, Coast, and Central regions with Western and Nyanza leading in production (Makini *et al*., 2018). Sweet potatoes are highly adaptable to different agroecological zones (AEZ). They thrive up to an altitude of 2400m above sea level, with temperatures of above 24^{o}C, and require annual rainfall of between 700-1000mm. Depending on the variety being cultivated, sweet potatoes have a growing period of between 3-6 months (Kaguongo *et al*., 2012). Several varieties are being grown in Kenya. These include Kemb 10, SPK 004 grown in most regions, KSP 20, KSP11, and CIP420009 which are mainly grown in the drier areas, SPK 013 which is mainly grown in the western and Nyanza regions, Kemb 23 and Ex-Diani for the central and coastal lowlands, and Mafuta which is mainly grown for foliage production (Makini *et al*., 2018). The roots, vines, and leaves of sweet potatoes are a source of cheap and nutritious food for humans and feed for livestock. In addition to providing food and nutrition security, sweet potatoes also contribute to improving soil fertility and reducing soil erosion.

Several factors constrain the optimal production of sweet potatoes in Kenya. These include limited availability of clean planting materials, inadequate technical know-how on improved variety, inadequate machinery, and equipment to advance research, de-linkages between research, extension, and smallholder farmers, and differing farmers' preferences and consumption needs among others.

To adapt to the changing climate, most smallholder farmers in Kenya have adopted the use of improved sweet potato varieties which are resistant to changes in climate and good agricultural practices such as field sanitation, early planting, crop rotation, or use of clean planting materials to reduce incidences and occurrence of pests and diseases. This study identifies the financial benefits in terms of costs and the benefits of adopting these practices at the farm level to enable smallholder farmers to make sound decisions based on collected evidence.

2.2.2 Faba beans, wheat, and honey value chains in Ethiopia

Faba beans remain one of the most important staple protein foods and feed legume crops in many countries including Ethiopia contributing to improved livelihood of most smallholder farmers (Maalouf *et al*., 2019). It is a valuable source of cheap protein for the poor. It has a high capacity to fix atmospheric Nitrogen value estimated at 50-330 Kg N hm^{-2}, facilitating the availability of phosphorous for the associated crops in intercrop or crop rotation systems. This synergistically helps to improve the soil's physical environment and microbial activity (Merga *et al*., 2019).

Faba bean is a moisture-loving crop capable of withstanding temperatures as low as -3^oC. It is therefore not recommended for areas where there is low precipitation or inadequate water available for irrigation. Most regions in Ethiopia are suitable faba bean growing areas and therefore was a critical value chain for the present study. The production of the crop in Ethiopia is however by the occurrence of pests and diseases and this is exacerbated by the prevailing changes in climate. This study, therefore, looks at the most viable adaptation strategies for smallholder farmers to adopt to sustainably increase their production of faba beans in Ethiopia.

In the Northern regions of Ethiopia, wheat is an important cereal crop and is commonly mix-cropped with barley. Due to the increase in population which is exerting pressure on scarce land and water resources, there is a need to produce more diverse food products (Agegnehu *et al*., 2006). As a result, most smallholder farmers in Ethiopia have recently adopted diversified cropping of pulses such as faba beans with improved varieties of wheat and tef.

2.2.3 Soybean and peanut value chains in Zambia

Soybean is a high-value leguminous plant mostly grown in the temperate and sub-tropical regions of the world. Zambia has great potential for soybean production and it is cultivated in nearly all the regions in Zambia (Lubungu *et al*., 2016). However, its productivity is constrained by the prevailing risks posed by climate change, the decline in soil fertility, low availability of inputs and improved seed variety, low expertise and market opportunities, and low use of microbial inoculum among others (Munene *et al*., 2017). To increase productivity, smallholder farmers in Zambia have adopted several practices and technologies including crop rotation, tillage practices, inoculation, and improved seed varieties among others although the adoption rate is still low. In addition, Lubungu *et al*. (2016) suggested additional strategies to address challenges within the soybean value chain. These are creating awareness of the benefits of inoculation and how to apply it in soybean production, engaging seed producers and agro-dealers in predicting demand for soybean seed and inoculum, and improving extension service concerning agronomic practices.

Peanuts (groundnuts) are produced by nearly half of the rural population in Zambia mostly among smallholder households. It is the second largest produced crop after maize in terms of production volumes and area under production. Peanut production in Zambia is largely concentrated in the Eastern province (Mofya-Mukuka & Shipekesa, 2013). Peanuts are less susceptible to droughts and floods. Furthermore, they fix nitrogen in the soil which enhances soil fertility and can boost the yields of subsequent cereal crops when grown in rotation. Peanuts also serve as an important raw material in the manufacture of peanut butter, oils, sweets, and animal feed. Despite its huge importance in improving the livelihood of rural communities, the production of peanuts in Zambia and persistently low due to the low use of improved/hybrid seed or the excessive recycling of seed. More so, peanuts are highly labor-intensive, particularly during weeding, harvesting, and shelling.

2.2.4 Soybean, peanut, and cassava value chain in Malawi

Soybean presents a suitable alternative to addressing malnutrition among communities who rely on agriculture as they comprise more than 36 percent protein, 20 percent oil, 30 percent carbohydrates, dietary fibre, minerals, and vitamins (Markowitz, 2018). In promoting the development of soybean in Malawi, the government often promotes the development of farmer-to-farmer teaching strategies to promote livelihoods, agroecology, nutrition, and local food market development. For example, capacity training programs to train community members on how best to process soybeans to cake, milk, and yogurt among others provide a means of expanding market access (Mubichi, 2017).

Peanuts are an important source of oil, folate, antioxidants, protein, and essential fatty acids (Zahran & Tawfeuk, 2019). In addition to maize, peanuts are an important staple crop grown in Malawi contributing significantly to the diet and agricultural exports. According to Hoffmann and Chanza (2018) on the evaluation of the financial implications of legume technologies on smallholder cereal farmers in Central Malawi, an estimated 73 percent of growers sell ground nuts. This makes it the highest income earner in Malawi compared to other legume crops such as cowpeas, beans, or soybeans.

Cassava is a staple food for almost 30 percent of the population in Malawi. The crop has a dynamic agroecological adaptation and is relatively more drought-tolerant compared to maize (Alene *et al*., 2013). The main cassava growing areas in Malawi are in the northern belt along the lakeshores, the southern belt, and the central belt of Dedza and Lilongwe. There has been innumerable research, development, and release of high-yielding and disease-tolerant cassava seed varieties in Malawi. However, the adoption is still low as these varieties do not meet the preferred consumption attributes highly valued by smallholder farmers (Kanyamuka *et al*., 2018).

2.2.5 Rice, Cassava, Potato, and Corn value chain in Nigeria

The main crops grown in Nigeria include rice, sorghum, millet, groundnuts, and sweet potato among others. The cultivation of cassava, millet, sorghum, groundnut, and maize is largely concentrated in the upland areas while rice cultivation is done in the lowland areas and the floodplain areas of river Niger. Areas under rice cultivation are referred to as fadama land (Tunde *et al*., 2011).

The main threat to the production of crops such as rice, maize, cassava, and potatoes among others is poor adaptation to climate change. Most farmers as opined by Arimi (2014) cite financial difficulties in adopting some of the adaptation technologies as the main constraint. Examples of the adaptation strategies adopted include the planting of improved varieties such as the Federal Agricultural Research Oryza (FARO) in rice cultivation, seeking early warning climate information, and shifting planting dates until weather conditions are favourable among others. To cushion farmers, and with the prevailing economic conditions in developing countries like Nigeria, there is a need to provide incentives to assist farmers in coping with drought and flood events. Evidence provided in this study on the costs and benefits of climate adaptation strategies and technologies will go a long way in helping all the stakeholders including smallholder farmers, government officials, agricultural researchers, and development agencies make informed and ration decisions on matters of adaptation to climate change especially for developing countries.

2.2 Theoretical Literature

2.2.1: Understanding adaptation

The concept of adaptation takes an inter-disciplinary approach and its understanding also requires a thorough understanding of economics, social sciences, production, and environmental studies. The economic aspects will aid in understanding the costs of adaptation, the main factors, and barriers to adaptation. The sociological aspect involves the understanding of human interactions and will to an extent help in identifying the social and institutional aspects that encourage or deter the processes of adaptation. Also, the impacts of any adaptation strategy on the functioning of an ecosystem are highly anthropocentric. Thus, are evaluated based on their impact on human beings and are a basis for understanding welfare economics (Tietenberg & Lewis, 2012). In the context of this study, it is important to distinguish between flow adaptation and stock adaptation. Millner and Dietz (2015) define flow adaptation as the set of adjustments where the costs and the benefits accrue in a single period. For example, the changes in variable inputs such as fertilizers, seeds, and crop varieties. Stock adaptation is a form of investment in which the costs are paid upfront while the benefits accrue in several future periods. For example, implementing different agroforestry systems, and investing in extension services, among others.

According to FAO, adaptation to climate change may take several forms such as temporary or permanent migration of populations, adoption of existing technologies, innovations and new technologies, increased range of attractive agricultural insurance products, and changes in agricultural production activities (FAO, 2018). Other literature like the IPCC reports, states five principles of adaptation which include supporting autonomous adaptation, increasing participation of all stakeholders especially the women and the youth in the development process, implementing no-regret adaptation options, building social and institutional learning platforms, and considerations of both scientific and indigenous knowledge when developing adaptation strategies (IPCC, 2014).

2.2.2 The theory of adaptation economics

Several studies have been undertaken to critically evaluate the general economic theories that primarily explain the modifications that economic agents make to deal with climate change. The theory of adaptation economics considers both aspects of the market and private adaptation (Callaway *et al*., 2016; Chambwera, *et al*., 2015) and public or joint adaptation (Mendelsohn, 2012). In this study, to aid our understanding, we consider this simply as the basics of welfare theory as it is applied in adaptation to climate change.

Mendelsohn (2012), critically evaluates this theory by advancing the theory of efficient adaptation as it applies to private individuals, firms, and the theory of optimal adaptation as it relates to public adaptation. If we assume that markets are perfect, with no externalities, perfect information, well-defined property rights, and no barriers, then private adaptation could be efficiently provided by markets. Under private adaptation and applying knowledge of welfare analysis, a rational individual, household or firm will maximize their utility function or profits subject to a resource constraint, Nicholson and Snyder (2012), where the utility equation is a function of a bundle of goods purchased or consumed. In the context of adaptation to climate change, according to Mendelsohn (2012), the utility function has a climate factor that enters the equation exogenously such that the optimization problem is as represented by Eq. 1;

$$\max_{x,c} U(X, C) \tag{1}$$

Subject to resource constraints,

$$Y = P.X \tag{2}$$

Where X is the bundle of all private goods and services purchased or consumed by the household, C is the climate factor, P is the market price and Y is the household's or individual's resource endowment. If the climate variable is not controlled for, then it would considerably alter the welfare of the household such that they will change their behavior by also changing the quality and quantity of their consumer goods. This change as a result of climate variability is what is known as private adaptation (Economides *et al*., 2018; Mendelsohn, 2012). Since climate change presents uncertainties, some economists in the climate change discipline believe that the assumptions of the utility theory cannot be fully satisfied with the understanding of climate change. (Leonardi, 2010). Eq. 1 and Eq. 2 only considered an individual in a static dimension. The main limitation of this is that the impacts of the adaptation strategy are realized after a given period which can be a year or more. It also affects not just the individual but the whole society and may require the use of social welfare functions in the analysis.

Adaptation actions in most instances create 'public goods' where the benefits are enjoyed by many and so a private individual or household or firm may not be able to fully capture the gains from adaptation (Chambwera *et al*., 2015). An efficient and optimal allocation of resources that result in public benefits requires the application of the 'Samuelson rule' knowledge from classical economics which observes that, in the provision of public goods, the sum of all the marginal willingness to pay values from all individuals should equal the marginal costs of provision (Sandmo, 2006). Such that to attain a welfare optimum, we maximize the net benefit to the whole society as represented by Eq. 3.

$$Max \sum B_i\ (Q) - C(Q) \tag{3}$$

Where $B_i(Q)$ represents the benefits to each household from adaptation, $C(Q)$ represents the costs of adaptation, Q represents the quantity of output and input resources. Public adaptation economics takes an aggregate of all benefits (direct and indirect) that impact the whole society. Applying the basic principles of welfare economics and accounting for damages as a result of climate change, a social planner will seek to maximize welfare to the whole society and this is represented by a social welfare function. Our optimization problem as evaluated by Sterner and Coria (2012) is thus shown in Eq.4.

$$\max_{i_n, a_n} W = \sum_n (P.Q_n\,(i_n, a_n\,) - C_n(i_n, a_n\,)) - D(\sum_n e_n(i_n, a_n\,)) \tag{4}$$

Where W is the social welfare function, which is dependent on the prices of outputs P, n is the number of observations, the total farm output Q, the inputs i_n, level of adaptation implemented a_n the costs of the firm's inputs C_n and the adaptation and, D is the environmental damage function as a result of climate change. Other studies on adaptation indicate that, under these circumstances, there will be an under-provision or completely no provision since the adaptation practice or innovation will not receive efficient private investment leading to market failure (Fisher-Vanden *et al*., 2013; Mendelsohn, 2000).

Factors that lead to market failure present the barriers or the main constraints to adaptation but also provide a rationale for public action by either international organizations, national governments, or NGOs. Examples of these barriers as evaluated include; transaction costs, presence of externalities and the ‘public good’ nature of adaptation actions, inadequate and lack of well-defined secure property rights, asymmetric information, moral hazardous behavior especially under climate insurance coverage, insufficient investment due to large fixed costs and asset specificity (Agrawala *et al*., 2011; Biesbroek *et al*., 2011; De Bruin & Dellink, 2011; Dow *et al*., 2013; Moser & Ekstrom, 2010). Socioeconomic factors also present barriers that hinder the capacity of an individual or a household to adapt to climate change. For example, the level of literacy evaluated using years of education, income distribution that represents equity considerations, access to financing observed by the lack of credit or insurance facilities, household size, and institutional quality (Fankhauser & McDermott, 2014).

2.2.3 Theoretical basis of Cost-Benefit Analysis

Economics plays a very critical role in decision-making by providing information about benefits and costs including the non-monetary aspects and the impacts of alternative policy actions on society (Chambwera *et al*., 2015). In the face of uncertainty, several techniques are employed to aid with efficient decision making but the choice of the most appropriate technique highly depends on the nature of the problem and the degree of uncertainty.

CBA, just like the theory of adaptation economics is also based on welfare economics, but further deals with situations where the effects of policy action are realized over time thus taking an intertemporal or a dynamic perspective (Perman *et al*., 2003). Other than the financial analysis of costs and benefits of policy actions, the basic strategy of CBA is to attach a monetary value to impacts on the environment whether desirable or undesirable. These are the social benefits and social costs.

In the allocation of scarce resources, CBA is a technique whose primary objective ensures that there is an efficient outcome. For instance, the impact on production outcomes from the implementation of a climate change adaptation strategy is evaluated in monetary units referred to as net benefits. Under project evaluation, this is done by calculating the NPV in which the rationale is provided by the potential compensation tests. The efficiency criterion for these tests, in a case of a welfare gain, is that the winners could potentially compensate the losers and still be better off. The benefits are based on consumers' willingness to pay (WTP) for the action or project to take place, measured by the relevant area under the demand curve. The costs, on the other hand, represent what the losers are willing to receive as compensation for giving up their resources (Brent, 2006). CBA can be evaluated on an ex-ante basis – that is, before the implementation of the project, can be an intermediary that is in the middle of project implementation, and also on an ex-post basis that is after the implementation. It helps to assess whether the innovations are economically viable and if they can be sustainable in the long run.

2.3 Empirical Literature

2.3.1 Prioritization of Climate-Smart Agricultural practices

The prioritization of CSA involves such considerations as its anticipated profitability, investment needs or access to credit, its technical feasibility, and marketability. The main priorities for the majority of smallholder farmers are yield and income, evaluated at the margins. Therefore, any innovations aimed at adaptation or mitigation of climate change should easily be translated into income to encourage uptake (Tuan *et al*., 2016).

Several approaches, tools, and frameworks have been applied in prioritizing CSA strategies. For instance, Mwongera *et al*. (2017) utilized the Climate-Smart Agriculture Rapid Appraisal (CSA-RA), which is a participatory bottom-up approach for prioritizing context-specific CSA technologies in Tanzania and Uganda. CSA-RA, as discussed, is a mixed-method approach that combines the Participatory Rural Appraisal (PRA) and the Rapid Rural Appraisal (RRA) tools in one methodology. Results from the application of the CSA-RA show that while many adaptation innovations are context-specific, some are generic and depend on the agroecological zone, natural hazard experiences, and slope degree. The study, however, only conducted a simple gross margin analysis and did not indicate the influence of adaptation innovation on the economic performance of the enterprises.

PRA tools emphasize gender and climate analysis and include such activities as; resource mapping which identifies the distribution of resources in a landscape, climate calendars to show particular weather stresses, cropping calendars that identify the main crops and when production takes place, organizational or institutional mapping, and pairwise ranking and comparison of the different CSA categories. The RRA tools include transect walks that identify important landmarks, vegetation patterns, land cover, land uses, biodiversity, and resource endowments within a community. It also involves key informant and farmer interviews which are conducted by the use of semi-structured questionnaires (Mwongera *et al*., 2017).

Shikuku *et al*. (2017) used a minimum data approach that incorporates both the Ruminant model and the Trade-offs Analysis Model for a Multi-Dimensional Impact Assessment (TOA-MD) approach to evaluate how improved livestock management activities are affecting the three pillars of CSA for a district in Tanzania, as defined by FAO. The two approaches used are however only applicable to ex-ante impact assessment and estimate of the economic, environmental, and social impact for both adopters and non-adopters of the CSA. Chaudhury *et al*. (2017) applied the Robust Adaptation Planning (RAP) framework, to plan and evaluate appropriate climate adaptation practices among smallholder farmers in Ghana. The RAP framework involves five steps; identifying and mapping networks among actors, selecting actors and adaptation interventions, applying a multi-actor participatory process to identify links to implement the selected adaptation interventions, comparing outcomes from the different networks to identify missing and overlapping links, and developing robust action plans for the different actors and at different levels. The RAP fives step framework requires a comprehensive understanding of the processes and a collaborative relationship among all participants.

The CSA prioritization framework (CSA-PF) was developed by the International Center for Tropical Agriculture (CIAT) and the CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS) with the main aim of prioritizing investment in CSA based on their impacts on the local or regional context. The CSA-PF is rigorous and is based on four critical phases; preliminary evaluation of CSA options, identification of the main CSA options, CBA analysis, and finally portfolio definition (FAO, 2010). This framework has been applied and is still being applied to several developing economies to encourage multiple stakeholder participation and scale-up CSA innovations (Sain *et al*., 2017; Sogoba *et al*., 2016).

2.3.2 The costs and benefits of adaptation to climate change

To a great extent, the costs and benefits of adaptation are bent on the objectives that are set to be achieved. That is, whether it is on economic efficiency, equity consideration, reducing the levels of risk, or the framework of analysis being used (Chiabai *et al*., 2015). Several studies and reports have examined models that have been used to assess these costs and benefits. For instance, the use of Integrated Assessment Models (IAM) which have long-term dimensions, has been utilized to quantify the economic impacts of climate change and also the costs and benefits of both mitigation and adaptation practices.

De Bruin *et al*. (2009) used an IAM that is the Adaptation in Dynamic Integrated model of Climate and the Economy (AD-DICE), to derive functions of adaptation costs and further present the trade-offs associated with a choice between mitigation and adaptation. The two strategies are seen as substitute strategies, in that, if the costs of adaptation are high, the demand to implement mitigation strategies goes up. They could also be complementary in that the best choice to reduce vulnerability to climate change would be to incorporate both in planning (Buob & Stephan, 2013). Bosello *et al*. (2012) utilized information on adaptation, mitigation, and climate change damages in several developed countries and calibrated it to fit the Adaptation in World Induced Technical Change Hybrid Model (AD-WITCH), to assess the costs and benefits of adaptation. Results from the study indicated that the consideration of both adaptation and mitigation strategies leads to an improvement in welfare. These are evaluated with an optimal mix of anticipatory adaptation strategies, reactive adaptation, and investment in adaptation innovations. It further considers both cooperative and non-cooperative scenarios.

In a non-cooperative scenario, each country maximizes regional welfare in the absence of mitigation and adaptation policies. In a cooperative scenario, there are the first-best policies. The global externalities are internalized and adaptation interventions are optimally implemented. However, the model only utilized partial information about non-market impacts and further considers several discount rates based on four no-policy scenarios. These are; the baseline scenario of the low damage-high discount rate, low damage-low discount rate scenario, high damage-high discount rate scenario, and the high damage-low discount rate scenario. The high discount rate applied was 3% and the low discount rate was 0.1%. The main criticism of the use of IAMs in assessing adaptation costs and benefits springs from the wrong representation of the climate change damage functions (Economides *et al*., 2018). While this indicates model misspecification, it may result in endogeneity during analysis.

Evaluation of costs and benefits of adaptation options for decision-making can also be analyzed by the use of various decision-making tools such as the Cost-Effectiveness Analysis (CEA), the Multi-Criteria Analysis (MCA), and the Cost-Benefit Analysis (CBA) (Noleppa, 2013; UNFCCC, 2011). In CEA, the overarching question is, which is the most cost-efficient way to achieve a particular objective given several alternatives? CEA, therefore, ranks the various adaptation strategies and it is only used if monetary values cannot be assigned to the benefits of adaptation strategies and if the benefits are evaluated in the same units. MCA is used when the benefits cannot be quantitatively measured or cannot be aggregated. MCA differs from CBA and CEA in that the ranking of the adaptation strategies is not only based on economic variables of costs and benefits but also qualitative variables such as ease of implementation, acceptability to the population, and the resources required (Noleppa, 2013). Using qualitative variables makes MCA a more subjective approach and the results or the outcome variables, therefore, lack clarity. CBA, MCA, and CEA are the three main techniques applied in the economic assessment of climate change adaptation options. While these differ in the extent to which the costs and benefits are estimated in monetary terms, they also differ from IAMs in the sense that the IAMs are not specifically designed to prioritize among the different alternatives.

A few studies have utilized the CBA approach for evaluating the costs and benefits of adaptation strategies. For instance, Ng'ang'a *et al*. (2017) used the CBA approach to assess the economic feasibility of proposed climate-smart agricultural practices in Ghana and evaluated both the private and social benefits and costs of the adaptation strategies. As earlier established, adaptation actions result in externalities and can either be positive or negative. These are not traded in the markets due to their 'public good' nature. Therefore, to estimate the shadow prices of these external effects, the study used the contingent valuation method to determine the marginal willingness to pay values.

Sain *et al*. (2017) in their assessment and comparative analysis of eight CSA practices in Guatemala applied the CSA-PF to prioritize the practices and further conducted a CBA for each of the practices that were deemed top priority among smallholder farmers in the maize and beans production systems. The results from the study were used to develop a CSA investment portfolio for the two production systems. This study modified and adopted this framework (Fig. 1) to assess the costs and benefits of prioritized innovations for selected agricultural value chains. The advantage of using these two approaches sequentially is that it allows different stakeholders within the specified value chains to assess the economic profitability and benefits of adopting CSA practices. This, in the long run, encourages the uptake, and up-scaling of these practices further boosts agricultural production, and reduction in risks associated with climate change.

2.4 Conceptual framework

The conceptual framework (Fig. 1) illustrates the interrelationship of key variables used in the study and how they assist to achieve the study's general objective. Prioritization is a fundamental step in developing a portfolio of economically viable climate adaptation strategies and innovations. The costs and benefits variables were evaluated on an incremental basis. Thus, the incremental costs and incremental benefits. To check whether the innovations, as prioritized made any economic sense to justify their implementation, four economic indicators were used: NPV, IRR, B/C ratio, and the payback period.

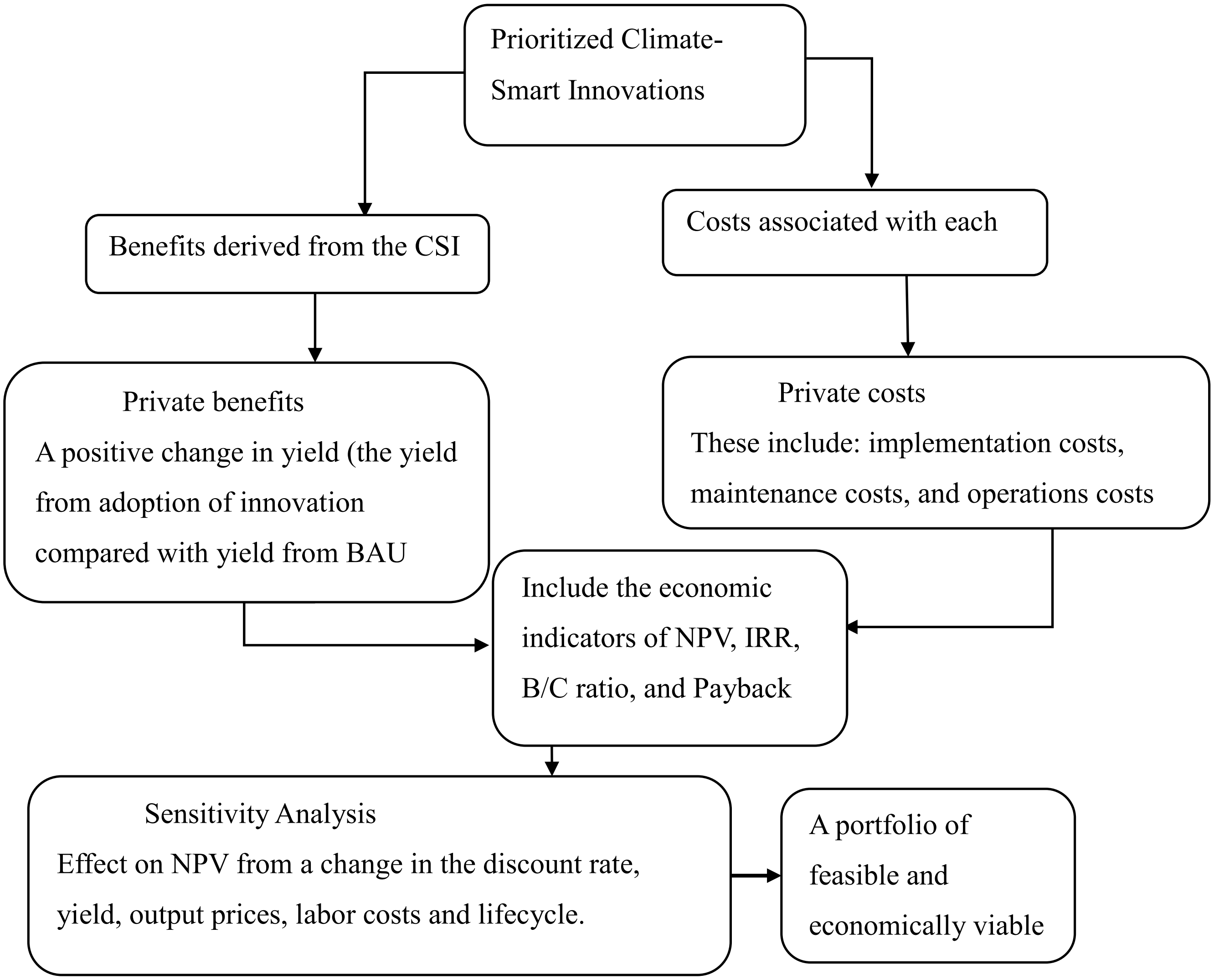

Figure 1: Conceptual framework

CHAPTER THREE

METHODOLOGY

3.1 Study areas

The main study areas were seven SSA countries; Ethiopia, Ivory Coast, Kenya, Malawi, Nigeria, Togo, and Zambia. However, two countries; Ivory Coast and Togo were later dropped from the analysis due to lack of response for the CBA data. The countries selected were among 16 others[3] with established GICs and a focus on the GIZ project in Africa being undertaken by the Alliance of Bioversity International and CIAT. The selected value chains were restricted to those specific to the GIZ project in each country. This was to ensure access to key resource persons; mainly agricultural experts and representative farmers to provide information on the climate risks and adaptation strategies being employed in the countries. For all the study countries, agriculture contributes a significant amount to the Gross Domestic Product (GDP) as indicated in Table 1 except for Zambia where the agricultural contribution to GDP is approximately eight percent. This is based on the fact that the economy of Zambia is predominantly characterized by copper mining (CIA World factbook, 2020).

Kenya and Ethiopia are located in the East Africa region characterized by a tropical climate. The mean annual temperatures for Ethiopia are in the range of 15-20^{o}C in the high-altitude areas and 20-30^{o}C in the lowlands. The temperature for Kenya is about 15^{o}C in the central highland regions which are cooler compared to the coastal lowland areas and experience highs of 29^{o}C on average. Rainfall for the two countries ranges between 50 and 350mm per month (Mcsweeney *et al*., 2010a; Mcsweeney *et al*., 2010b).

Malawi and Zambia are located in the eastern and central regions of southern Africa respectively with both experiencing a tropical climate. Mean temperatures for Malawi range between 18-19^{o}C in the winter season, and between 22-27^{o}C in the warm seasons. In Zambia, winter temperatures range between 15-20^{o}C and between 22-27^{o}C in the warm seasons. Rainfall for both countries ranges between 150-300 mm per month during the wet seasons (Mcsweeney *et al*., 2010c; Mcsweeney *et al*., 2010d)

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[3] The other countries within the project framework include Benin, Burkina Faso, Cameroon, India, Mozambique, Mali, and Tunisia.

Nigeria, Togo, and Ivory Coast are located in the West Africa region, all characterized by a climate mosaic ranging from tropical and semi-tropical to semi-arid in the northern regions. The climate of the West African region is highly influenced by the interaction of the Inter-tropical Convergence Zone (ITCZ) and the West African Monsoon or the Harmattan winds (Barry *et al.*, 2018; Karmalkar *et al.*, 2010). The rainfall variability in all the countries is highly influenced by the timing and the intensities of the ITCZ which is also caused by the *El Niño* Southern Oscillations. These result in climate shocks in the regions and coupled with anthropogenic activities, present challenges in achieving sustainable development, especially for the countries highly dependent on rain-fed agriculture.

Table 1. Description of the study areas

Country	**Agriculture contribution to GDP (%)**	**Specific areas**	**Value chains**
Kenya	35	Siaya, Bungoma, Kakamega, Nyandarua	Sweet potatoes, Milk
Malawi	29	Central Region	Soybeans, peanuts, cassava
Zambia	8	Eastern and Southern Provinces	Peanuts, Soybeans, Milk
Nigeria	21	Ogun, Oyo, Benue, Nassarawa, Kano, Kaduna, Plateau	Corn, Rice, Potato, Cassava
Togo	29	Maritime, Plateau, Kara, Centrale, Savanes	Soybeans, Cashew
Ivory Coast	21	Bas-Sassandra, Lagunes, Comoe	Cassava and Plantain
Ethiopia	35	Arsi region	Wheat, Broad beans
Average	**25%**		

GDP-Gross Domestic Product

The study counties were consciously chosen to represent the SSA region. Furthermore, the countries had active Green Innovation Centres and this eased access to the respondents with the help of experts on the ground. The countries are among 16 others under the GIZ project including Benin, Burkina Faso, Cameroon, India, Mali, Mozambique, Tunisia, and Vietnam.

3.3 Target population and sampling procedure

The population of interest was smallholder farmers who have adopted or implemented climate-smart adaptation strategies in the seven SSA countries. The multi-stage sampling procedure was employed. In the first stage, the seven SSA countries were purposively selected from the 16 other countries as they are representative of the three regions of SSA. In the second stage, the value chains of interest were selected based on those with active GICs. The value chains selected were based on their importance in increasing the yield per unit area to the smallholder farmers. The main goal of the GICs is to strengthen the resilience of smallholder farmers through promoting climate adaptation strategies and innovations that improve productivity, food and nutrition security. In the final stage, a purposive sampling procedure was used to reach the respondents with the assistance of GIC experts on the ground in each of the studied countries.

3.4 Data collection

3.4.1 Data collection process

Data were collected from two separate but consecutive online surveys using structured questionnaires (Appendix C and D). The main goal of the first interview was to gather data on climate adaptation strategies adopted among the smallholder farmers in the study areas as well as get detailed data on strategies that were prioritized. The second interview was aimed at collecting data on the costs and benefits associated with implementing the prioritized strategies. The prioritization process aimed to narrow down the strategies to facilitate computing their costs and benefits and involved four steps:

i. A detailed listing by key experts of the strategies that were considered most effective in increasing smallholder farmers' resilience to climate change.

ii. The respondents then selected at least two strategies at each stage of the value chain (input supply, on-farm production, post-harvest management, and marketing). The purpose was to select the strategies that had the highest impact on minimizing the effects of climate change in the selected countries for the specified value chains.

iii. From the selected strategies, the respondents then ranked each strategy based on their importance on a scale of one to eight, and factors such as ease of implementation, economic profitability, ease of use, and improving resilience to climate hazards. A score of one was indicative of high importance while a scale of eight represented low importance.

iv. The highly prioritized strategies (at least two) in each value chain were selected for further analysis of their costs and benefits.

During the second online survey, data was collected on the costs related to the implementation, maintenance, and operations costs during the entire lifecycle of the strategies and were compared with those incurred for BAU. The benefits involved the changes in yield multiplied by the prevailing market price both as they related to implementing the strategy and BAU.

3.4.2 Tools for data collection

The data and information were collected by the use of structured digitized questionnaires through online surveys. The questionnaires used in the study were designed in Microsoft Word Structural Character Modeling Language (ScML) format that enabled ease of filling by the respondents. The first set of questionnaires was administered to experts purposely selected from diverse sectors including research organizations, government institutions, and institutions of higher learning. The experts selected had been working closely with the GICs in the studied countries and were well conversant with the adaptation strategies adopted among smallholder farmers. The second set of questionnaires was administered to representative farmers purposively selected and identified in each value chain with the assistance of the GICs and GIZ project team in each of the countries (Table 2). Two top-priority strategies were selected in each value chain and setting a minimum threshold of five respondents for each, the number of respondents in each country was determined using Eq 5.

$$Respondents\ per\ country = VC \times INV \times MinR \tag{5}$$

Where VC represents the number of value chains per country, INV is the number of prioritized innovations per value chain, which is two, in the context of this study, $MinR$ is the minimum number of respondents to be targeted for each innovation.

Table 2: Total number of respondents in each country

Country	**Number of value chains**	**Number of innovations**	**Minimum respondents per innovation**	**Total**
Kenya	2	2	5	20
Zambia	3	2	5	30
Malawi	3	2	5	30
Nigeria	4	2	5	40
Togo	3	2	5	30
Ivory Coast	2	2	5	20
Ethiopia	2	2	5	20
Total				**190**

In the context of this study, data was collected within the first and second quarters of 2020, a period when most countries around the world were under lockdown and strict travel restrictions due to the emergence and rapid spread of the COVID-19 pandemic. The use of online surveys, though with the disadvantage of having sampling issues and lower response rates, especially in the agricultural sector where most researchers often rely on face-to-face contact with the farmer or farmer groups, presented an opportunity that enabled access to relevant information from key experts and representative farmers at a lower cost and within a shorter period. The internet has proven to be an important domain for conducting survey research especially for targeting virtual communities. Thousands of individuals, groups, and organizations, especially in SSA, are gradually embracing the use of technology in their operations.

Upadhyay and Lipkovich (2020) opined that the use of online interviews could help achieve a diverse sample of participants. With the current status of the COVID-19 pandemic, it is becoming increasingly urgent to refine the use of remote research methods. Although using online interviews is a marginalized method for data collection, it has the potential of eliminating time and space boundaries, reducing research costs, and encouraging an iterative reflection where both the participant and researcher can keenly reflect on the questions and provide thoughtful answers (Bowden & Galindo, 2015).

To overcome the limitations associated with online interviews, the participants were actively engaged with the help of GIC experts in each region and were informed before building a good rapport. The participants were also informed of the project time frame and reminders were sent about answering the interview questions. During the data collection stages, the respondents were encouraged to provide information that was adequate and relevant to the objectives of the research. This was done to mitigate challenges associated with sample adequacy. More so, a list of the experts interviewed was provided by the GIC contact personnel on the ground for each country. The representative farmers selected (also with the help of GIC experts) were highly knowledgeable about the adaptation strategies implemented at the time of the surveys (May-June 2020).

3.5 Data types and sources

The study utilized secondary data from published peer-reviewed articles to evaluate the first objective on the potential trade-offs and synergies of climate-smart practices among smallholder farmers in SSA and primary data collected through an online survey to achieve the second, third, and fourth objectives.

3.6 Data analysis

Both qualitative and quantitative techniques were used to analyze the data. The data and information from the online survey and interviews were entered directly into the CBA tool and STATA software for analysis (StataCorp, 2019). The CBA tool allowed for a systematic analysis of the benefits and costs associated with the adaptation innovations or practices, determined by how much the benefits exceed the costs or vice versa. Furthermore, the information provided a basis for making comparisons on the most economically viable option to choose among alternatives. The unit of analysis was based on the application of the adaptation strategy per unit of hectare under cultivation.

3.7 Analytical framework

3.7.1 Objective 1: To evaluate the trade-offs and synergies of climate adaptation innovations in each country.

The study undertook a systematic analysis of both published and grey literature. The Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) statement was used, Fig. 3 (The PRISMA Group, 2009). This approach was employed to assist in assessing the quality of the data and information from the literature sources. The literature search was conducted in the English language using a Boolean search function in the Scopus and Google Scholar search engines. The Scopus database was purposively selected since it provides easy access to articles with complex search terms; it also offers extensive coverage both in terms of discipline and quality of publication (Totin *et al*., 2018).

The search of the literature in the Scopus database was conducted in the English language using a Boolean search function. The search terms and phrases were separated using the Boolean operator (i.e., OR). That is “trade-offs” OR “synergies” OR “adaptation” OR “agriculture” OR “climate change” OR “climate-smart” OR “sub-Saharan Africa” OR “cost-benefit” OR “cost-effectiveness” OR “willingness to pay” OR “willingness to accept” OR “strategies” OR “innovations” OR “practices”. The search was conducted in the advanced document search field in Scopus (https://www.scopus.com).

The search in Google Scholar was also conducted using keywords and phrases. The articles that had at least one of the keywords in the title were selected. We limited the search in the following ways to further refine the results: (1) all literature is open access; (2) some literature comes from the research in Scopus in the last five years (2016–2020), and others comes from the Google Scholar in the last ten years (2011–2020); (3) subjects are agricultural and biological sciences and environmental sciences; (4) the document type is article; (5) the publication stage is the final stage; (6) the study area is only conducted in SSA; (7) the source type is journal; and (8) the language of the article is English. The literature search in both Scopus and Google Scholar was conducted from June 2020 to July 2020.

The articles were then exported in a Comma Separated Values (CSV) excel file with the main elements, including authors’ names, article titles, source titles, abstracts, and keywords. Using the exclusion/inclusion criteria described in the PRISMA flow diagram (Fig.3), the articles were screened to remove all duplicates and any irrelevant literature in the CSV excel file. This was followed by the screening of the title so that all publications that did not mention any of the keywords were excluded. The abstract and full-text screening was the final step. Full articles that were deemed relevant for the study were downloaded and later exported to the Mendeley citation application for full-text review. This review only included information that discussed the trade-offs and synergies of climate change adaptation strategies in SSA. The total number of articles considered for inclusion was 77 (Fig. 3).

The assessment criteria included the study area, the specific adaptation strategies, the methodology used, and the identification of the potential trade-offs and synergies of the strategies as those assessed in the previous literature. The findings from the literature on the trade-offs and synergies were organized into five broad categories under adaptation management: crop management, risk management strategies, soil/land management, water management, and livestock management strategies.

3.7.2 Objective 2: Evaluating the CSI among smallholder farmers in the selected value chains for each country

For the selected value chains in each country, the study conducted a descriptive analysis of the innovations that are being implemented by smallholder farmers. This was computed in proportions per country to see how the innovations are distributed. A comparison of innovations in similar value chains across countries was conducted to establish why a particular innovation may be predominant in one country as compared to another. The proportions were also computed per value chain to see how the innovations relate to the severity of the climate hazards as indicated by the respondents, and their distribution in each stage of the value chain: input supply, on-farm production, post-harvest, and marketing stage. The results are presented in tables as percentages and supplemented with information from other literature sources to see whether the findings corroborate with other research.

3.7.3 Objective 3: Assessing the prioritized Climate-Smart Innovations

The assessment of the prioritized innovations followed several steps as established by the CSA-PF (Fig. 2). The framework provides a process of targeting investments in top innovations and does this by identifying existing and promising CSI, assessing trade-offs, identifying the costs and benefits, and possible barriers of adoption (Corner-Dolloff *et al*., 2010). Information obtained from the online survey from the prioritization process was evaluated in STATA using simple tabulation. The scores were aggregated and standardized. From the initial assessment of the CSI options, a shortlist (at least 2 innovations per value chain) of the prioritized innovations was obtained for each country. The result of the ranking process with the criteria chosen for the ranking was presented in tables. This was done for each selected value chain in the seven countries. In this method, to develop a ranking of the innovations, a total of the rank values was obtained in each category. Spearman's rank-order correlation was computed to determine the relationship in the ranking of the innovations based on the climate hazards for each value chain Eq 6.

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \qquad (6)$$

Where ρ is Spearman's correlation coefficient, d is the difference between the ranks in each observation, n is the number of observations. The null hypothesis tested was that there is no significant difference between the ranks, $\rho = 0$, and the counterfactual in the relevant indicating that there is a relationship between the ranks $\rho \neq 0$. In Spearman's correlation coefficient, the ρ can take values from $+1$ to -1. A ρ of $+1$ indicates a perfect association of ranks, ρ of zero indicates no association, and ρ of -1 indicates a negative association of the ranks. The closer the rho is to zero the weaker the association between the ranks

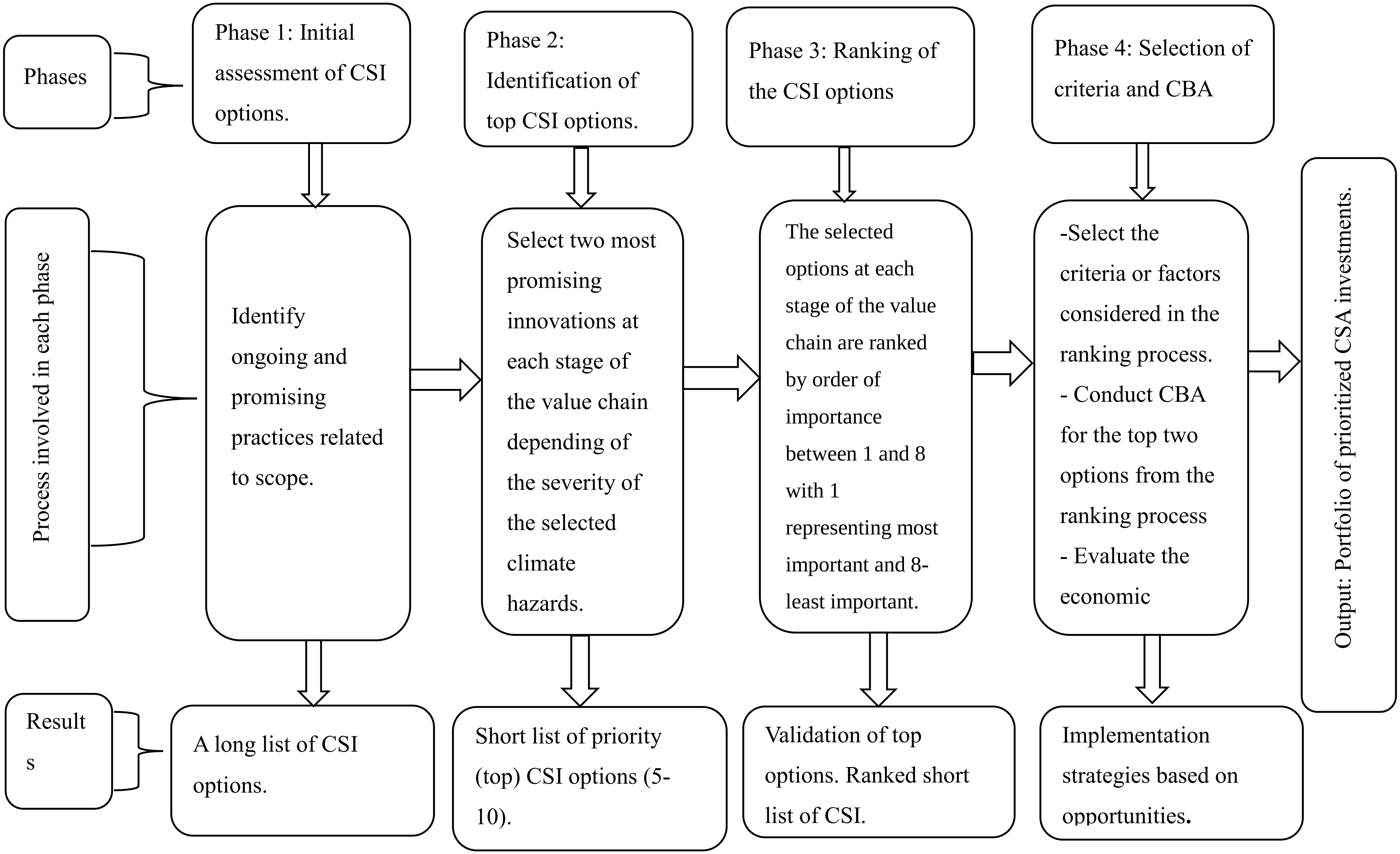

Figure 2: Climate-Smart Agriculture Prioritization Framework (CSA-PF)

3.7.4 Objective 4: Cost-Benefit Analysis of prioritized CSI for each value chain

The main objective of the CBA model, with a view on efficiency, was to maximize the difference between the benefits and costs of a given climate-change adaptation innovation. This study used four decision criteria under CBA (NPV, IRR, BCR, and the payback period). Assuming that there is a stream of costs and benefits that accrue and are realized from the implementation of a given adaptation innovation from the period ($t = 0$) to the terminal year ($t = T$), the general formula for NPV, that is, the sum of the discounted net benefits is represented by Eq. 7;

$$NPV\ (B, C) = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{7}$$

Where T represents the time to be considered, B represents the benefits, C represents the costs, and r is the relevant discount rate. The CBA approach uses a criterion whereby a particular policy action or project can or cannot be recommended on Cost-Benefit grounds. The innovation is deemed worthwhile if the NPV is greater than zero;

$$NPV\ > 0 \tag{8}$$

A positive NPV, Eq. 8, shows that at a particular point in time, the project is realizing more benefits than costs and it is therefore implemented. Provided that the projects or policy actions are independent and there are no constraints on the number that can be undertaken. This study compared the changes in costs and benefits of the proposed innovation compared to the BAU practice. The incremental benefits were evaluated in terms of the positive changes in yield multiplied by the price of the commodity. The incremental costs were evaluated as the changes in quantities used for inputs, services, labour and machinery, and equipment as they relate to the implementation, maintenance, and operations costs multiplied by the respective unit costs. Breaking down Eq. 5 to represent these changes is represented by Eq. 9 customized by Ng'ang'a *et al*. (2017).

$$NPV_j^{INV-BAU} = \sum_{t=1}^{T} \frac{1}{(1+r)^t} \left[\sum_j^j P_{jt} \times \Delta Y^{INV-BAU} - \sum_{j=1}^{j} C_n \times \Delta Q_{jt}^{INV-BAU}\right] \tag{9}$$

Where P_{jt} is the per-unit price of the commodity j in time t and was assumed to be constant, ΔY in the annual change in yield of commodity j between the BAU practice and the innovation, C_n represents the per-unit cost for the inputs/machinery/services/labour and was also assumed to be constant, $\Delta Q_{jt}^{INV-BAU}$ is the annual change in the units of inputs/machinery/labour/services used for the innovation compared to the BAU, r is the discount rate and T represents the lifecycle of the innovation. The second decision criteria under CBA are the IRR and the BCR tests. The IRR is an approach that calculates the discount rate which gives the project an NPV of zero and then compares this with the predetermined discount rate given by Eq. 10;

$$B_0 - C_0 + \frac{B_1 - C_1}{(1+i)^1} + \frac{B_2 - C_2}{(1+i)^2} + \cdots + \frac{B_T - C_T}{(1+i)^T} = 0 \qquad (10)$$

Where i, represents the discount rate that solves the equation (IRR). The decision rule while considering the IRR, Eq.11, is to consider implementing the innovation if the calculated IRR is more than the predetermined discount rate.

$$IRR \ > r \qquad (11)$$

The BCR test is given in Eq.12.

$$^{B}/_{C} = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} \Big/ \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \qquad (12)$$

The decision rule for the BCR, Eq.12, is similar to that of NPV where a policy action or project is deemed worthwhile if the ratio is positive and greater than 1. This implies that the benefits realized from adopting the adaptation strategy can completely offset the costs incurred with some residual benefits. Calculation of the payback period is a simplified way of evaluating the risk associated with investing in agricultural innovation. It represents the time required for the total amount invested to be repaid by the net cash flow generated (Mutenje *et al*., 2019). The payback period is represented by Eq. 13.

$$Payback\ period = \frac{Initial\ Investment}{Net\ cashflow\ period} \qquad (13)$$

3.7.5 Main variables for the CBA: Cost and benefit variables

The costs and benefits used in this study were evaluated while considering private adaptation as opposed to public adaptation. The costs included; initial capital investments, costs of seed purchase, cost of land preparation, the costs of maintenance of the innovation, and operational costs. For example, labour, inputs used, and costs of services during the period of adoption of the adaptation practice. The total cost function, in this case, is represented by Eq. 14;

$$TC_i = C_{0i} + \sum_{t=1}^{t=T} VC_i \qquad (14)$$

Where C_{0i} represents the initial capital investment required to implement an adaptation innovation, VC_i represents the variable costs associated with each adaptation strategy. Since the initial capital expenditure is a once-off payment, basically a stock resource, it is important to convert it into a flow by use of the annuity factor (Brent, 2006). This is expressed in Eq. 15

$$AF = \sum_{t=1}^{t=T} \frac{1}{(1+i)^t} \tag{15}$$

Equation 14 represents the sum of the present value of a unit stream of effects, in this case, costs. The relationship between the stock and the flow resource can be represented by Eq. 16

$$E = {C_{0i}} \Big/ {\sum_{t=1}^{t=T} \frac{1}{(1+i)^t}} \tag{16}$$

Where C_{0i} represents the initial capital sum and E is the equivalent annual cost of capital (flow resource). The main incremental benefits variables to be included in the analysis include the direct benefits from increased yields or output multiplied by the current market price for the output evaluated using Eq. 17.

$$TB = \Delta Y \times P_i \tag{17}$$

$$\Delta Y = Y^{INV} - Y^{BAU} \tag{18}$$

Where TB represents the total benefits, ΔY is the change in yield from BAU practice Y^{BAU} to the adoption of the innovation Y^{INV} from Eq.18, and P_i is the current market selling price for the output.

Table 3: Description of the CBA variables

Item	Description
Costs:	
Implementation costs	Includes the costs incurred at the beginning of implementing the practice (once-off costs and every year or every season).
Maintenance costs	Costs that are incurred every year or per season depending on the crop but exclude the one-off costs
Operational costs	Costs that deal exclusively with the harvest threshing, labour for harvesting, machinery used for harvesting, storage facilities
Machinery and equipment	Includes all the machinery, tools, and equipment used at the beginning of the practices (panga, wheelbarrow, ox plough, hoe, rope, spraying machine
Inputs	Includes for example costs of seeds, fertilizers, pesticides, and storage bags.
Services	Includes, for example, greasing of equipment, transportation costs sharpening of tools
Labour	Land preparation, land opening, fertilizer application, sowing, weeding, threshing, harvesting
Benefits: **Increased yield**	Increased yield/output from implementing the innovation. (Kgs/ltrs) compared to the BAU
Discount rate:	The current commercial bank interest rate on investment loans (%)
Practice lifecycle	Captures the period in years between implementing the practices to when they stop, then implement a new practice.
Price of outputs (Y)	Evaluated using current market prices of the specific product (USD per unit)
Price of Inputs	Evaluated using current market prices of specific inputs used (USD per ha)

USD stands for the United States dollars, Kgs stands for kilograms, ltrs stands for litres, BAU stands for Business, as Usual, and ha stands for hectares

3.7.6 Sensitivity analysis

Sensitivity analysis illustrates the effect of a change in a variable on the NPV. The treatment of uncertainty is very critical in any CBA study and especially when dealing with the subject of climate change. In the climate change adaptation discipline, sensitivity analysis is quite different from the basic analysis since it is based on scenario analysis. The optimistic-pessimistic scenarios approach was applied in conducting the sensitivity analysis. Five variables were tested on their effect on the NPV and the difference was tabulated and graphed (selling price, yield per hectare, annual labour costs, the discount rate, and the practice lifecycle). The optimistic scenario involves a 10 % increase in the selling price, yield, and practice lifecycle and a 10% decrease in the annual labour costs and discount rate. The vice versa is applicable for the pessimistic scenario. The results are further verified by using the switching values methodology. This involves finding the value of each of the five variables that give an NPV of zero. In both the scenario analysis and the switching values methodology, one variable is changed at a time *ceteris paribus* (keeping the other variables constant).

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter is organized into four sections. The first section 4.1 Trade-offs and synergies of climate-smart adaptation strategies present the trade-offs and synergies of climate change adaptation strategies from a systematic review of current literature. The second section 4.2 Evaluating the adaptation strategies for the selected GIC value chains shows descriptive statistics of the main Climate-Smart Innovations adopted among smallholder farmers within the Green Innovation Center (GIC) value chains in seven SSA countries. The third section 4.3 Assessing the prioritized innovations among smallholder farmers for selected value chains in five SSA countries**.** presents the results of the ranking of the prioritized innovations among smallholder farmers in the selected study sites. Finally, the fourth section 4.4 Cost-Benefit Analysis of prioritized innovations for selected value chains in the SSA countries**.** presents the results of the Cost-Benefit Analysis (CBA) for selected innovations in five Sub-Saharan African (SSA) countries for selected value chains.

4.1 Trade-offs and synergies of climate-smart adaptation strategies

The search produced 1528 from the Scopus database and 62 from Google Scholar documents after filtering using the criteria discussed in Scopus, a total of 1590 documents were considered for screening (Figure 3). The assessment criteria for the reviewed literature included the main methodologies applied, the specific SSA country, the climate-smart adaptation strategies, and finally the potential trade-offs and synergies associated with each strategy (see appendix A: Table A1).

By applying the PRISMA framework, results indicated that about 33% of the literature was review articles, and 13% incorporated various frameworks in the assessment. Approximately nine percent of the articles used the choice experiment modeling and nine percent utilized the Multivariate Probit and Simulation or scenario analysis. Other methodologies used included regression analysis, correlation analysis, Logistic model, contingent valuation (CVM), on-farm trials (OFTs), cost-benefit analysis (CBA), and the Trade-Off Analysis of Multi-Dimension Impact Assessment (TOA-MD). The Systematic Literature Review (SLR) methodology used in this paper could also be applied in the assessment of the trade-offs and synergies. SLR provided a step-by-step and all-inclusive approach to the literature search thus providing for a formal synthesis of the research findings.

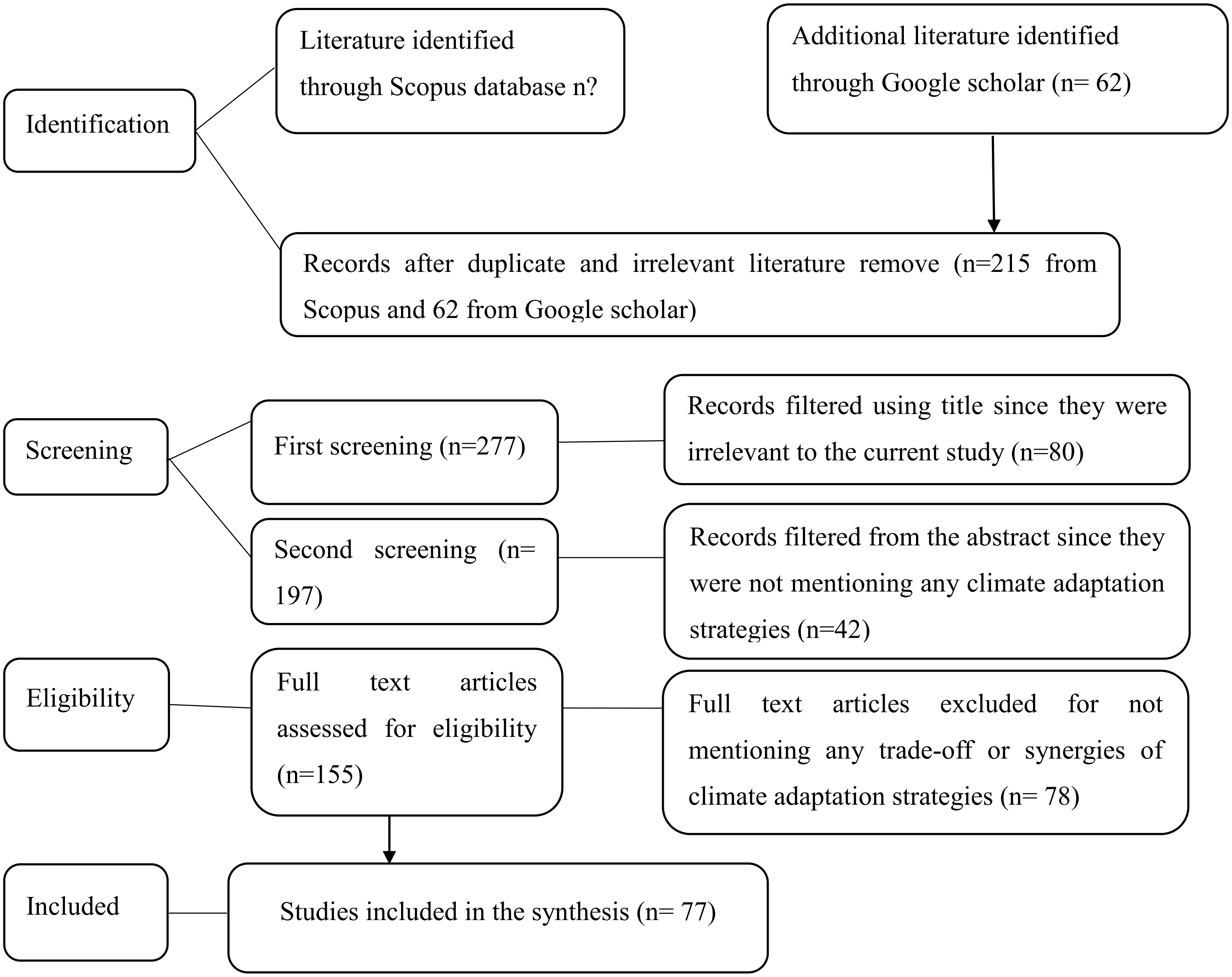

Figure 3: Flow diagram of the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA)

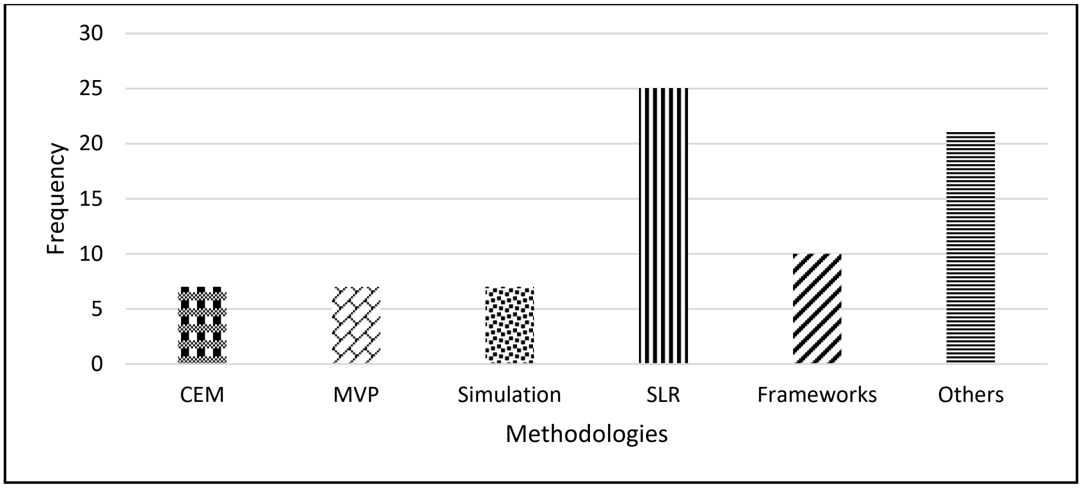

Figure 4: Main methodologies used in the reviewed literature

Note CEM- choice experiment methodology, MVP-multi-variate probit, SLR- systematic literature review.

Another criterion applied in the systematic literature review method was the identification of the specific country(s) or region(s) in SSA. Articles that mention Ethiopia as the study country were 15%, Kenya 12%, Ghana 7%, Burkina Faso 8%, and Malawi 7%. Other countries mentioned like Benin, Tanzania, Togo, Zambia, and Zimbabwe accounted for 1%. Forty-five percent of the articles mentioned the general SSA regions as the focus. However, these articles did not specify the focus country and were therefore categorized under SSA. This was applicable, especially in the review articles (Fig. 4).

The main climate adaptation strategies in this review included the introduction of new crop varieties, crop rotation, intercropping, use of index-based insurance, minimum/zero tillage, mulching, agroforestry, half-moons and *Zaï* pits, stone/soil/vegetation bunds, use of mineral fertilizers and/or manure, water storage or water harvesting, irrigation, and livestock management. The most frequently mentioned strategy was the introduction of new crop varieties while the least mentioned strategy was the half-moons and *Zaï* pits (Appendix A: Table A1).

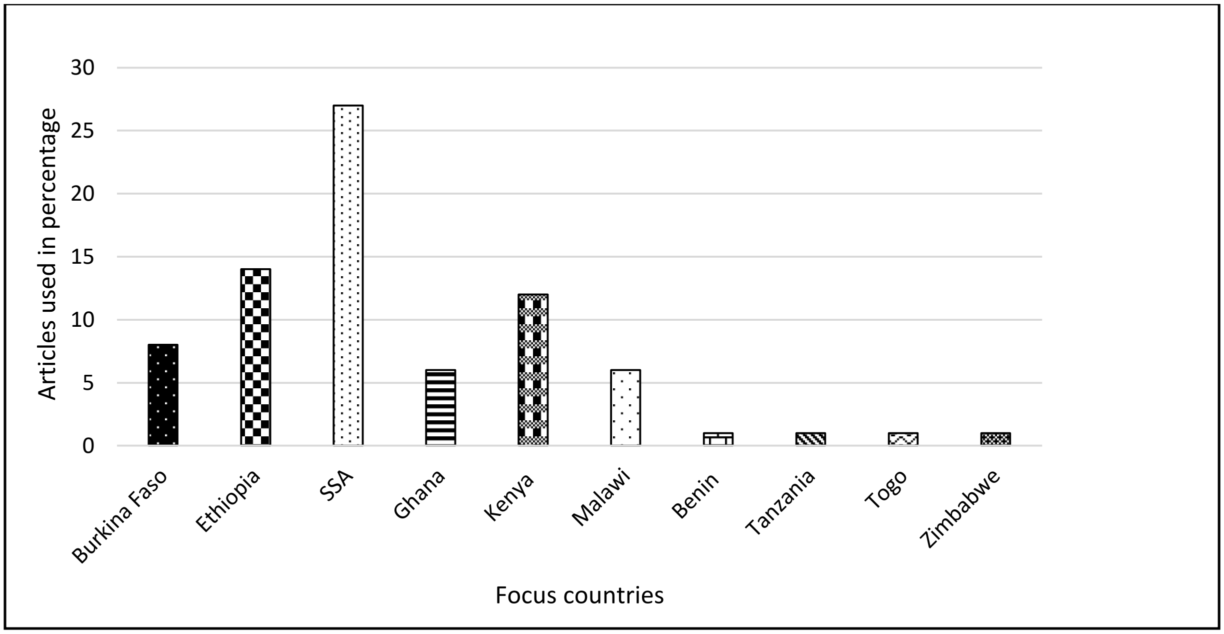

Figure 5: Study areas mentioned in the reviewed literature.

Results from the review indicated that implementing different climate adaptation strategies can not only produce substantial benefits alone but also produce significant benefits when integrated with other strategies. However, each strategy also presented trade-offs, often assessed as opportunity costs. These may be in the forms of added costs, increased or decreased labour requirements, competition with other systems, objectives to be achieved, or competition with the available resources. Since climate change is negatively affecting agricultural production in SSA, the most obvious trade-off is whether to implement an adaptation strategy or not. Morrison-saunders and Pope (2013) believed that this is a process trade-off because it reflects the realities of decision-making in an imperfect world with limited resources.

Climate change adaptation strategies are rife with substantive trade-offs because the decision-making process involves selection among competing uses. Although the present study only considered planned adaptation strategies, substantive trade-offs did involve substitution in time, place, or in-kind (Morrison-saunders & Pope, 2013). For instance, deforestation for commercial agricultural production may aim at improving the socio-economic aspects in terms of improved food security and job creation. However, this is at the expense of environmental protection and the destruction of traditional land used for hunting and foraging. Adaptation strategies such as agroforestry could help counter such trade-offs.

Table 4: Characteristics and categorization of data from the systematic literature review

Broad	Specific adaptation strategies	Study area	Sources
Crop management	New crop varieties	Burkina Faso, Ethiopia, Tanzania, Ghana, Benin, SSA	Hansen *et al*. (2019), Lankoski *et al*. (2018), Lasco *et al*. (2005), Loboguerrero *et al*. (2019), Maredia *et al*. (2019), Segnon *et al*. (2015), Sanou *et al*. (2016), Vom-Brocke *et al*. (2020), Webber *et al*. (2014), and Williams *et al*. (2018).
	Crop rotation	Ethiopia, Ghana, Benin, Kenya, Malawi, Togo, Nigeria, SSA	Agula *et al*. (2019), Asmare *et al*. (2019), Debaeke *et al*. (2017), Hansen *et al*. (2019), Njeru (2018), Segnon *et al*. (2015), and Rosenzweig and Tubiello (2007).
	Intercropping	Ghana, Burkina Faso, Benin, Kenya	Agula *et al*. (2019), Nassary *et al*. (2020), Sanou *et al*. (2016), and Segnon *et al*. (2015).
Risk Management	Index-based insurance	Burkina Faso, Togo, Ethiopia, Kenya, Nigeria, Tanzania	Agula *et al*. (2018), Ali *et al*. (2020), Asmare (2018), Fonta *et al*. (2018), Hansen *et al*. (2019), Loboguerrero *et al*. (2019), Teklewold *et al*. (2019), Vom-Brocke *et al*. (2020), and Wiréhn *et al*. (2020).

Soil/land management	Minimum tillage	Kenya, Ghana, Malawi, Tanzania,	Agula *et al*. (2018), Beddington *et al*. (2012), Fonta *et al*. (2018), Kiboi *et al*. (2017), Lankoski *et al*. (2018), Peter (2018), Rosenzweig and Tubiello (2007), Rhodes *et al*. (2014), Totin *et al*. (2018), Vermeulen *et al*. (2012), and Ward *et al*. (2016).
	Mulching	Ghana, Kenya, Zimbabwe, West Africa, Ethiopia, Malawi, Burkina Faso	Agula *et al*. (2018), Beddington *et al*. (2012), Debaeke *et al*. (2017), Homann-Kee *et al*. (2015), Kiboi *et al*. (2017), Peter (2018), Wainaina *et al*. (2016), Ward *et al*. (2016), and Zougmoré *et al*. (2018).
	Agroforestry	Malawi, Nigeria, Kenya, Benin	Beedy *et al*. (2014), Homann-Kee *et al*. (2015), Kakhobwe (2011), Loboguerrero *et al*. (2019), Rhodes and Atewamba (2019), Toth *et al*. (2017), and Teklewold *et al*. (2017).
	Half-moons and Zai pits	West Africa, Kenya	Zougmore (2018).
	Soil/stone/vegetation bunds	Kenya, Ghana, West Africa, Ethiopia	Ahiale *et al*. (2019), Asrat and Simane (2017), Lankoski *et al*. (2018), Tarfasa *et al*. (2018), Wainaina *et al*. (2016), Wolka *et al*. (2018), and Zougmore (2018).

	Mineral fertilizer and /or manure	Kenya, Ethiopia, Zimbabwe, Malawi	Cedrez *et al*. (2020), Homann-Kee *et al*. (2015), Kakhobwe (2011), Kurgat *et al*. (2020), Olubode *et al*. (2018), Teklewold *et al*. (2019), Tongwane and Moeletsi (2018), and Wainaina *et al*. (2016).
Water management	Water storage	Kenya, SSA	Hölscher *et al*. (2017), Lankoski *et al*. (2018), Oremo *et al*. (2020), and Recha *et al*. (2016).
	Irrigation	Nigeria, Kenya, Togo, Ethiopia, SSA	Gadédjisso-Tossou *et al*. (2018), Kurgat *et al*. (2020), Mabhaudhi *et al*. (2018), Njoroge *et al*. (2018), Olubode *et al*. (2018), Suckall *et al*. (2014), and Tarfa *et al*. (2019).
Livestock management	Breeding of climate-tolerant species, matching stocking rates to pasture production and pasture rotation, changing animal feeds, livestock insurance, uptake of animal health services, and improvement of animal husbandry	Malawi, Zimbabwe, Kenya, Nigeria, West Africa, SSA	Bjornlund *et al*. (2017), Descheemaeker *et al*. (2016), Lankoski *et al*. (2018), Loboguerrero *et al*. (2019), Wainaina *et al*. (2016), and Wiréhn *et al*. (2020).

Note: SSA refers to sub-Saharan Africa. West African countries include Ghana, Nigeria, Togo, Mali, Burkina Faso, and Ivory Coast

The trade-offs and synergies as assessed relate to changes in productivity, allocation of scarce financial and natural resources, labour requirements, and the resultant effects on the environment such as emission of greenhouse gases (GHG), thus air quality or protection of biodiversity (more information is provided in appendix A Table A1).

Results from the review indicated that implementing the different climate adaptation strategies produces substantial benefits not only as stand-alone but also when integrated with other strategies. However, each strategy also presented trade-offs often assessed as opportunity costs. These were in the form of added costs, increased labor requirements, competition with other systems, objectives to be achieved, or competition with the available resources. Since climate change is negatively affecting agricultural production in the SSA region, the most obvious trade-off lies in the decision to implement an adaptation strategy or not. This, according to Morrison-saunders and Pope (2013) was categorized as a process trade-off because it reflects the realities of decision-making in an imperfect world with limited resources.

Consequently, climate change adaptation strategies are rife with substantive trade-offs because the decision-making process involved selecting among competing uses. Since the present study only considered planned adaptation strategies, substantive trade-offs do involve substitution in time, place, or in-kind (Morrison-saunders & Pope, 2013). For instance, clearing forests for commercial agricultural production may aim at improving the socio-economic aspects in terms of improved food security and job creation. However, this is at the expense of environmental protection and the destruction of traditional land used for hunting and foraging. Adaptation strategies such as Agroforestry could help counter such trade-offs.

4.1.1. Crop management strategies

These are strategies or innovations that are aimed at improving crop production under climate change. These include the breeding and cultivation of new crop varieties, crop rotation, intercropping, and multi-cropping.

New crop varieties

Climate change is affecting cropping systems in SSA with varying degrees of intensity. New crop varieties with increased resistance to heat shocks are recommended especially in areas with high temperatures and water scarcity (Debaeke *et al*., 2017). Different choices include the use of short gestation crops, the use of flood and or drought-tolerant crops, planting of disease and pest-resistant crops among others (Webber *et al*., 2014). New crop varieties, when combined with soil management practices, such as mulching or use of fertilizers, provide a buffer to effectively cope with climate risks (Sanou *et al*., 2016), resulting in increased yield (Loboguerrero *et al*., 2019) and high income (Lasco *et al*., 2005). The additional income earned from the selling of output can also be used to purchase food for the household, thus contributing further to food and nutrition security according to Vom-Brocke *et al*. (2020), and dietary diversity (Lasco *et al*., 2005; Loboguerrero *et al*., 2019). Varieties with shorter cropping cycles have a positive effect on households' food security than those with longer cycles (Vom-Brocke *et al*., 2020). Diversifying the cultivars increases production outputs and reduces yield variations (Hansen *et al*., 2019). The high yields, in turn, result in high biomass production for farmers to use as mulch or as feed for livestock (Sanou *et al*., 2016). The mulch further provides mitigation benefits as they help to increase the soil carbon storage capacity (Lankoski *et al*., 2018), and enhances the provisioning function of ecosystems (Suckall *et al*., 2014).

The decision to adopt new varieties may present opportunity costs or trade-offs within the production system. For instance, farmers may incur additional transaction costs of acquiring reliable information about new varieties and even face moral hazardous behavior of being sold for poor quality seeds. Suppliers could also face added costs of information search on farmers' preferences and may face the risks of having unsold inventory (Maredia *et al*., 2019). Timely and accurate information and technical advisory services are therefore crucial for making informed investment decisions (Williams *et al*., 2018).

New varieties are often cultivated in intense systems with heavy reliance on agrochemical inputs such as fertilizers and pesticides. These lead to environmental degradation, loss of biodiversity, soil, and water pollution from leaching or surface run-off, and increased greenhouse gas (GHG) emissions (Segnon *et al*., 2015). They may also be bred for specific characteristics that make them unable to cope with seasonal or site-to-site fluctuations (Njeru, 2018). Furthermore, the breeding process takes a longer period before it can be distributed to farmers and realize the benefits from adoption (Rosenzweig & Tubiello, 2007). The breeding is also knowledge-intensive and requires careful selection since they may differ in their ability to utilize and fix nitrogen from the atmosphere and improve soil fertility (Nassary *et al*., 2020). Cultivation of new varieties is a long-term adaptation strategy and may cause significant changes in the socio-technical system like the development of cooperatives or farmer groups, seed companies, and consultants with possible lock-ins in the adoption of innovations (Debaeke *et al*., 2017).

Crop rotation

Asmare (2018) defines crop rotation as a practice of growing and managing more than one type of crop across space or time and taking advantage of the benefits from the interactions of different crops. The system allows for the variation in the choice of crop to be planted every season or year (Agula *et al*., 2018). Most farmers make use of leguminous crops in the rotations which allow for better utilization and efficient use of organic fertilizer, reduces N_2O emissions, and enhances N fixation in soils (Debaeke *et al*., 2017). This, in turn, increases soil fertility, increases soil organic matter content, and water-holding capacity, and eventually results in increased yield (Hansen *et al*., 2019; Rosenzweig &Tubiello, 2007).

The use of the different types of crops in the rotations provides room for the cultivation of high-biomass crops (Peter, 2018). These further provide mitigation benefits such as improving carbon sequestration, nutrient cycling, reduction in soil degradation (Debaeke *et al*., 2017), enhancing the resilience of ecosystems, and aiding in having varied seasonal requirements of resources, both financial and natural (Asmare *et al.*, 2019).

Intercropping

This type of cropping system involves the cultivation of two or more crops at the same time during the same cropping year or season on the same piece of land (Nassary *et al*., 2020). Like crop rotation, intercropping is often done with leguminous crops such as beans, cowpeas, and soybeans among others. The legumes fix nitrogen from the atmosphere through a synergistic relationship with Rhizobium *spp*. bacteria (Agula *et al*., 2018). This process restores the fertility of degraded soils and provides residual nutrients for the subsequent cereal crop (Sanou *et al*., 2016).

According to Nassary *et al*. (2020), intercropping cereals and legumes increase the efficiency in the utilization of limited resources. For example, the cereal crop improves the availability of iron (Fe), requirements for the legume crop while the legume crop augments the N and P intake for the cereal crop. Smallholder farmers who implement intercropping in their farming systems can get more than one output from the same piece of land. This is an excellent food security strategy, since households can diversify their diet requirement, sell more than they would have in mono-cropped systems, and the extra income could be utilized in other households' investments. Further, the more the output, the more biomass is generated, providing more forage for livestock feed or as mulch in improving soil fertility and soil water infiltration capacity.

Though the cultivation of intercrops may be utilizing environmental resources synergistically, intercropping, especially in interspersed rows, is labor-intensive (Sanou *et al*., 2016). Labor is mostly required for operations in the field such as sowing, weeding, and spraying to suppress pests, weeds, and diseases seeing that mechanization is impossible. This presents a trade-off in the reallocation of available labor among the existing systems. Intercropping also provides a canopy cover which results in a micro-climate with higher relative humidity. This micro-climate may catalyze the occurrence of pests and diseases (Nassary *et al*., 2020). As a result, a farmer may be forced to invest in alternative methods to deal with the pest and diseases presenting a trade-off in terms of added costs.

4.1.2 Risk management strategies: index-based insurance

Risk management strategies have the potential to effectively stabilize farm production and income, mitigate extreme events, and overcome any adoption barriers (Hansen *et al*., 2019). Most literature defines index-based insurance as a climate adaptation strategy or innovation that stimulates pay-outs based on a weather index that correlates with agricultural losses (Asmare *et al.,* 2019; Vom-Brocke *et al*., 2020). For example rainfall, area average yield, vegetation remote sensing, or modeled water stress. Insurance helps farmers to overcome moral hazardous behavior or hidden action, adverse selection or hidden information, and the high costs of verifying losses since it is based on an index (Agula *et al*., 2019; Asmare *et al.*, 2019; Tarfa *et al*., 2019). The uptake of insurance also protects farmers' assets against the adverse effects of climate events (Hansen *et al*., 2019), promotes access to credit, and stimulates the adoption of improved farm technologies and practices (Loboguerrero *et al*., 2019). Index-based insurance makes faster pay-outs to farmers which enables them to make further investments in agricultural inputs leading to higher outputs and income (Fonta *et al*., 2018). The fast pay-outs also help farming households maintain their productive capacity by minimizing the need to liquidate assets in case of any shocks (Teklewold *et al*., 2019), strengthening their resilience as well as assisting them to get out of the vicious circle of poverty.

The insurance industry in Africa accounts for only 0.5% of the world's insurance industry (Fonta *et al*., 2018). This could be attributed to the high premiums that prevent farmers from taking up insurance (Ali *et al*., 2020). Insurance also involves direct costs to the farmer thus affecting the farm economy directly (Wiréhn *et al*., 2020). This presents a trade-off with financial resource allocation among different household uses. It also has rigid enrolment criteria and requires coherent stakeholder involvement in analyzing insurance products and policies. This implies that smallholder farmers with little or no knowledge of the available insurance products are unlikely to take up insurance. The provision of education and information especially through farmer groups or cooperatives is, therefore, a viable policy option to increase the uptake of insurance products.

1.1.3 Soil/ land management strategies

These are innovations and strategies that focus on improving or enhancing soil health (Aggarwal *et al*., 2016). These include minimum/ zero tillage practices, mulching, agro-forestry, half moons and Zai pits, stone/soil/vegetation bunds, use of mineral fertilizers, and manure.

Minimum/zero tillage

Minimum tillage is one of the principles of conservation agriculture that advocate for very minimal soil disturbance to prevent any adverse impacts on the soil's structural properties (Peter, 2018). It helps maintain and restore soil fertility (Fonta *et al*., 2018; Totin *et al*., 2018; Vermeulen *et al*., 2012), prevents soil erosion, increases the soil water holding capacity, and helps to conserve soil carbon which enhances the agricultural soil structure and fertility (Agula *et al*., 2018). According to Rosenzweig and Tubiello (2007), minimum tillage practices can help to store about 8GT of carbon in agricultural soils, thus providing mitigation benefits and reduced field operations and input requirements.

However, there are various trade-offs associated with minimum tillage practices. For instance, there are fixed costs associated with the practice and it takes a relatively long time horizon (3 years or more) before any perceived benefits can be observed (Ward *et al*., 2016). It increases the incidences of pests and diseases and soil waterlogging (Lankoski *et al*., 2018). The trade-off in terms of weed management may result in shifts of labor use from other farm operations like land clearing to weed management (Rhodes *et al*., 2014). Minimum tillage could also lead to lower yields especially if it is solely adopted. Tied ridge tillage, for example, if combined with mulching could lead to significant increases in yield performance and stability.

Mulching

Agula *et al*. (2018) defined mulch as a layer of materials, most often leaves that are applied to the soil surface to conserve soil moisture, reduce the growth of weeds, and improve soil fertility. The mulch impedes the evaporation of water from the soil surface by protecting it from direct solar radiation (Kiboi *et al*., 2017). This further improves the efficiency of water use and increases water infiltration, and aggregate soil stability (Wainaina *et al*., 2016).

The mulch provides adequate moisture, temperature, and organic materials which then creates a conducive environment for microbial activities (Peter, 2018). These microbial activities improve the soil structure, and soil nutrient cycling, and enhance soil carbon sequestration (Debaeke *et al*., 2017). The increased concentration of soil organic matter from additional mulch significantly prevents soil erosion from wind and water by reducing the impact on the soil. When combined with the use of organic or inorganic fertilizers, it could increase the relative yields by 229.5% (Homann-Kee *et al*., 2015). Furthermore, if mulching is combined with contour stone or soil bunds it could result in improved yield and reduces the runoff of fine sediments to water sources downstream (Zougmore, 2018).

In considering the trade-offs, there are opportunity costs of retaining the mulch from crop residues (Ward *et al*., 2016). For example, the use of mulch as feed for livestock may reduce the volume available to be used in the cropping system and vice versa (Beddington *et al*., 2012; Rigolot *et al*., 2015). Reduction in feed availability from the mulch may have great repercussions on milk production, mortality, and calving rates, especially during the dry seasons (Homann-Kee *et al*., 2015). It is also labor intensive and the uptake depends on farm labor availability. Additional labor is especially required for weed control and transporting the mulch to feed the animals (Debaeke *et al*., 2017). Mulching is also not applicable in areas with high rainfall since it may result in water logging thus having negative impacts on yield and productivity.

Agroforestry

Agroforestry entails the cultivation of multi-purpose fodder trees on farmlands (Toth *et al*., 2017). Beedy *et al*. (2014) explained agroforestry as a set of land-use practices that combines trees, shrubs, palm trees, or bamboo with crops or animals. Example of agroforestry systems being promoted in the SSA region includes: mixed intercropping for example maize and tree species, annual under-sowing, dispersed systematic intercropping homestead, boundary, and woodlots, improved fallow[4], agro-pastoral parkland, fodder banks, multi-storey or home garden and contour hedgerows (Beedy *et al*., 2014).

Agroforestry systems contribute to significant reductions in GHG emissions from agricultural production activities (Loboguerrero *et al*., 2019). This is achieved through an increased rate of soil carbon sequestration (Homann-Kee *et al*., 2015; Teklewold *et al*., 2020). The system also provides multiple income sources for farming households for example timber and wood fuel production from rotational woodlots (Rhodes *et al*., 2014; Toth *et al*., 2017). In the long run, it positively impacts the food and nutrition security of smallholder farming households (Partey *et al*., 2017).

Agroforestry, when combined with crop diversity such as intercropping or crop rotation, maximizes the use of soil resources such as water and nitrogen (Debaeke *et al*., 2017). This is based on the fact that trees recycle crop nutrients from below the crop root zone back to the upper soil layers thus improving soil fertility (Kurgat *et al*., 2020). The different tree species provide habitat for biodiversity, modify the micro-climate to reduce high-temperature extremes, contribute to environmental protection, and suppress the occurrence of pests and weeds (Segnon *et al*., 2015). Short-term tree species in agroforestry systems may increase crop yields by 200%. This results in an increased build-up of biomass and the crop residues may further be incorporated into the soils as mulch or utilized as feed for animals (Beedy *et al*., 2014). However, there is a potential for reduced yields of smaller crops due to the competition with trees for water, sunlight, and soil nutrients (Lankoski *et al*., 2018). This competition for resources can also be through allelopathy[5]. In a mixed system where there is also livestock production, the area of land allocated for the tree seedlings needs to be protected to prevent destruction from the animals while grazing (Kurgat *et al*., 2020). These present substantial trade-offs concerning the objectives to be achieved and also competition among the different crop and livestock systems.

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[4] An Agroforestry technology consisting of planting mainly legume tree/ shrub species in rotation with cultivated crops.

[5] Refers to the chemical inhibition of one plant or organism by another due to the release of substances into the environment that act as germination or growth inhibitors.

Half-moons and Zai pits

A Zai is a small pit dug manually, especially during the dry season and a handful of animal manure or compost is supplied per pit. A half-moon is a basin 2 meters in diameter manually dug with a hoe and a barrowful of animal manure or compost is supplied to each half-moon. These are applicable in dry areas or on extremely degraded soils and help in improving the productivity of the soils. The incorporation of animal manure or compost provides the benefits of increasing agricultural productivity, vegetative cover, and carbon sequestration. They also catalyze the regrowth or regeneration of local species. The major trade-off associated with the half-moons and Zai pits is that they are labor-intensive and their adoption depends on labor availability.

Stone/soil/vegetation bunds

Soil bunds are embankments made by ridging soils on the lower side of a ditch along a sloped contour. They act as barriers to prevent run-offs, reduce soil erosion, and further increases the water retention capacity of soils (Ahiale *et al*., 2019). Contour stone bunds are erosion control structures that are built using quarry rocks or stones placed in a series of two or three at a height of between 20-30 cm from the ground and spaced 20-50 m apart depending on the topography (Zougmore, 2018). In high-rainfall areas, the bunds can be planted with grass for livestock fodder or with trees that provide fruit or fuel (Asrat & Simane, 2017b).

Tarfasa *et al*. (2018), in a case study from south Ethiopia, found that plots with stone/soil bunds in semi-arid areas were more productive than those without. However, areas with higher rainfall were not constructing the bunds due to the moisture-conserving effects of the technology. In the case of heavy rainfall events, it could lead to production losses (Lankoski *et al*., 2018). The bunds help in controlling floods and soil erosion and reduce the sedimentation of water bodies, leaching, and transportation of chemicals such as fertilizers, herbicides, and pesticides to water bodies, thereby improving life underwater (Ahiale *et al*., 2019). Incorporating the use of biological measures such as mulching, organic fertilizer, and planting grass, or trees with the bunds was found to enhance the efficiency of water and nutrient use.

On the flip side, the construction and maintenance of the bunds are labor-intensive and present added costs and more labor time requirements (Wolka *et al*., 2018). They also take up a significant portion of the land thus reducing the areas available for crop cultivation presenting trade-offs concerning the allocation of scarce land and labor resources (Tarfasa *et al*., 2018).

In areas of high rainfall, the bunds may cause waterlogging thus having deleterious effects on crop production. In mixed crop-livestock systems, if the bunds are not properly constructed, they could easily be destroyed by roaming animals (Teklewold *et al*., 2020). The implementation of the bunds could also involve a huge initial investment yet it takes a substantial period before the benefits are realized. Financially, resource-limited farmers may consider this as a trade-off and would rather invest their money in economically viable options. The benefit, however, lies in their longer lifetime compared to other practices. Tesfaye *et al*. (2016) found the effective lifetime of soil and stone bunds to be 12 and 8 years respectively if they are properly maintained.

Use of mineral fertilizers and/or manure

Involves the use of either organic or mineral fertilizers since they present different benefits to the texture and fertility of soils (Wainaina *et al*., 2016). The combined use of both leads to greater yield responses as opposed to using one at a time or on its own. The application of fertilizer also requires better timing, precision, and effectiveness through improved placement and use of appropriate quantities. This helps to reduce the amounts of nitrogen lost (Tongwane & Moeletsi, 2018). Also, applying fertilizer near the plant root, at smaller or more frequent rates, especially in periods of high crop demand, has the potential of reducing losses and improving yield quality and quantity (Olubode *et al*., 2018). When fertilizers use is incorporated with modern seed or improved seed varieties, they provide the synergistic effects of enhancing productivity and producing more crop residue that can be used as mulch in smallholder farming systems. If used in combination with crop diversification strategies such as intercropping or crop rotation, especially with leguminous crops, it may result in increased efficiency of fertilizer use (Homann-Kee *et al*., 2015).

The majority of smallholder farmers in the SSA region rely on inorganic fertilizers to sustain crop production. However, yields are still low and a synthesis of the literature indicated that this was attributed to low fertilizer use among smallholder farmers in the region (Cedrez *et al*., 2020). The utilization of chemical fertilizers is low due to their high costs, inaccessibility, or limited availability to smallholder farmers. The adoption of integrated soil fertility management was found to be labor-intensive and costly especially because of the necessity of purchasing inorganic fertilizer (Kurgat *et al*., 2020). The manufacturing of nitrogen fertilizer also results in emissions of GHG (Tongwane & Moeletsi, 2018). Any excessive use, especially near water catchment areas, could lead to the pollution of waterways and aquifers resulting in damage to aquatic ecosystems (Beddington *et al*., 2012).

4.1.4 Water management strategies

These are strategies aimed at improving the efficient utilization of water resources as required for improved agricultural productivity. Most smallholder farmers in SSA heavily rely on rainfall as the main source of water for crop and livestock production.

Water storage or water harvesting

Smallholder farmers have constructed water harvesting structures within their farms such as water tanks, open earth dams, boreholes, and ponds to supply the water needed for drinking and household consumption, livestock, and crop production (Recha *et al*., 2016). These go a long way in improving food production without any additional water requirements from the ecosystems thus contributing to the conservation of biodiversity (Oremo *et al*., 2020). If these systems are well-designed and consistently maintained, they result in higher yields, reduced production variability, and greater climate resilience. Roof water harvesting reduces excessive flow on land thus reducing soil erosion. It also acts to bridge the irrigation water gap, thus relieving any excess pressure for water requirements from local water sources such as streams and rivers, and further promotes responsible water use (Hölscher *et al.*, 2017).

However, the construction of the water storage facilities requires huge capital investments and under apt conditions, the farmers can recover the cost of investment within 2-4 cropping seasons (approximately two years) (Oremo *et al*., 2020). This presents trade-offs in terms of added costs and re-allocation of financial resources among the different household uses. Also, smallholder farmers who have implemented open earth dams and ponds are faced with the challenge of increased evaporation rates in the dry seasons, seepage losses, and siltation resulting in reduced water quality and quantity (Recha *et al*., 2016). In the long run, this results in substantive negative effects on water and food security for the households.

Irrigation

Irrigation allows for reliable access to water required for crop production which protects farmers from the periodic shocks of climate change and variability (Kurgat *et al*., 2020; Njoroge *et al*., 2018). Efficient systems such as micro-irrigation (drip and sub-surface) should be favored in place of macro-irrigation (overhead or sprinkler). This is based on the fact that micro-irrigation systems result in the efficient use of scarce water resources without much wastage (Mabhaudhi *et al*., 2018). As stated in FAO, drip irrigation technology may increase input use efficiency by 90% compared to flood irrigation (50%) (FAO, 2018). Kurgat *et al*. (2018), in a survey of 685 farming households in rural and peri-urban regions of Kenya observed that improved irrigation systems are also less labor-intensive and conserve water compared to the use of traditional methods such as watering cans which may take 13% of the total costs and high application rates (approximately 640-1600mm/year). This reduces production costs and guarantees an increase in household income even during the dry season. The majority of farming households combine irrigation with land/soil management practices such as increased soil fertilization or diversification of crops (Tarfa *et al*., 2019). This allows for maximum productivity and improved quality of the harvest (Olubode *et al*., 2018). It also allows for year-round agriculture, reduced emissions, increased water security, increased income, and improved household food and nutrition security (Suckall *et al*., 2018).

Deficit irrigation which is the activity of intentionally and systematically under-irrigating a crop increases water productivity which construes in lower energy and increased water use efficiency (Mabhaudhi *et al*., 2018). Intermittent irrigation which is a strategy mostly applicable under the System of Rice Intensification (SRI) involves alternate irrigation and passively or actively drying the field for several days (Beddington *et al*., 2012). This strategy may reduce methane emissions by over 40% as reported by Jarvis *et al*. (2011), without having any negative effects on the yields.

The proliferation of areas fit-out for irrigation agriculture provides smallholder farmers with the opportunity of increasing yield and productivity in a sustainable way. However, this may bring challenges, especially with resource governance thus negatively impacting ecosystems in riparian lands (Oremo *et al*., 2020). The governance challenges stem from conflict resolution in resource use especially between public and private users or between the upstream and downstream users of a river (Bjornlund *et al*., 2017). This further increases the challenge of supplying irrigation water to the farmlands through increased investment costs for operations and maintenance. The costs are even more in cases where the farm is located far from the water sources. Therefore, in the initial stages of implementing an irrigation system, cash is an important requisite for purchasing equipment such as generators, drill boreholes, wells, and labor (Nigussie *et al*., 2017; Toth *et al*., 2017).

In as much as irrigation may be an effective adaptation option, it could significantly result in increased GHG emissions if the system is fuelled by fossil energy. The use of water in irrigation, if not efficiently managed, influences N dynamics in the soil and could ultimately lead to N_2O emissions in the atmosphere (Tongwane & Moeletsi, 2018). This is because Nitrogen is highly volatile. Also, it is challenging to incorporate livestock production within the irrigation systems because of the competing uses, and the livestock can destroy or disturb the irrigation lines especially if it is an improved system such as drip irrigation (Kurgat *et al*., 2020).

4.1.5 Livestock management strategies

The indirect effect of climate change from heat stress has significantly increased the vulnerability of livestock to diseases, and reduced milk production, and fertility (Lankoski *et al*., 2018). Main climate adaptation strategies under livestock management include the breeding of climate-tolerant species, matching the stocking rates to pasture production, changing animal feeds or improving the feed, and uptake of livestock insurance and good animal health and husbandry (Bjornlund *et al*., 2017; Descheemaeker *et al*., 2018).

Livestock keeping facilitates the use of organic manure in crop production and is also attributed to the lower rates of fertilizer use among smallholders in SSA since the farmers may see these as substitutes (Wainaina *et al*., 2016). The application of manure from livestock waste serves to improve soil fertility, increased soil organic matter, improve soil water holding capacity, and have the potential for carbon sequestration (Mekonnen *et al*., 2020; Rosenzweig & Tubiello, 2007). The livestock also provides food, draft power, social status, and saving, may serve as collateral in credit or loan applications, and act as a buffer against risks. Thus, it allows for the uptake of other adaptation and mitigation options (Tarfa *et al*., 2019). The integration of livestock in irrigation systems has the potential of improving productivity. However, systems without fencing or unrepaired fencing may allow the livestock in the farms to cause damage. If the livestock does not have an alternative source of water, the fence could also be perceived as a barrier in preventing the livestock from accessing water (Bjornlund *et al*., 2017).

Estimates indicated that by the year 2000, the livestock sector contributed to approximately 18% of the total GHG emissions. This figure, as projected in a study by Loboguerrero *et al*., (2019), is expected to rise by 40% by 2050 if we continue with business-as-usual practices. The main emissions from livestock production are through enteric fermentation[6] by ruminants and livestock manure. In SSA, enteric fermentation contributed to about 85% of the total methane emissions between the periods of 1994 and 2010 (Tongwane & Moeletsi, 2018). A possible mitigation for these emissions includes the provision or cultivation of forage with higher digestibility and energy-dense foods (Tongwane & Moeletsi, 2018). Other options include the recovery of biogas for on-farm energy production (Rosenzweig & Tubiello, 2007), reducing the feed quantity and quality (Campbell *et al*., 2016), proper management of pasture lands can also aid in carbon sequestration and offset some of the emissions from livestock production (Lankoski *et al*., 2018).

Areas with high and persistent rainfall could increase the incidences of diseases and pests that particular livestock species may not be adapted to. This results in a trade-off since it may require the farmer to change their livestock composition and management strategies presenting additional costs of investments (Zougmore, 2018). These are also based on an index and are aimed at protecting herders' main productive assets in the event of a shock or herd loss (Vom-Brocke *et al*., 2020; Zougmore, 2018). The initial uptake of insurance may present added costs to the farmer/pastoralists having an impact on income. However when they receive payments from the insurance in case of a shock, then this has a positive effect on the farm economy thus enabling productivity increases or the purchase of more livestock and feed (Wiréhn *et al*., 2020).

4.2 Evaluating the adaptation strategies for the selected GIC value chains in the study countries

Table 5 represents the distribution of the respondents in each country after the two online surveys were conducted. A total of 306 respondents were reached in the first phase while 153 respondents were interviewed in the second phase. Togo and Ivory Coast were later dropped from CBA analysis due to lack of response.

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[6] It is a process that occurs within the digestive system of ruminant animals (cattle, buffalo, sheep, and goats) where the microbes' resident in the animal ferment the feed consumed and methane is emitted as a by-product when the animal exhales.

Table 5: Total number of respondents interviewed in each country

Country	Respondents from Phase 1	Respondents from Phase 2
Ethiopia	46	20
Kenya	46	22
Malawi	34	29
Nigeria	78	54
Ivory Coast	22	N/a
Togo	48	N/a
Zambia	32	28
Total	**306**	**153**

Table 6 presents the main climate adaptation innovations adopted among smallholder farmers at different stages within the milk and sweet potato value chains in Kenya. The results indicated that within the milk value chain, the four main adaptation strategies adopted by a majority of the respondents were commercial forage (63%), zero-grazing (17%), and the use of good agricultural practices (GAPs) (20%). In the sweet potato value chain, results indicated that the main ongoing adaptation strategies include the use of GAPs (93%), the use of clean seed varieties (71%), and the development of storage centres and aggregation units for farmers (18%). High adoption of commercial forage was highly attributed to the increase in demand for animal products such as milk and meat and this emerging market has to be supported by robust forage and fodder availability.

Table 6: Adaptation innovations in the milk and sweet potato value chain in Kenya

	Value chains		
Adaptation innovations	Milk (%)	Sweet potatoes (%)	Stage of the value chain
Commercial forage	63	n/a	Input supply
Zero grazing	17	n/a	On-Farm production
GAP	20	93	On-Farm production
Use of clean seed varieties	n/a	71	Input supply
Storage centers/ Milk coolers	10	18	Post-harvest

GAP stands for Good Agricultural Practices and n/a stands for not applicable.

The use of quality forage is most common since it results in improved livestock productivity (milk and meat). The quality of the forages is therefore important to animal production, fertility, health, and business productivity. Smallholder livestock farmers are constrained by small landholdings (1-5 acres). As a result, they purchase fodder to supplement the forages produced on-farm. This presents added costs to the farmer and therefore policy should be geared toward encouraging farmers to produce their fodder to meet the deficit.

In Kenya, the forage species that contribute to ruminant diets are mainly tropical grasses and are supplemented with forage legumes and crop residues. These include elephant grass (*Pennisetum purpureum*), Rhodes grass (*Chloris gayana*), maize (*Zea mays*), Lucerne (*Medicago sativa*), Kikuyu grass (*Pennisetum clandestinum*), Masai love grass (*Eragrostis superba*), African foxtail grass (*Cenchrus ciliaris*), among others. Forage legumes in Kenya have the potential of being used as a source of protein in forage. Examples include vetch (*Vicia sativa*), lablab, and sweet potato vines (*Ipomea batatas*). However, the use of forage legumes in Kenya is still low due to inadequate information and education on their benefits.

Zero grazing systems are being promoted as an intervention by a national policy requiring the efficient utilization of scarce land resources and also preventing the overexploitation and degradation of rangelands. Market linkages are also evolving with the active participation of all chain actors and especially cooperative societies and producer groups. Storage facilities or milk coolers help to minimize any post-harvest losses and ensure that the quality of output (for both milk and sweet potato value chains) is maintained.

In the sweet potato value chain, the use of clean planting material at the production stage reduces the incidence of pests and diseases such as the sweet potato weevil (*Cylas formicarius*), sweet potato virus, or Alternaria leaf spot. Good practices such as crop rotation, field sanitation, early planting, destruction of infected vines, and spraying of insecticides and herbicides could minimize the occurrence of these pests and diseases. Proper management, therefore, ensures increased productivity and quality of output. These results are akin to the findings of Mbayaki and Karuku (2021) which evaluated agronomic practices adopted among smallholder farmers in Kenya including new varieties of sweet potatoes and comparison between yield and growth of monocrops compared to intercrops.

Table 7 presents the main adaptation innovations among smallholder farmers in Ethiopia in the broad beans (faba or horse beans) (*Vicia faba*), honey, and wheat (*Triticum aestivum*) value chains. Results indicated that a majority of smallholder farmers producing broad beans that were interviewed adopted crop rotation (29%), use of hermetic bags (29%), and use of improved ploughing technique (Berken Maresha) (29%). In the wheat value chain, the main innovations include the use of improved seeds (20%), the use of mobile seed cleaner (20%), crop rotation and diversification (13%), and the adoption of the Alemayehu Row-seed Technology (ART) (10%). In the honey value chain, agroforestry (33%) and the use of modern hives (17%) were the main climate adaptation strategies adopted. Incorporating faba beans (*Vicia faba*), in crop rotation systems was popular among smallholders in Ethiopia due to its ability to fix atmospheric Nitrogen by up to 200 kg N ha^{-1} (Karkanis *et al*., 2018). This, therefore, translates to significant improvements in soil physical properties, maintains soil fertility, reduces GHG emissions, and minimizes the use of inorganic fertilizers. Faba bean is often used as a break crop in cereal production due to its potential of increasing the yield and seed protein content of the successive cereal crop.

Table 7: Climate adaptation innovations in the broad beans, wheat, and honey value chains in Ethiopia

Adaptation innovations	Value chains			Stage of the value chain
	Faba beans (%)	Wheat (%)	Honey (%)	
Use of hermetic bags	29	n/a	n/a	Post-Harvest
Crop rotation	29	13	n/a	On-Farm production
Improved plough (Berken maresha)	29	n/a	n/a	On-Farm production
Composting	13	n/a	n/a	On-Farm production
Agroforestry	n/a	n/a	33	On-Farm production
Modern hives	n/a	n/a	17	Input and production
Mobile seed cleaner	n/a	20	n/a	Input supply
ART	n/a	10	n/a	Input and production
Crop diversification	n/a	13	n/a	On-farm production
Use of improved seeds	n/a	20	n/a	Input-supply

ART stands for Alemayehu Row-seed Technology and n/a stands for not applicable.

The hermetic storage of cereals and legumes as defined by Leal *et al*. (2017), is the use of plastic containers and hermetic (polythene) bags to prevent any oxygen penetration into the stored product. Thus, a hermetic storage unit is air-tight and moisture-tight. The technique has gained popularity in Ethiopia as it helps to prevent insect and pest infestation thus preserving the quality of the harvest. Hermetic storage is beneficial as it eliminates the use of pesticides or refrigeration for food preservation. It also significantly reduces the build-up of aflatoxins in the harvest which pose a major public health hazard (Villers *et al*., 2010)

Soil tillage with the maresha plough was adopted among smallholder farmers in Ethiopia and was often used to prepare flat seedbeds either during sowing or after crop emergence. Pulled by two oxen, the maresha plough breaks but doesn't turn the soil (Nyssen *et al*., 2011). As a result, the technique allows for soil and water conservation in the farmland. It helps to conserve soil moisture, therefore, improving water productivity and reducing weed growth (Leye, 2007). When combined with other adaptation strategies such as composting, the maresha plough has the potential of providing positive synergistic effects of increased yield, soil fertility, biodiversity protection, and mitigation benefits. However, in another study conducted in Northern Ethiopia, cross-ploughing using the maresha plough was found to increase surface run-off thus leading to severe land degradation and subsequent water pollution (Muche *et al*., 2014).

Row planting of wheat gained popularity among smallholder farmers in Ethiopia due to its positive impact on welfare compared to traditional broadcasting (the sowing of seed at a high seed rate without consideration for spacing or arrangement). Row planting results in increased yield as it provides sufficient space for weeding, branching out, nutrient uptake, and reduced competition among the seedlings. Climate adaptation strategies such as crop rotation, use of mobile seed cleaner, crop diversification, use of the improved seed, agroforestry, and extension services ensure increased yield, product quality, climate resilience, and sustainability within the different value chain systems. Compared to the findings of Ayele and Tarekegn (2022) in comparing the technical efficiency of row planting to traditional broadcasting who opined that there is room to increase wheat yield using broadcasting through proper regulation of the amount of fertilizer, urea, labor, and seed requirements.

The main climate adaptation innovations among smallholder farmers in the milk, peanut, and soybeans value chain in Zambia are presented in Table 8. Results indicated that a majority of the respondents in the milk value chain adopted feeding regimes and/or fodder production (33%), ratification insemination (25%), and proper management of dairy cows (25%). Results also presented similar climate adaptation strategies among respondents in the peanut and soybean value chains. Thus, the use of certified seeds/local seed banks (39% and 36%), conservation farming/agroforestry practices (30% and 21%), and dry season land preparation (21%) in the soybean value chain.

Table 8: Climate change adaptation innovations in the milk, peanut, and soybean value chains in Zambia

Adaptation innovations	Value chains			Stage of the value chain
	Milk (%)	Peanut (%)	Soybean (%)	
Feeding regimes/ fodder production	33	n/a	n/a	Input stage
Ratification insemination	25	n/a	n/a	On-farm production
Management of dairy cow	25	n/a	n/a	On-farm production
Use of certified seeds	n/a	39	36	Input stage
Conservation farming/agroforestry	n/a	30	21	On-farm production
Dry season land preparation	n/a	n/a	21	On-farm production

n/a stands for not applicable

The growth in population, rapid urbanization, and increased income among households in Zambia have resulted in a rise in demand for livestock products (milk and meat). The livestock sector, therefore, needs to improve the productivity of dairy animals to keep up with the demand. Supplementary feeding and efficient utilization of crop residues as feed was seldom adopted among smallholder dairy farmers in Zambia. The farmers are more inclined to allow the livestock to freely graze on natural grass. During drought periods, this practice is unsustainable as the farmers incur huge losses from poor milk yield and increased animal mortality rate as there is inadequate and poor quality grass for grazing.

In recent years, the government of Zambia has increased its efforts toward encouraging farmers to improve dairy animal productivity for increased income. One of the strategies applied is to motivate dairy farmers to grow their forage as they are assured of the feed quality. Also, the animals will receive a balanced diet in terms of proteins, carbohydrates, and minerals contained in the forages in the form of legumes and grasses. As a result, they will realize increased calving rates and increased milk production of dairy animals.

Another strategy applied was the promotion of good animal husbandry through the provision of artificial insemination and veterinary services. These strategies were aimed at improving the conception and calving rate, reducing disease infection, and minimizing the mortality rate of dairy animals.

Improved Information and Communication Technology (ICT) in agricultural value chains has proved to be a useful tool for knowledge transfer. This is because it is a cost-effective method for training farmers and enables information to reach and be accessible even in remote areas. Similar to findings from a study conducted by Young and McComas (2016) in which results indicated that in Zambia, the Farm talk[7] radio show and the Better life book[8] are the most popular media utilized by smallholder farmers to access information. Both information sources are aimed at increasing agricultural productivity, household income, food security, and household health. They further encourage dialogue among farmers on sustainability and GAPs such as the use of compost, agroforestry, sustainable tillage practices, improved crop varieties (Table 8), and mulching (Nash *et al*., 2016; Young & McComas, 2016).

Table 9 presents the main climate-smart innovations among smallholder farmers in Malawi within the cassava, peanut, and soybean value chains. Results show that a majority of smallholder farmers in Malawi used improved seed varieties in all value chains (cassava (60%), peanut (31%), and soybeans (50%). Other important adaptation innovations implemented include conservation agriculture (46%), processing of cassava flour (20%), mulching (23%), and inoculation of soya seeds (50%).

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[7] Farm talk is a radio show in Zambia that is aired twice weekly (Wednesday and Friday) by radio Breeze produced by Community Markets for Conservation (COMACO).

[8] The Better life book is a laminated print publication that is distributed to lead farmers and contains information often discussed in the farm talk show.

Table 9: Climate change adaptation innovations in the cassava, peanut, and soybean value chains in Malawi

Adaptation innovations	Value chains Cassava (%)	Peanut (%)	Soybeans (%)	Stage of the value chain
Improved seed varieties	60	31	50	Input supply
Processing of cassava flour	20	n/a	n/a	Post-harvest/ marketing
Seed multiplication	20	n/a	n/a	Input supply
Conservation agriculture	n/a	46	n/a	On-Farm production
Mulching	n/a	23	n/a	On-Farm production
Inoculation of soya seed	n/a	n/a	50	Input supply

n/a stands for not applicable

Improved cassava seed varieties are high-yielding and tolerant to the Cassava Mosaic Virus Disease (CMD). However, most smallholder cassava farmers in Malawi use local seeds that are susceptible to CMD thus resulting in low yields (Alene *et al*., 2013). Some of the constraints to the adoption of improved varieties include inadequate availability of clean planting materials and inadequate information on their availability (Kanyamuka *et al*.,2018). Processing cassava into flour is a value-added strategy that allows farmers to get additional income from the sale of output. The processed flour can be utilized as a mix in porridge or cake making thus increasing food and nutrition security for the households. Results from another study by Kanyamuka *et al*. (2018), show that the processing of fermented cassava flour (*Kondoole*) in Malawi is mainly executed by farmers in rural areas. At the formal level, businesses and cooperatives are also engaged in processing both *Kondoole* and High-Quality Cassava Flour (HQCF) that are sold in formal markets and supermarkets.

According to Mugwagwa *et al*. (2019), the production of soybeans in Malawi is characterized by the use of proper management practices such as appropriate land preparation, good seed variety, choosing the appropriate planting and harvesting time, facilitating good nitrogen supply through conservation tillage practices and mulching (Table 8) and application of inoculants. Plausible reasons why inoculation is popular among soybean producers in Malawi are that it ensures good seed germination and growth, adds to soil fertility, and prevents insects and crop root diseases. Similar to the findings of Vugt (2018) an on-farm experimental study conducted among smallholder farmers in Malawi found that inoculation of the soybean seeds resulted in better nodulation. Also, when inoculation was combined with fertilizer application it resulted in a tripling of the profits within 1 year.

Table 10 presents the main climate-smart innovations in the cassava, maize, potato, and rice value chains in Nigeria. The results indicated that most smallholder farmers have adopted GAP (35%) in the cassava and rice value chain (33%), use of ICT in the maize value chain was adopted by 24% of the respondents. In the potato value chain, the majority of the respondents adopted controlled water management (56%), while 44% adopted changing planting times as a climate adaptation strategy.

Table 10: Climate change adaptation innovations in the cassava, maize, potato, and rice value chains in Nigeria

	Value chain				
Adaptation innovations	Cassava (%)	Maize (%)	Potato (%)	Rice (%)	Stage of the value chain
GAPs	35	n/a	n/a	33	On-farm production
Use of ICT	n/a	24	n/a	n/a	Marketing
Controlled water management	n/a	n/a	56	n/a	On-farm production
Changing planting time	n/a	n/a	44	n/a	On-farm production

Similar to cassava production in Malawi, a majority of the respondents were engaged in cassava processing since processing increases the shelf life, removes any cyanogenic compounds, and increases the product’s acceptability among consumers. The results from Table 9 resonate with those of Tambo and Abdoulaye (2012) who present the use of drought-tolerant variety and shifting of planting dates as the main adaptation innovations among smallholder farmers in the Nigerian savanna. In a study of smallholder rice farmers in Southwestern Nigeria, Arimi (2014) outlined the use of early warning information, the use of shallow groundwater, planting of drought-resistant rice seeds, and taking up farm insurance as the most common climate adaptation strategies.

Table 11 outlines the main climate adaptation innovations in the cashew and soybean value chains in Togo. There were no responses to the ongoing adaptation strategies in the peanut value chain. The results indicated that in both the cashew and the soya value chains, most respondents in Togo implemented the use of improved seed (54% and 48% respectively) and change in sowing date (24%) in the soybean value chain.

Table 11: Climate adaptation innovations in the cashew and soybean value chains in Togo

	Value chain		
Adaptation innovations	Cashew	Soybean	Stage of the value chain
Improved seeds (availability and quality)	54	48	Input supply
Change in sowing time	n/a	24	On-farm production

Production using improved seeds is practiced by most smallholder farmers since it minimizes the risks of crop failure, especially during prolonged drought periods. Improved seed varieties are high-yielding, climate-resilient, and resistant to most pests and diseases. These results (Table 11) are akin to those determined by Ali *et al*. (2020) for a study in rural Togo in which from a sample of 500 smallholder farmers, an average of 54% used improved seeds that are high yielding and drought-tolerant. An average of 58% adjusted the planting dates in response to variability and changes in climate. From the same study, climate intelligence innovations such as improvement in agro-meteorological information forecast and advertisement were found to help farmers increase their adaptive capacity, improve crop yield, and reduce poverty incidences.

4.3 Assessing the prioritized innovations among smallholder farmers for selected value chains in five SSA countries.

Figure 6 presents the results of a customized framework for phase 2 and phase 3 of the CSA-PF. The two most promising innovations in each stage of the value chain for the selected enterprises are presented. A shortlist of the prioritized innovations is generated for CBA computation (Table 12). Results indicate that in most of the countries, the highly prioritized innovations, in terms of importance, were the use of improved varieties that are high yielding and tolerant to climate change. For the milk value chains in Kenya and Zambia, the highly prioritized innovation was commercial fodder production. Plausible reasons why the use of improved seed varieties was highly prioritized in most crop value chains was because they reduced the risks of crop failure or yield losses. This is most applicable, especially during extreme climate events such as prolonged drought, late onset of rainfall, or long flood periods. In the long run, this ensures household income is stabilized, and household food and nutrition security are enhanced due to the all-year-round food supply. Improved varieties have also been proven to be highly nutritious containing essential minerals and vitamins for proper human growth and development, especially in infants. For instance, sweet potato tubers contain proteins, carbohydrates, fiber, energy, vitamins A, B1, B2, B3, B6, C, E, and minerals such as Calcium, Phosphorous, and Folate, Magnesium, Iron, Potassium, Zinc. The yellow and orange-fleshed roots also provide pro-vitamin A (Makini *et al.,* 2018).

Table 12: Standard rank of the most prioritized innovations

Country	Value chain	Innovation	Standard Rank
Kenya	Sweet Potato	GAP	1
		New/improved seed varieties	2
	Milk	Commercial fodder production	1
Nigeria	Potato	New/improved seed varieties	3
	Rice	GAP	1
Malawi	Cassava	New/improved seed varieties	4
	Soybeans	Conservation agriculture	2
		New/improved seed varieties	1
Zambia	Peanut	Conservation agriculture	3
	Soybean	New/improved seed varieties	2
	Milk	Commercial fodder production	1
Ethiopia	Faba beans	New/improved seed varieties	3

GAP=good agricultural practices

The three most prioritized innovations among smallholder farmers in all areas were the adoption of good agricultural practices, the adoption of improved seed varieties, and conservation farming. The main evaluation criteria for prioritization were the importance of innovation in increasing productivity, building resilience against climate change risks, and mitigation. Innovations that had ranks between 1 and 4 were selected. A rank of 1 indicates that innovation is deemed to be very important. A Spearman’s correlation was run to assess the relationship between the ranks of the strategies at each stage of the value chain (Table 13). All the ranks were independent of each other.

Table 13: Spearman's Rank correlation coefficients

Variables	Promising-Rank_1	Promising-Rank_2	Promising-Rank_3	Promising-Rank_4
PromisingRank_1	1.000			
PromisingRank_2	-0.087	1.000		
PromisingRank_3	-0.414	-0.232	1.000	
PromisingRank_4	-0.282	-0.276	-0.111	1.000

Spearman rho (r_s) =-0.111

The correlation coefficients indicate that there was a negative but insignificant relationship between the ranks for 153 of the observations, r_s= -0.11. This implies that the ranking of the strategies in each stage was independent of each other. Plausible reasons could be because the impact of each innovation is stage-specific. At the input stage, smallholder farmers consider the application of fertilizer to be very important for stable/ improved productivity. At the farm production stage, the use of clean seeds, mulching, or minimum tillage practice were ranked as very important. At the post-harvest and/or the marketing stage strategies such as strengthening cooperatives and farmers' groups are deemed important (Fig. 6). The main reason for prioritizing the innovations as cited by a majority of the respondents was that they were able to realize increased productivity and thus more income from the practices. More so the practices were easy to implement on the farm. However, the quantification of the costs and benefits as it pertains to membership in a group or cooperative is complex and requires the application of institutional theories and institutional economics.

A similar study by Khatri-Chhetri *et al*. (2017) used a participatory assessment method to evaluate the top CSA practices among farmers in 16 villages of Rajasthan in India. The results from the study indicated that most farmers prioritized crop insurance, weather-based crop agro advisories, rainwater harvesting, site-specific integrated nutrient management, contingent crop planning, and laser land leveling. These results may differ slightly from the findings of the present study as the criteria and methodology used for the prioritization process are different. In the study by Khatri-Chhetri *et al*. (2017), farmers' preferences were obtained using two steps, first the study conducted a farmer-focused group discussion and was asked to rank the technologies on a score of 0-3. The second stage involved a bidding exercise using pseudo money for only those technologies that were prioritized to evaluate farmers' willingness to pay values. However, similarities do occur in prioritizing soil nutrient management through the adoption of conservation agriculture practices and crop planning through the adoption of improved seed varieties or GAPs such as proper timing of planting.

The prioritization of climate-smart innovations is imperative as it allows for better adaptation planning. Dogulu and Kentel (2015) identified additional criteria used for prioritization such as the costs, benefits, effectiveness, sustainability, time spent for planning and implementation, flexibility, social acceptance, and equitability among others. Shirsath *et al*. (2017) used the three criteria for climate smartness (productivity, resilience, and mitigation) to identify the most prioritized practices for different future climate scenarios. The application of different frameworks and methodologies in the prioritization of climate adaptation strategies allows for diversity in portfolio development and management (Khatri-Chhetri *et al*., 2017; Mwongera *et al*., 2017; Shirsath *et al*., 2017).

	KENYA	ETHIOPIA	ZAMBIA	MALAWI	NIGERIA
INPUT SUPPLY	**Milk:** Commercial forage, early warning information **Sweet potato:** Use of GAP, improved seed variety	**Faba**: Improved seed, compost manure. **Honey**: extension services, alternative pollen sources. **Wheat**: improved seed, quality inputs	**Milk**: forage production, financial services **Peanut**: improved seed, dry season land preparation **Soybean**: Improved seed,	**Cassava:** Seed multiplication, improved seeds **Peanut:** crop diversification, improved seed **Soybean:** Improved seed, inoculation	**Cassava:** contract farming, GAP **Maize:** GAP, quality inputs **Potato:** GAP, changing planting time **Rice:** GAP, alternate
ON-FARM PRODUCTION	**Milk**: Storage of hay, GAPs **Sweet potato:** Early warning information, use of GAPs	**Faba**: Crop rotation, compost manure **Honey**: extension services, agroforestry. **Wheat**: Row-seed technology, crop diversification	**Milk**: dairy cow management, financial services **Peanut**: Agroforestry, mulching **Soybean**: Improved seed, agroforestry	**Cassava:** Improved seed, seed multiplication **Peanut:** crop diversification, improved seed **Soybean:** improved seed, inoculation	**Cassava:** contact farming, GAP **Maize:** quality inputs, GAP **Potato:** changing planting time, on-farm water management **Rice:** quality inputs, broad based training
POST-HARVEST	**Milk**: Dairy cooperative, storage of hay and silage **Sweet potato**: Storage centers, value addition (flour production	**Faba**: Hermetic bags, market linkages. **Honey**: Extension services, value addition **Wheat**: Extension services, service centers	**Milk:** Milk hygiene, market linkages **Peanut:** cooperatives, lead farmer networks **Soybean:** 'Farm talk', early warning tech.	**Cassava:** Improved storage, processing flour **Peanut:** Aflotoxin control, high yield varieties **Soybean:** improved seed, farmer groups	**Cassava:** post-harvest management, processing plants **Maize:** GAP, post-harvest technology **Potato:** post-harvest management, changing planting time
MARKETING	**Milk**: Dairy cooperative, one stop shop **Sweet potato**: market linkages, value addition	**Faba**: Service centers, market linkages. **Honey**: market linkages, value addition **Wheat:** extension services, market linkages	**Milk:** market linkages, cooperatives **Peanut:** 'Better life book, lead farmer networks **Soybean:** 'Farm talk', weather index insurance	**Cassava:** Processing flour **Peanut:** High yield variety, Aflotoxin control **Soybean:** farmer groups, improved varieties.	**Cassava:** SME-loop, contracts **Maize:** market linkages, cooperative business schools **Potato:** GAP, changing planting time **Rice:** 3D animations, broad based training

Figure 6: The two most prioritized innovations in each country at each stage of specified value chains-results of step 2 of the CSA-PF.

4.4 Cost-Benefit Analysis of prioritized innovations for selected value chains in the SSA countries.

CBA is computed for three innovations; GAP, improved seed varieties, and conservation agriculture for selected value chains (Table 14). The main economic indicators under consideration included the NPV presented in USD, the IRR, the BCR, and the payback period. The results indicate the profitability and viability of all the prioritized climate adaptation practices in all the countries. The discount rate used in most countries was 10% except for Malawi and Ethiopia where the discount rates were 14% and 12% respectively. This is because the rate used was similar to the interest rates used by banks in advancing investment loans which vary across countries. The payback period, which is the time it takes for the practice to fully repay its initial capital, varied between 1 and 2 years for most of the practices (Table 14). This indicates acceptability among smallholder farmers since the shorter periods allow them to repay any credit advanced to them and at the same time enjoy the profits from the investment.

Table 14: Cost-Benefit analysis of prioritized innovations in 5 SSA countries

			Probability distribution average					
Country	Value Chain	Practice	r (%)	NPV (USD)	IRR (%)	B/C	T (Yrs)	PP (Yrs)
Kenya	Sweet potato	Improved seed	10	8,738	111	2	10	2
		GAP	10	28,044	328	4	10	1
Nigeria	Potato	Improved seed	10	6,301	196	3	5	2
	Rice	GAP	10	2,182.4	148	4	10	2
Malawi	Soybeans	Improved seed	13.5	1490	602	6	5	1
		CA	13.5	508	493	14	5	1
	Cassava	Improved seed	13.5	6,460	327	4	6	1
Zambia	Peanut	CA	10	2,796	368	15	20	1
	Soybeans	Improved seed	10	1,563	252	3	10	1
Ethiopia	Faba beans	Improved seed	12	2,366	175	2	5	2

NB: r=discount rate at which the NPV has been discounted, IRR=internal rate of return, T=practice life cycle, PP=practice payback period, B/C=Benefit-Cost ratio, GAP=Good agricultural practices, CA=Conservation Agriculture USD stands for United States Dollars.

The lifecycle period for the prioritized innovations ranged between five to 20 years. Adoption of improved seed varieties had a minimum lifecycle of five years while CA for the peanut value chain in Zambia had a maximum life cycle of 20 years. However, the lifecycle is value chain and country-specific given that CA for the soybean value chain in Malawi had a life cycle of five years. The costs used in the CBA calculations were those analogous to the implementation, maintenance, and operational activities of the CSA practice on 1 ha for 1 year. The prices of the inputs and outputs were constants.

4.4.1 Private profitability

All the practices had a positive NPV meaning that all were deemed worthwhile (Table 14). The number of years for which the cost and benefits were evaluated was value chain specific and also dependent on the practice life cycle. For instance, considering the results from the present study, in Kenya, GAP and improved seed varieties in the sweet potato value chain had a lifecycle of 10 years and so the benefits and costs were evaluated for the entire lifecycle period.

In evaluating the private profitability, GAP in the sweet potato value chain in Kenya had the highest NPV (USD 28,044) while CA in the soybean value chain in Malawi had the lowest NPV (USD 508). The NPV values for the other practices ranged from USD 1,000 to USD 8,900 (Table 14). The results of the IRR also indicated that all the practices were profitable since they were all greater than the corresponding discount rate. Improved seed varieties in the sweet potato value had the lowest IRR (111%) while CA in the soybean value chain in Malawi had the highest IRR (493%). The difference in the IRR between the two practices could be attributed to the varying cash flow patterns given that conservation agriculture in soybean presented the lowest NPV (Table 14). CA, for instance, had a very low initial capital investment (USD 26). The incremental cost flows for the subsequent years were all negative (USD -7). In comparison to improved seed in the sweet potato value chain where the initial capital investment was estimated at USD 1,619 and the cash outflows for the subsequent years were all positive (USD 1,424).

The use of IRR as a profitability indicator yields unreasonable values that might be challenging to interpret for quantitative purposes. The high values of IRR obtained in Table 13 imply that less value will be attached to future cash flows than it ought to be. As a result, the NPV is the best measure in assessing the profitability of the adaptation practice compared to the IRR. The benefit-Cost ratios (BCR) for all the practices were greater than one (Table 14). A clear indication that the benefits realized for each practice can fully cover the costs associated. CA in the peanut value chain, Zambia had a BCR of 14.6 while the lowest BCR, two, was realized in the improved seed in the sweet potato value chain in Kenya. This is despite the differing values of their NPV (USD 2,796 and USD 8,738) respectively. Of all the CBA profitability indicators discussed (NPV, IRR, and BCR), NPV is the most appropriate measure to show whether a practice is worthwhile or not. The IRR and the BCR are applicable where there is only one alternative under consideration while the NPV is very useful where there is more than one alternative to choose from (Branca, 2018). The findings from this study are similar to Ng'ang'a *et al.* (2017) which evaluated the costs and the benefits of climate-smart soil practices including the use of organic manure, intercropping, agroforestry, improved seeds, inorganic manure, and liming. The study recorded positive NPV values for all the practices (USD 2857 ha^{-1}, USD 5218 ha^{-1}, USD 6216 ha^{-1}, USD 6767 ha^{-1}, USD 6730 ha^{-1}, USD 5164 ha^{-1}). The practices also presented higher IRR values compared to the discount rate and payback period of between 2-4 years.

Tables 15 and 16 further elaborate on the cash flows for the improved seed and GAP in the sweet potato value chain in Kenya to better understand how the economic indicators were evaluated. This is populated for the entire practice life cycle (10 years). The cash flow patterns for the other countries are presented in appendix B. The results indicate no benefits in the first year since the adaptation innovation or practice was still in the implementation stage. As such benefits were realized in the subsequent years. On the other hand, in the first year, of adopting an improved seed variety the farmer incurred an equivalent of USD 1619.40ha^{-1} on the adoption cost with a reduction to USD 1424ha^{-1} in the subsequent years (reduction of $195.40).

Table 15: Cash flow patterns for improved seed variety in the sweet potato value chain in Kenya

CSI: Improved seed variety- Sweet potato value chain in Kenya										
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Gross benefits flow	0	3222.36	3222.36	3222.36	3222.36	3222.36	3222.36	3222.36	3222.36	3222.36
Adoption cost flow	1619.40	1424	1424	1424	1424	1424	1424	1424	1424	1424
Net benefits flow	-1619.40	1798.36	1798.36	1798.36	1798.36	1798.36	1798.36	1798.36	1798.36	1798.36
Discounting rate % (2011-2020)	8.40	15.75	8.83	8.5	10.13	10.63	10	9.33	8.92	7.23

Source of discount rate: Central Bank of Kenya

The discount rate used was a 10-year average (2011-2020) of the rate used by the central banks to advance investment loans as sourced from the Central Bank of Kenya website (average of 9.74% ≈ 10%). This is also applicable to the other SSA countries under study (see appendix B). In the case of improved seed variety, the benefit was obtained by multiplying the changes in productivity (thus 594 bags from adaptation innovation less 198 bags for the BAU) by the prevailing market price per bag estimated at an average of USD 6.16. The adoption costs incurred included machinery, equipment, inputs, services, and labour related to the implementation, maintenance, and operations evaluated on an incremental basis. The adoption of GAPs (Table 16) resulted in a cost of USD 1565.20ha^{-1} in the first year, a reduction to USD 1497.90ha^{-1} in the subsequent years with benefits of USD 5141.30ha^{-1}. A plausible reason for this cost reduction was that, in the first year, the farmer incurred costs related to purchasing an asset, machinery such as a tractor, or equipment which translates to one-off costs that he/she may not need to purchase in the subsequent years.

Table 16: Cash flow pattern for GAP in the sweet potato value chain in Kenya

CSI: Improved seed variety- Sweet potato value chain in Kenya										
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Gross benefits flow	0	6639.15	6639.15	6639.15	6639.15	6639.15	6639.15	6639.15	6639.15	6639.15
Adoption cost flow	1565.20	1497.90	1497.90	1497.90	1497.90	1497.90	1497.90	1497.90	1497.90	1497.90
Net benefits flow	-1565.20	5141.30	5141.30	5141.30	5141.30	5141.30	5141.30	5141.30	5141.30	5141.30
Discounting rate % (2011-2020)	8.40	15.75	8.83	8.5	10.13	10.63	10	9.33	8.92	7.23

Source of discount rate: Central Bank of Kenya

The response curve that illustrates the yield pattern associated with the implementation of the CSA practice takes on the shape of a Liebig production function (Sain *et al*., 2017). It follows a linear plateau preceded by a time lag demonstrated by the difference in yield between t1 (the period when the physical response starts) and t2 (the period when the physical response reaches a maximum) (Fig. 7)

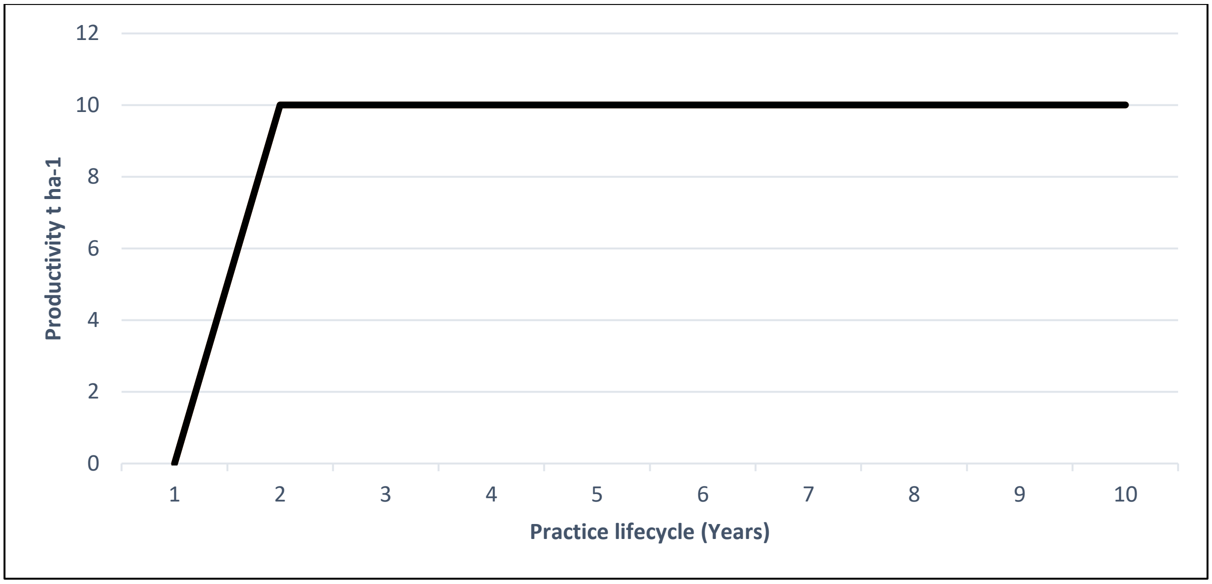

Figure 7: The response curve associated with the climate adaptation strategy

The Y-axis represents the productivity increase associated with the practice. The X-axis represents the entire lifecycle of the practice. The concept behind the Liebig production function is that at any moment there is only one factor, said to be in minimum supply, which limits production. For instance, the level of nitrogen (N) in the soil. If the supply is increased through the use of fertilizer rich in N, then production will increase proportionally up to a point where a second factor now limits production (Williams *et al*., 2020). For example, water availability. As illustrated in Fig 7, there is an abrupt transition from one limiting factor to another.

4.4.2 Externalities

All climate adaptation strategies generate externalities. They may be positive or negative. In the context of this study, externalities refer to the social and environmental costs and benefits. Although the scope was limited to only private profitability, information was sourced from various literature that discussed the externalities associated with adopting climate change adaptation strategies. The externalities include the effect on crop and soil biodiversity, air quality, water availability, soil erosion, and social impact which is evaluated as an increase/decrease in labour requirement.

To evaluate the effect on biodiversity, Sain *et al*. (2017) applied a biodiversity index developed by The Tropical Agricultural Research and Higher Education Centre (CATIE). A biodiversity index of 0.64 was obtained. This value was then multiplied by the shadow price of biodiversity to estimate the impact. The shadow price was used as a proxy for the market price to indicate the value the society is willing to pay or the value they are willing to receive for an extra unit of the eternality. The closer the biodiversity index is to one (>0.5) the more diverse the ecosystem is. Thus, in this case, presenting positive externalities. A biodiversity index is used to estimate the complexity, stability, and general health of an ecosystem. It is calculated by dividing the number of species in an area by the total number of individuals in the area. Thus the closer the index is to 1 the more diverse the ecosystem.

Williams *et al*. (2020) used soil fertility as a proxy for soil and crop biodiversity. In this case, an increase in soil fertility increased plant species per unit area thus increase in crop biodiversity. The use of organic manure to increase soil fertility resulted in improvement in below-ground soil activity. In estimating the effect on biodiversity, the soil fertility per hectare was estimated by the product of the change in N gained by the shadow price. Ng'ang'a *et al*. (2017) applied the Monte Carlo Simulation and estimated the value of increased biodiversity from implementing CSA practice to be approximately USD 22 ha^{-1} $year^{-1}$.

Climate change poses a challenge for communities to attain air quality standards that affect the environment and poses risks to human health. To estimate the effect of climate adaptation strategies on air quality (reduced GHG emissions/ increased carbon sequestration), valuation is universally done through the use of the global market price of carbon USD 6.00 $t^{-1}CO_{2e}$ (Sain *et al*., 2017). This allows estimation of the level of carbon sequestered by the practice. For a case study in Ghana, Ng'ang'a *et al*. (2017) estimated this value at about USD 15 ha^{-1} $year^{-1}$. This means that the adoption of practices such as mulching, agroforestry, and minimum tillage help minimize GHG emissions thus improving air quality.

Improved water quality translates to reduced soil erosion and agrochemical residues in rivers and streams. The valuation is done by using opportunity costs. Water quality improvements associated with agroforestry systems with hedgerows were estimated at a total of USD 514 depending on the area covered. Conservation tillage with mulch was valued at USD 90 (Sain *et al*., 2017). CSA practices have the potential for improving the environment and rural livelihood. Improved water quality translates to water available for agricultural production, and household use such as cooking and cleaning, and increased fish species in the rivers that can be sourced for food and sold for income.

Table 17 presents the social impact or externality of adopting the CSA strategies evaluated by the effect on change in labour requirement. In this case, survey data collected for the CBA was used in the assessment with the assumption that implementation and maintenance of the CSA in the five countries for the selected value chains required the use of additional labour. The change in the labour requirement was then multiplied by the corresponding market price of labour which was country-specific to obtain the change in the value of labour. High labour requirements for the CSA practices were applied during the harvesting and threshing. In resource-constrained households, the high demand is supplemented by family labour which presents a trade-off against engaging in other off-farm activities.

Table 17: Estimated impact on labour due to the adoption of CSA practice

Country	Value Chain	Adaptation Practice	Change in labour requirement (Man-days/season)	Price of labour (USD MD^{-1})	Change in the value of labour (USD)
Kenya	Sweet potato	Improved seed	277	2.83	784
		GAP	83	2.83	235
Nigeria	Potato	Improved seed	N/A	1.28	N/A
	Rice	GAP	-61	1.28	-78
Malawi	Soybeans	Improved seed	-49	1.03	-50
		CA	-49	1.03	-50
Zambia	Cassava	Improved seed	50	7.53	377
	Peanut	CA	-32	1.24	-40
	Soybeans	Improved seed	N/A	2.30	N/A
Ethiopia	Faba beans	Improved seed	31	2.73	85

N/B: MD represents man-days, GAP stands for Good Agricultural Practices, CA stands for Conservation Agriculture, USD stands for United States Dollars

CSA strategies that require the use of additional labour translate to additional employment for the vulnerable population, especially the youth and women. Although it may present a welfare loss to the farmer due to added costs, the ability of the practice to create employment means a welfare gain to society. The strategies that present negative values mean that less labour was required as compared to the BAU practice (Table 17). This implied a welfare gain to the farmer due to reduced labour costs but a welfare loss to society due to fewer employment opportunities. The results of strategies presenting negative values are contrary to findings in most literature where all of the strategies evaluated have positive impacts on the value of labour (Ng'ang'a *et al*., 2017; Sain *et al*., 2017; Williams *et al*., 2020).

4.4.3 Sensitivity analysis

Using CBA data on drought-tolerant sweet potato seed varieties in Kenya (Fig. 8), sensitivity analysis was conducted using an optimistic-pessimistic scenario and the switching values methodology to assess the responsiveness of the NPV to changes in several variables (price, yield, annual labour costs, practice lifecycle, and the discount rate.

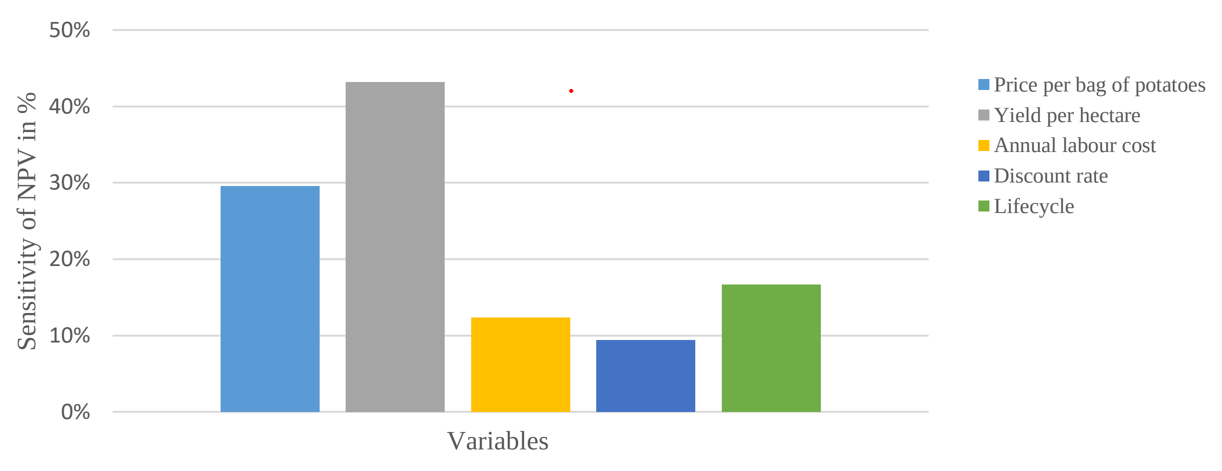

Figure 8: The sensitivity of NPV to the percentage change of different variables (drought tolerant sweet potato in Kenya).

In the pessimistic scenario, the values of price per bag, yield per ha, discount rate, and lifecycle are 10% lower than the base value while the annual labour cost is 10% higher than the base value. The contrary applies to the optimistic scenario. Fig. 8 depicts the sensitivity of the

NPV to changes in the different variables. At a discount rate of 10% and a lifecycle of 10 years, the NPV was estimated at USD 8,738 and the IRR at 111%. The practice also increased the value of labour to USD 783.9. The range of values for the variables considered was ±10% (Table 18). These include the price per bag, the yield per hectare, annual labour cost, the discount rate, and the practice lifecycle. The NPV values for the two scenarios (pessimistic and optimistic) were estimated and their differences were calculated to check changes in the variables.

Table 18: Sensitivity analysis using the pessimistic-optimistic scenarios approach

				NPV (USD)	
Variables	Base value	10% lower	10% higher	Pess	Opt
Price per bag	600	540	660	7,447	10,029
Yield per ha	594	535	653	6,801	10,574
Annual labour cost	300	270	330	8,201	9,276
Discount rate	10%	9%	11%	8,338	9,162
Lifecycle (Yrs)	10	9	11	7,975	9,431

NB: Pess represents pessimistic and Opt represents Optimistic

The results indicate that NPV is most sensitive to changes in yield per hectare. These results are also replicable in all the value chains with different variations in the values. NPV is moderately sensitive to the output selling price and the practice lifecycle. The results also indicate that the NPV is least sensitive to changes in annual labour costs and discount rates as evidenced by the very high IRR. Results from applying the switching values method in the sweet potatoes value chain verify these findings (Table 19). For detailed sensitivity results for the other value chains, see appendix B.

Table 19: Sensitivity of the NPV to different variables using switching values

Variables	Base value (1)	Switching value (2)	Difference (1-2)	IRR (%)
Price per bag	600	193.92	406.08	10
Yield per hectare	594	326.02	267.98	10
Annual labour costs	300	787.08	487.08	10
Discount rate	10	111	101	111
Practice lifecycle	10	2	8	10

Note: IRR=internal rate of return. The switching value is the value of the variable that gives an NPV of zero

The switching value is the value of the variable under consideration that will give an NPV or zero (Table 19). Results show that NPV was most sensitive to any small changes in the yield variable compared to the other variables as evidenced by the small difference between the base value and switching value. The least sensitive variable was the annual labour cost as seen by the huge difference. In some cases, such as the improved seed varieties in the potato value chain in Nigeria and soybean in Zambia, the labour presented no value (low or high) that could give an NPV of zero.

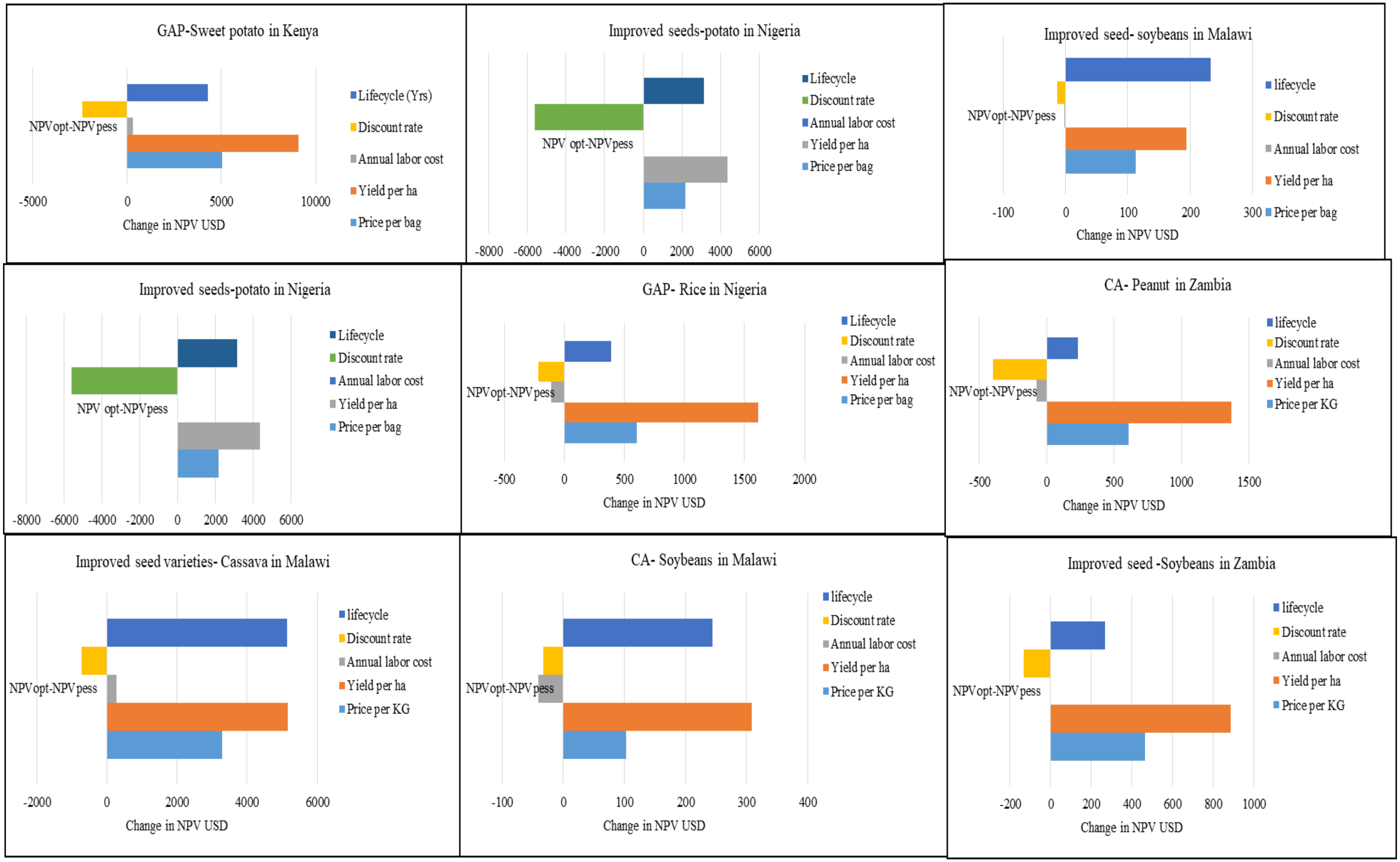

Figure 8b: The sensitivity of NPV to changes in different variables (All the other value chains)

CHAPTER FIVE

CONCLUSIONS AND POLICY RECOMMENDATIONS

5.1 Trade-offs and synergies associated with climate adaptation innovations among smallholders

In this study, the potential trade-offs and synergies of adaptation strategies among smallholder farmers were assessed using a systematic literature review methodology. These strategies were grouped into five broad categories crop management, soil/land management, risk management, water management, and livestock management strategies.

The results showed that the identification of the potential synergies and trade-offs especially at the initial stages before implementation is very crucial. Also, the potential trade-offs relate to competition among available resources (land, water, and labour), the production systems, and the objectives to be achieved.

The synergies on the other hand are realized through the effects associated with implementing two or more strategies consecutively. For example, mulching and the adoption of planting pits such as half-moons and Zai pits are labour-intensive. However, when these are adopted together with water management or fertilizer application, they could result in high yield and increased productivity.

The development, research, and application of more powerful and useful frameworks for trade-off assessment are required, for instance, the Gibson trade-off rules. These rules require that each chosen alternative should have a net sustainable increase, the burden of argument on trade-off proponents, avoidance of significant adverse effects, protection of future generations, and explicit justification and that the decision-making should be an open and effective participatory process (Gibson, 2006).

Although these measures are often implemented in sustainability assessment processes, their application to climate change adaptation will ensure the selection of cost-effective strategies to help build resilience capacity for smallholder farmers in SSA. Policies designed within the climate change adaptation discipline should, therefore, be geared towards minimizing the trade-offs and maximizing the synergies.

5.2 Adaptation innovations adopted among smallholders in sub-Saharan Africa

Climate change is and will adversely affect the agriculture sector in most SSA countries. For instance, the past five years have seen the region experience floods and droughts events. Lakes and oceans in various countries have been on a steady rise causing major destruction of agricultural lands and farm produce.

To cushion these negative impacts, adaptation strategies become paramount in increasing productivity and building the resilience of smallholder farmers. In this study, descriptive statistics were used to determine the main climate change adaptation innovations adopted among smallholder farmers in SSA.

The results indicated that the practices are country-specific and vary from one value chain to another. The most popular strategies among smallholders as evaluated were the adoption of improved seed varieties, conservation agriculture practices (minimum/zero tillage, crop rotation, and mulching), and the adoption of good agricultural practices. Ensuring the sustainability of agricultural systems is a complex process.

To improve nutrition and food security now and in the future and with the prevailing climate change, population growth, and industrialization, agricultural systems across SSA need to effectively and quickly adapt.

Policy response should target production at the local farm level. Constant provision of information and education on best practices to cope with climate change should be the main agenda among stakeholders and governments.

Establishment of a ready market for the product to minimize losses, strengthening farmer groups and cooperatives, access to formal credit facilities, inclusion, and representation of smallholder farmers, including women and youth in decision-making are strategies that have the potential for improving agricultural productivity

5.3 Prioritized climate adaptation innovations among smallholders in SSA

Focusing on selected countries and selected value chains under the GIZ project (GICs), the main adaptation innovations among smallholder farmers in Kenya, Nigeria, Ethiopia, Malawi, Zambia, Togo, and Ivory Coast were identified. These were assessed at each stage of the selected crop/ milk value chains (Table 1 and Fig. 6).

The ranking was done to determine the prioritized innovation based on importance. A CBA was then computed for the most prioritized innovations in selected value chains. This was limited to only five out of the targeted seven SSA countries.

These innovations include the adoption of improved seed varieties, CA practices, and GAPs. These three were deemed most important in most value chains due to their ability in increasing productivity and building the resilience of smallholder farmers.

A critical component for prioritization to be successful is stakeholder involvement. These include the representation of all actors across the value chain, from input supply to when the product reaches the consumer.

Prioritization is a significant step in adaptation decision-making as implementation is often constrained by insufficient resources and capacity. Principles of flexible management could be applied in the process as it allows for improving adaptation based on advanced knowledge, experience, and technology.

5.4 Cost-benefit analysis of prioritized innovations among smallholders in SSA

The CBA involved the assessment of four indicators: the NPV, the BCR, the IRR, and the payback period. Results showed that all the innovations were financially profitable. Investing in improved seed varieties was the most popular of all the value chains.

All the practices had a positive NPV and a higher IRR compared to the predetermined interest rate. Also, all the innovations showed a relatively short payback period implying that they are most desirable among smallholder farmers.

The findings imply that in any decision-making process, policymakers should always consider the market environment. This can be done through monitoring variables that are beyond the farmers' control such as interest rates, labour costs, and output prices.

Also, the potential trade-offs and synergies should be evaluated and accounted for. This will aid in the development of a portfolio of strategies that are congruent with the objectives of smallholder farmers (increasing productivity and building resilience to climate shocks).

The cost related to the implementation (initial investment), periodic or annual maintenance, and operations of the adaptation strategies was one of the factors that constrain the uptake and up-scaling, especially among resource-poor farmers. The availability of low-cost innovations would therefore result in major improvements in productivity and resource utilization.

There are debates among scientists on the choice of the optimal discount rate to be used in climate change adaptation. Some scientists have proposed the use of lower discount rates based on environmental protection and sustainability (Agrawala *et al*., 2011; Callaway *et al*., 2016; Sterner & Coria, 2012). The proposed discount rates could be in the range of one and five percent.

Other scientists argue that very low discount rates may lead to the misallocation of private resources and a misguided value of future benefits of a project (Mendelsohn, 2012). For public adaptation and future climate change to matter, then the use of lower discount rates is appropriate. This would favor a shift of policy decisions from adaptation to mitigation.

5.5 Policy recommendations per country

i. In Kenya, sweet potato is grown for food, feed, and sold for income generation and therefore constitutes an important food security crop. This study recommends the use of improved sweet potato varieties that are drought and pest resistant since these are highly profitable and or the use of clean planting material as a good agricultural practice. The orange-fleshed variety has, over the years, attracted much attention since it is naturally bio-fortified with beta-carotene which helps combat vitamin-A deficiency in children. More so improved variety has higher biomass that can be used for mulch and the sweet potato vines are a great source of livestock feed.

ii. Rice is a major staple food in Nigeria produced in almost all the agroecological zones. Potato on the other hand is mainly cultivated by smallholder farmers in the marginal rural area. However, both rice and potato farmers in the country do not have clear information about the effect that climate change has on agricultural production and how best to cope and adapt to the changes. This study, therefore, recommends climate adaptation training and information dissemination to smallholder farmers on good practices in rice farming such as the system of rice intensification, changing of plating dates until weather is favorable, or alternate wetting and drying of the rice field to enhance water-use efficiency. The study further recommends that the relevant authorities make available improved seed potato varieties to ease access by farmers, improve productivity, and reduce transaction costs.

iii. In Ethiopia, faba beans are an important highland pulse crop for food and feed and take the largest share of the area under production. However, there are several constraints to the production and productivity of faba beans in Ethiopia. These are the frequent occurrence of diseases and parasitic weeds, increased soil acidity, and decline in soil fertility. This study, therefore, recommends the adoption of improved varieties that are high-yielding and resistant to pests and diseases. Furthermore, this study recommends the integration of other adaptation strategies together with improved variety such as the use of both organic and inorganic soil amendments to achieve the crop yield potential in Ethiopia.

iv. Despite its huge potential, the soybean value chain in Malawi remains dormant in terms of improved productivity and quality. For over 20 years, smallholder soybean farmers in Malawi have been cultivating the same varieties, with seed recycling lowering the quality of the available varieties. This study recommends to researchers and relevant government authorities make available improved soybean varieties that are well-suited to the different agroecological zones of Malawi. In addition, this study recommends smallholder farmers consider integrating improved soybean variety and conservation agriculture practices such as mulching, minimum tillage, and crop diversification strategies of inter-cropping or crop rotation. Cassava is another staple food in Malawi for almost 35% of the population but the lack of improved seed variety is largely attributed to minimal efforts to make available the seeds to farmers. This study, therefore, recommends that the government provides financial resources for research, development, and information dissemination of available improved cassava varieties to smallholder farmers across the country.

v. In Zambia, the climate highly favors the production of soybeans and peanuts. The two crops are cultivated in nearly all the regions in Zambia. However, low fertilizer use, poor soils, inadequate agricultural advisory services, and smallholder farmers' inability to access improved soybean seeds do hinder the quality and quantity of production. This study recommends to smallholder farmers adopt conservation agriculture to adapt to the changing climate. Further recommends government subventions in the research and development of improved soybean seed varieties that are climate resilient.

General recommendations

Issues within the climate change discipline are interdisciplinary as adaptation strategies often require efforts from more than one sector. Cross-sectorial coordination needs to be recognized and fostered through suitable institutions for effective actions on adaptation strategies. In the context of this study, several policy recommendations are suggested.

Institutions and governments should make available low-cost adaptation strategies as this could result in improvements in productivity and resource utilization. The strengthening of these institutions through the development of property rights and encouraging participation will to a great extent encourage farmers to effectively adapt to a changing climate. This can further be enhanced through consulting experts and connecting stakeholders in all sectors, advocating for more coordinated approaches that allow for feedback, and creating hubs for smallholder farmers that will help create ideal market dynamics. Through these institutions, constant provision of education to farmers can be enhanced to expand the knowledge base on the use of new technologies. In the process, new knowledge could also emerge on how best to improve the efficiency of technologies already familiar among smallholder farmers in developing economies.

It is important to note that adaptation strategies are context-specific. Thus, they could vary depending on the agricultural value chain under consideration and the country or focus region. Therefore, local solutions and innovations should be developed to adapt to local problems. For instance, the establishment of technologies such as seasonal weather forecast information can play a crucial role in guiding decision-making on climate change adaptation. Finally, the application of nexus sound solutions that contribute to optimal resource allocation and utilization could lead to increased economic growth and ensure environmental sustainability.

5.3 Suggestions for further research

An elaborate methodology should be applied in future in the evaluating the potential trade-offs and synergies associated with climate adaptation strategies. Future research should also include the assessment of externalities resulting from implementing adaptation strategies to reflect their true economic value.

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APPENDIX A: Potential trade-offs and synergies of climate adaptation strategies

Table A1: Potential trade-offs and synergies of climate adaptation strategies

Broad category	Specific adaptation strategies	Potential Trade-offs[9]	Potential Synergies[10]	Analytical method applied
Crop management	Shifting planting dates	Farmers will need to adjust the planting season accordingly or otherwise risk losses in yield (knowledge requirements)	Low-cost strategy Increases productivity. Shortens the length of the growing period	Systematic Literature Review Climate-Smart Agriculture Approach Multi-Variate Probit

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[9] Trade-offs occur when implementation of the strategies result in negative effects or when the gain in one sector result in a loss to another sector

[10] Synergies are based on the assumption that then combined effect of implementing the strategies is greater than the sum of their effects if they were to be implemented separately

	New crop varieties	Additional transaction costs (market access/ information search costs); reduced yield stability (works best in favorable environments), requires the repeated purchase of seed to maintain crop yield, increased transaction costs (acquiring reliable information about the new variety, discovering farmers' demand preferences), the moral hazard of being sold for poor quality seeds, knowledge-intensive (requires strict agronomic and post-harvest practices to maintain the quality. Increased costs of feed and inputs e.g. new seeds, and fertilizer requirements. Mixed	Improves water use efficiency and increases the yield Improves productivity, income, and household food security. Improves the food self-sufficiency and income of smallholders without having to increase more land New varieties contribute to increased biomass production for food and livestock feed Higher/ additional crop sales and more labour time for leisure and alternative economic activities	Systematic Literature Review On-Farm trials Trade-Off Analysis Impress method Multi-variate probit Simulation Generalized Linear model Rainfall-use Efficiency model Endogenous Switching Regression model

		crop-livestock systems are a major source of GHG emissions Increased transaction costs for the farmer e.g. information search costs, transport to and from the input source		
	Crop rotation		Brings more resilience to the production system; better nitrogen management will have positive effects on ecosystem services such as water quality; mitigates the risks associated with crop failure from mono-cropping; Diversifies the seasonal requirement for labour (reduces the per hectare family labour requirement), stabilizes farm income through an evening out	Systematic Literature Review Negative Binomial Regression Endogenous Switching Regression model Multi-Linear Regression Generalized Linear Model Multi-Variate Probit model

			the impact of price fluctuations, a buffer against the risk of extreme climate events like drought, and risk management through diversification of output Increases the amount of nitrogen fixed in the soil resulting in better utilization of growth resources, increases soil organic matter, improves soil water holding capacity improves soil fertility at the same time reducing the amount of nitrogen fertilizer requirement for the subsequent crop (Non-legume crop), alters soil moisture requirements, nutrients, pH, and structure. Reduces incidences of pests and diseases, therefore, saves on the	Choice Experiment model

			cost of labour, fertilizer, and pesticide purchase reduces the quantity of labour required for pest and weed control	
	Multi-cropping	Requires adjusting cultivation practices e.g. adopting minimum tillage and also changes in the market system Irrigation is required especially in areas with water scarcity, presenting additional costs to farmers	The efficacy and abundance of natural predators in mixed crop systems reduce the occurrences of pests and diseases, increasing the quality and quantity of production. Farmers avoid costs associated with the purchase of pesticides and chemicals and maximize the use of resources (land, labour, capital, water)	Systematic Literature Review Climate-Smart Agriculture approach Endogenous Switching Regression Multi-Variate Probit

		Multiple cropping is also prone to wind erosion, risking soil health	Increase crop productivity while at the same time protecting the fertility of the soil and storing soil carbon	
	Intercropping e.g. cereal such as maize and legumes such as beans, peas, or cowpeas	The decision to adopt will risk the additional investment costs but increase yields though in the long run.	Climate tolerant legumes provide additional fodder for livestock in mixed systems, help to sequester carbon, reduce GHG[11] emissions, and improve the aesthetic value of the landscape	Integrated Assessment Modelling Framework Generalized Linear Regression Correlation analysis On-Farm Trials Climate-Smart Agriculture approach Poisson and Negative Binomial Regression

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			Enhances mineral fertilization through increased soil organic matter Restores soil fertility Nitrogen fixation that will benefit the consecutive crop The farmer benefits from a double-crop product from one plot Improves soil water holding capacity	Multi-Linear regression model
Soil/Land management	Reduced or minimum tillage,	Labour demanding (fewer opportunities to engage in leisure or other off-farm activities); larger families may be forced to switch part of the labour force to off-farm activities to ease the consumption pressure; reduces	Accumulates carbon in the soil (i.e., carbon sequestration); reduces the amount of carbon released in the atmosphere (i.e., mitigation); enhances the ability of soil to retain or hold moisture, and to better withstand erosion, builds on the	Systematic Literature Review Trade-off Analysis Simulation Integrated Adaptation and Mitigation Framework

		agricultural productivity in the short term; increases transaction costs in acquiring inputs.	resilience of ecosystems, improves water infiltration.	Climate-Smart Agriculture approach Companion Modelling [12]process Multi-Variate Probit Negative Binomial Regression Model Multi-Linear Regression Choice Experiment Modelling
	Tied ridge tillage	May induce water-logging	Reduced run-off Soil water conservation Increased rate of nutrient fertilization and transportation to roots	On-Farm Trials

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[12] ComMod- A Companion Modelling process that involves a Role- Playing game with farmers and an Agent-Based model.

	Use of fertilizers,	Poses great consequences on human health[13] and Agri-ecological systems[14]. Increases the emissions of GHG in the atmosphere High transaction costs (e.g. transportation, information search costs)	Reduces the occurrences of pests and weeds. Increases in crop productivity due to an increase in soil fertility. .	Systematic Literature review Multi-Variate Probit Climate-Smart Agriculture approach Choice-Experiment Model Trade-Off Analysis On-Farm Trials
	Organic manure	Requires additional economic costs for transporting manure to the fields.	Organic production improves nutrition and taste (helps curb the spread of diseases) and ensures the resilience of ecosystems by the maintenance of water quality	Random Parameter Logit Model Choice Experiment Model Multi-Linear Regression Simulation

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[13] Skin lesions when not wearing protective equipment and diseases such as cancer

[14] Based on interactions between biological and ecological systems and the potential offered by ecosystem services such as water resources, air, biodiversity, soil etc (Lankoski *et al.*, 2018)

	Mulching,	Reduction of livestock feed Reduction of residue for mulching Labour intensive Additional costs of implementing Economical only on larger farms.	Reduces soil water evaporation and increases soil water storage Increases soil porosity and stability Improves crop water use efficiency Reduces N leaching (thus conserves the quality of water resources) Environmental protection since the crop residues and not burnt	Systematic Literature Review Simulation Choice Experiment Model Multi-Variate Probit On-farm trials Multi-Linear Regression Participatory Video Approach Trade-Off Analysis Integrated Assessment Tool Sustainable Intensification Assessment Framework Stochastic Frontier Maximum Likelihood Negative Binomial Model

	Agroforestry	The production of biofuels presents competition with food production Additional land required for fallow Labor-intensive shrub management Additional water requirements for nursery operations Requires upfront costs while the benefits to be realized through productivity, resilience, and mitigation may not be realized for several years. The shading effect Competition for resources with other systems i.e. water, nutrients, rain, light)	Stores large amounts of carbon in the plant systems thus contributing to mitigation objectives A good example is the mixed Taungya system in Ghana where the trees can store carbon in the woody biomass, therefore, contributing to mitigation, they also act as a buffer against drought, desertification, and bushfires. Local farmers can get additional skills, tools, and revenue from the management of the forest and sell timber Soil fertility and microclimate improvement	Systematic Literature Review Climate-Smart Agriculture approach Integrated Assessment Framework Logistic regression Multi-Variate Probit Generalized Linear Model and Correlation analysis Contingent Valuation Model Binary Logistic Model Socio-Ecological Resilience Model

		Competition among land uses impacts water availability and may affect soil biodiversity. In combination with livestock production, livestock can interfere with areas where the young seedlings are growing. Additional costs required for establishment are quite high. Providing shade may affect the productivity of coffee and cocoa plants The energy requirements for adaptation options e.g. use of renewable energy susceptible to climate change. Increased irrigation and cooling may result in increased	Conservation of soil, water, and biodiversity Environmental protection. Combined with crop diversity: trees can recycle nutrients from below the crop root zone back to upper soil layers, therefore, maintaining soil fertility and health Biomass from tree cutting can be incorporated into the soil as mulch, and the poles can further be used for electricity connection and fuelwood/ charcoal burning. Increases fodder availability for animal feed Increases soil carbon sequestration and reduces GHG emissions,	

		emissions of GHGs in the atmosphere.	Improves soil nutrient use efficiency Increased yield due to increased soil fertility Conserves soil moisture thus improving crop productivity. Reduces pests and disease incidences and reduces surface runoff and soil erosion. FTT improves human and animal health Builds resilience of ecosystems Fodder is a source of green manure Will enhance both adaptive and mitigation capacity with a significant improvement in the standards of living for the poor.	

			Forests regulate the well-functioning of ecosystem services[15] Forest products offer supplementary income and food during periods of scarcity to adjacent communities.	
	Reforestation	Reforestation practice involves foregoing fuelwood production and supply to allow trees to grow which will result in lower water yield. The activities will require additional investments Competition with other land uses negative impacts on the Nitrogen and Phosphorous cycle, water availability, and depletion	Provides soil protection and modification of the micro-climate Enhances carbon sequestration Ensures continuation of important plant and animal species	Systematic Literature Review Matrices

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[15] For example: provision of clean air through carbon sequestration, clean water, pollination, habitat for wild plants and animals, pest regulation etc.(Ingalls and Dwyer, 2016)

	Soil/stone/vegetation bunds, Fanya juu terraces	The introduction of new farming practices results in additional costs to the farmers Are labour-intensive (e.g. construction of stone terraces) Requires significant fixed costs (large volume of material). Additional land requirement (Not economical for smallholders), reduces space available for cultivation of the main crop Risks of erosion if adopted on steep slopes Are resource and knowledge-intensive	Act as carbon sinks, while at the same time improving crop production and quality of the environment; avoided damage costs to the environment and ecosystem (prevents siltation and flooding downstream) Increases value of production Continuous maintenance results in greater payoff in the long-run Improves rainwater infiltration Combined with compost results in increased yields. Combined with tree cover helps to lower soil temperature and protects against wind erosion.	Use of a systems approach Cost-Benefit Analysis Multi-Variate Probit Systematic Literature Review Probit Logit Climate-Smart Agriculture approach Negative Binomial Regression Chi-Square test Contingent Valuation Model Multi-Linear Regression

		Difficult to repair and are susceptible to damage when poorly used. Requires frequent inspection	Reduces the sedimentation and deposition of agricultural chemicals into water bodies, therefore, improving the quality of water and aquatic life.	Choice Experiment Model
	Half-moons[16] and Zai[17] pits	Requires knowledge of implementation to avoid maladaptation Labour intensive	Enhances soil mineral fertilization (increased productivity) Combined with improved varieties offers a buffer against risks of rainfall variability Facilitates water infiltration Facilitates runoff water harvesting The organic matter attracts insects such as termites that assist in maintaining soil aeration	On-farm trials Rainfall-use Efficiency model Climate-Smart Agriculture approach Choice Experiment Model

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[16] Utilize animal manure or compost to rehabilitate sealed and bare soils

[17] Zai pits concentrates runoff water and organic matter in small pits/ basins

Risk management	Index-based insurance	Price fluctuations are resulting in a cycle of dependency, especially in poorly managed communities. Moral hazardous behavior and adverse selection	Protection of productive assets fosters investment and intensification Protects farmers' assets, eliminates costly farm visits thus saving on administration costs, lowers premium payments, and provides more timely payments to farmers. Increases the adoption of more profitable production technologies and practices.	Systematic Literature Review Choice Experiment Model
Water management	Water harvesting	Competition for water (Livestock Vs household use and consumption	Available drinking water for livestock Saves energy and time Improves farm-level livestock and crop productivity without the use of additional water from	Livestock-water budget Crop-water model Systematic Literature Review Climate-Smart Agriculture Approach

			the ecosystem provides supplemental water for crop irrigation, and improves water for domestic use.	Choice Experiment Model
	Irrigation	Additional costs for implementation (capital intensive) Labour intensive Added transaction costs in collaboration among stakeholders Added pressure on scarce water resources Degradation of freshwater ecosystems. Competition among other uses (tourism and industries)	Alternate wetting and drying (water saving, reduced methane emissions, promotes root development, reduces waterlogging) Properly managed irrigation schemes result in water use efficiency Improves livelihoods through socio-economic development; maintains the integrity of natural systems	Multi-Variate Probit Systematic Literature Review Model of Agricultural production and its effect on the Environment (MAgPIE[18]) Binary Logistic Model Climate-Smart Agriculture approach Ordered Logit Contingent Valuation Model Discrete Choice Model

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[18] MAgPIE- A global land and water use allocation model

		Influences Nitrogen dynamics in the soil resulting in N_2O emissions. Less water for food may result in food insecurity and less water to the environment may negatively affect ecosystems. In mixed crop-livestock systems, livestock can easily interfere with irrigation lines (added costs for repair and maintenance) Requires technical knowledge and huge initial capital investment.	Combined with crop diversity (intercropping or crop rotation) provides farmers with a better market orientation through the sale of a diversity of crop products.	

Livestock management practices	Breeding heat-tolerant breeds, Matching stocking rates to pasture production and pasture rotation, changing animal feeds.	Additional costs in the acquisition and purchase of feed and inputs (Increased nutritional requirements) In the long run, may affect supporting ecosystem services (e.g. air or water quality) High-quality fodder e.g. Napier grass, if harvested yearly will lead to localized but slow soil degradation Increased herd size due to increased productivity will increase methane emissions (rise in overall GHG emissions) Reduced resilience (Temperature variability and reproductive potential of the animals) Improved genetics means a reduction in herd sizes thus reduced productivity in the very short run. Investments in feed and animal health requirements reduce the investments in crop and soil fertility, especially in mixed systems	Through genetic improvements e.g. the west African dwarf sheep are very robust and have strong vigor that enables them to withstand climate stress. Increases the long-run productivity of Milk and meat. Resource use efficiency. Provide food for the household, income from sales, manure for crops, drought power, and social status, and are a form of assets to be used as collateral. Livestock provides draft power required for crop cultivation and provides manure to fertilize the crop. In turn, the crop residues can be used as both feed and mulch	Systematic Literature Review Generic framework[19] Trade-Off Analysis Binary Logistic Model Simulation Sustainable Intensification Assessment Framework Multi-Variate Probit

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[19] Entailed mapping out recommendation domains, assessing adoption potential and estimating impacts

APPENDIX B: Cash flow patterns for the climate innovations for the rest of the SSA countries' value chains

CSI: Improved seed variety- potato value chain in Nigeria

	Y1	Y2	Y3	Y4	Y5
Gross benefits flow	0	3453.04	3453.04	3453.04	3453.04
Adoption cost flow	1187.30	1090.60	1090.60	1090.60	1090.60
Net benefits flow	-1187.30	2362.40	2362.40	2362.40	2362.40
Discounting rate % (2016-2020)	10.22	10.87	10.31	10.14	10.6

Source of discount rate Central Bank of Nigeria

CSI: GAP -rice value chain in Nigeria

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Gross benefits flow	0	206.19	412.37	618.56	618.56	618.56	618.56	618.56	618.56	618.56
Adoption cost flow	136.30	121.30	121.30	121.30	121.30	121.30	121.30	121.30	121.30	121.30
Net benefits flow	-136.30	84.90	291.10	497.26	497.26	497.26	497.26	497.26	497.26	497.26
Discounting rate % (2011-2020)	6.67	6.64	7.53	9.16	10.67	10.22	10.87	10.31	10.14	10.60

Source of discount rate Central Bank of Nigeria

CSI: Improved seed variety- soybean value chain in Malawi

	Y1	Y2	Y3	Y4	Y5
Gross benefits flow	0	616.44	616.44	616.44	616.44
Adoption cost flow	89.10	80.10	80.10	80.10	80.10

Net benefits flow	-89.1	536.30	536.30	536.30	536.30
Discounting rate % (2016-2020)	12.7	16.7	24.7	-13.9	20.6

Source of discount rate The World Bank

CSI: Conservation Agriculture- soybean value chain in Malawi

	Y1	Y2	Y3	Y4	Y5
Gross benefits flow	0	102.74	205.48	205.48	205.48
Adoption cost flow	25.70	-6.70	-6.70	-6.70	-6.70
Net benefits flow	-25.70	109.50	212.20	212.20	212.20
Discounting rate % (2016-2020)	12.7	16.7	24.7	-13.9	20.6

Source of discount rate The World Bank

CSI: Conservation Agriculture-peanut value chain in Zambia

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	Y18	Y19	Y20
Gross benefits flow	0	192.31	384.623	384.62	384.62	384.62	384.62	384.62	384.62	384.62	384.62	384.62	384.62	384.62	384.62	384.62	384.62	384.62	384.62	384.62
Adoption cost flow	57.30	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60	22.60

Net benefits flow	-57.30	169.70	362	362	362	362	362	362	362	362	362	362	362	362	362	362	362	362	362	362
Discounting rate % (2001-2020)	9.58	10.20	9.78	12.46	15.50	12.91	11.56	9.52	10.78	6.92	7.58	7.15	6.40	8.50	9.42	11.48	10.34	10.67	10.50	12.56

Source of interest rate Bank of Zambia

CSI: Improved seed variety-soybean value chain in Zambia

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Gross benefits flow	0	403.85	403.85	403.85	403.85	403.85	403.85	403.85	403.85	403.85
Adoption cost flow	115.70	112.40	112.40	112.40	112.40	112.40	112.40	112.40	112.40	112.40
Net benefits flow	115.70	291.50	291.50	291.50	291.50	291.50	291.50	291.50	291.50	291.50
Discounting rate % (2011-2020)	9.58	10.20	9.78	12.46	15.50	12.91	11.56	9.52	10.78	6.92

CSI: Improved seed variety-Faba bean value chain in Ethiopia					
	Y1	Y2	Y3	Y4	Y5
Gross benefits flow	0	1421.93	1421.93	1421.93	1421.93
Adoption cost flow	535.80	466.50	466.50	466.50	466.50
Net benefits flow	-535.80	955.40	955.40	955.40	955.40

APPENDIX C: Sensitivity analysis tables for the value chains

GAP- Sweet potato in Kenya

Variable	Base value	10% lower	10% Higher	NPV Pessimistic	NPV Optimistic	Opt-Pess	Switching value	Difference	Difference (%)
Price per bag (90kg)	2,500	2,250	2750	25,524	30,563	5,039	-282.55	2,782.55	111
Yield per hectare	334	300.60	367.40	23,507	32,580	9,073	127.53	206.47	62
Annual labour costs	500	450	550	27,889	28,198	309	10,733.40	10,233.40	2047
Discount rate	10	9	11	26,902	29,258	2,356	328	318	318
Lifecycle	10	9	11	25,863	30,135	4,272	2	8	80

Improved seed varieties- Potato in Nigeria

Variable	Base value	10% lower	10% Higher	NPV Pessimistic	NPV Optimistic	Opt-Pess	Switching value	Difference	Difference (%)
Price per Kg	250	225	275	5207	7396	2189	106.08	143.92	58
Yield per hectare	10,000	9,000	11000	4112	8490	4378	7121.50	2878.50	29

Annual labour costs	1	0.9	1.1	6301	6301	0	-	-	-
Discount rate	10	9	11	6142	6466	324	196	186	186
Lifecycle	5	4	6	4688	7845	3157	2	3	60

GAPs- Rice in Nigeria

Variable	Base value	10% lower	10% Higher	NPV Pessimistic	NPV Optimistic	Opt-Pess	Switching value	Difference	Difference (%)
Price per bag (50kg)	16000	14400	17600	1881	2484	603	4425	11575	72
Yield per hectare	40	36	44	1378	2987	1609	29.15	10.85	27
Annual labour costs	500	450	550	2236	2128	-108	1525.2	1025.20	205
Discount rate	10	9	11	2078	2293	215	148	138	138
Lifecycle	10	9	11	1971	2363	392	2	8	80

Improved seed varieties- Soybean in Malawi

Variable	Base value	10% lower	10% Higher	NPV Pessimistic	NPV Optimistic	Opt-Pess	Switching value	Difference	Difference (%)
Price per Kg	300	270	330	1308	1671	363	53.7	246.3	82
Yield per hectare	2500	2250	2750	1187	1792	605	1269	1231	49
Annual labour costs	1	0.9	1.1	1510	1469	-41	-6.366	7.366	737
Discount rate	13.5	12.15	14.85	1447	1535	88	604	590.5	4374
Lifecycle	5	4	6	1167	1785	618	1	4	80

Conservation Agriculture- Soybean in Malawi

Variable	Base value	10% lower	10% Higher	NPV Pessimistic	NPV Optimistic	Opt-Pess	Switching value	Difference	Difference (%)
Price per Kg	300	270	330	457	560	103	3.50	296.50	99
Yield per hectare	1500	1350	1650	354	663	309	1006	494	33
Annual labour costs	1	0.9	1.1	529	488	-41	-1.513	2.513	251.3
Discount rate	13.5	12.15	14.85	493	525	32	493	479.5	3552
Lifecycle	5	4	6	381	625	244	1	4	80

Improved seed varieties- Cassava in Malawi

Variable	Base value	10% lower	10% Higher	NPV Pessimistic	NPV Optimistic	Opt-Pess	Switching value	Difference	Difference (%)
Price per Kg	200	180	220	5717	7202	1485	26	174	87
Yield per hectare	19000	17100	20900	4651	8269	3618	12214	6786	36
Annual labour costs	5500	4950	6050	6366	6554	188	43376	37876	689
Discount rate	13.5	12.15	14.85	6234	6698	464	327	313.5	2322
Lifecycle	6	5	7	5378	7438	2060	1	5	83

Conservation Agriculture- Peanut in Zambia

Variable	Base value	10% lower	10% Higher	NPV Pessimistic	NPV Optimistic	Opt-Pess	Switching value	Difference	Difference (%)
Price per Kg	12.5	11.25	13.75	2492	3100	608	1.01	11.49	92
Yield per hectare	900	810	990	2112	3481	1369	532.4	367.6	41
Annual labour costs	1	0.9	1.1	2834	2758	-76	-6.385	7.385	738.5

Discount rate	10	9	11	2607	3006	399	368	358	3580
Lifecycle	20	18	22	2672	2903	231	1	19	95

Improved seed variety- Soybean in Zambia

Variable	Base value	10% lower	10% Higher	NPV Pessimistic	NPV Optimistic	Opt-Pess	Switching value	Difference	Difference (%)
Price per Kg	5	4.5	5.5	1330	1795	465	1.64	3.36	67
Yield per hectare	2000	1800	2200	1120	2006	886	1294.5	705.5	35
Annual labour costs	30	27	33	1563	1563	0	-	-	-
Discount rate	10	9	11	1498	1632	134	252	242	2420
Lifecycle	10	9	11	1439	1706	267	1	9	90

Improved seed variety- Faba beans in Ethiopia

Variable	Base value	10% lower	10% Higher	NPV Pessimistic	NPV Optimistic	Opt-Pess	Switching value	Difference	Difference (%)
Price per Kg	40	36	44	1934	2798	864	18.085	21.915	55
Yield per hectare	2900	2610	3190	1403	3330	1927	2187.65	712.35	25

Annual labour costs	100	90	110	2331	2401	70	774.70	674.7	674.7
Discount rate	12	11	13	2306	2428	122	175	163	1358
Lifecycle	5	4	6	1759	2918	1159	1	4	80

APPENDIX D: Online Survey Questionnaire

Question 1: Do you consent to take part in the study? ________________ (1= Yes (Oui) 0= No (Non)

Question 2: Select your country________________________?

1	Benin	(Bénin
2	Burkina Faso	
3	Cameroon	(Cameroun)
4	Ivory Coast	(Côte d'Ivoire)
5	Ethiopia	(Éthiopie)
6	Ghana	
7	India	(Inde)
8	Kenya	
9	Malawi	
10	Mali	
11	Mozambique	
12	Nigeria	
13	Togo	
14	Tunisia	(Tunisie)
15	Vietnam	
16	Zambia	(Zambie)

Question 3: What is your name ____(first name) _____(Last Name)

Question 4: What is your email address _________________?

Question 5: Please select the value chain you were requested to provide information on, or are more knowledgeable about. _________

1	Apple	
2	Baobab fruit	(Fruits de baobab)

3	Broad Beans (Faba or horse beans)	(Fèves (Faba))
4	Cashew	(Noix de cajou)
5	Cassava	(Manioc)
6	Cocoa	(Cacao)
7	Corn (maize)	(Maïs)
8	Honey	(Miel)
9	Mango	(Mangue)
10	Milk	(Lait)
11	Peanut	(Cacahuète)
12	Pigeon peas	(Pois d'Angole (Pois Cajan))
13	Plantain	(Plantain)
14	Potato	(Pomme de terre)
15	Poultry	(Volaille)
16	Rice	(Riz)
17	Sesame	(Sésame)
18	Soya	(Soja)
19	Sweet potato	(Patate douce)
20	Tomato	(Tomate)
21	Wheat	(Blé)

Question 6: Select two hazards related to climate that present the most significant risks/are most problematic for the value chain selected above? __________

1	Drought	Sécheresse
2	Floods	Inondations
3	Heat stress	Stress thermique
4	High temperatures	Températures élevées
5	Storms	Orages
6	Strong winds	Vents forts
7	Early-onset of rainfall	Précipitations précoces

8	Late-onset of rainfall	Précipitations tardives
9	Delay in the cessation of rainfall	Retard dans l'arrêt des pluies
10	Increased dry spells in the growing season	Augmentation des périodes de sécheresse pendant la saison de croissance
11	Hail storm	Grêle
12	Extreme Rainfall	des précipitations extrêmes
13	Decreased general length of rainy season	Diminution de la durée générale de la saison des pluies

Question 7: What is the severity of the selected hazard on Input Supply Stage? _________

1=Low (Faible), 2=Moderate (Modéré), 3=Major (Majeur), 4=Severe (Sévère)

Question 8: What is the severity of the selected hazard on the On-Farm Production Stage?_____

1=Low (Faible), 2=Moderate (Modéré), 3=Major (Majeur), 4=Severe (Sévère)

Question 9: What is the severity of the selected hazard in Post-Harvest Stage? _________

1=Low (Faible), 2=Moderate (Modéré), 3=Major (Majeur), 4=Severe (Sévère)

Question 10: What is the severity of the selected hazard on Output Market Stage? ________

1=Low (Faible), 2=Moderate (Modéré), 3=Major (Majeur), 4=Severe (Sévère)

Question 11: Please select choices from the listed that represent the current/ongoing adaptation strategies for all production stages (Input Supply to On-Farm Production to Post-Harvest and Output Marketing) for the selected value chain

1	Commercial forage production
2	Financial inclusion
3	Use of ICT (Digi-farm)
4	Strengthening of dairy cooperative
5	Zero grazing
6	Use of good agricultural practices
7	Introduction of animal health measures.
8	Low cost biogas production.
9	One stop shop

10	Use of pulverizers
11	Early warning information
12	Financial institutions such as insurance companies, microfinance, and banks offer credit
13	New Fodder varieties (., bracharia)
14	Use of ICT for extension services
15	Provision of milk coolers by County Government
16	Strengthening of farmer groups
17	The revival of cattle dips
18	introduction of improved AI services
19	Water harvesting for fodder production and animal use.
20	Storage of hay and silage,
21	Introduce solar-powered coolers.
22	Promote the use of new clean varieties and commercial vine multiplication

Question 12: Are there any other adaptation strategies for all production stages (supply up to output marketing) missing from the list? _________________ (1= Yes (Oui) 0= No (Non)

Question 13: How many other adaptation strategies? _________________ (Number)

Question 14: Specify additional current/ongoing adaptation strategies to the selected hazard for the selected Value chain

1	
2	
3	
4	

Question 15: What are the 2 most promising adaptation strategies that would be beneficial to adapt to the consequences of the selected Hazard at the input supply stage for the Selected Hazard

1	
2	

Question 16: What are the 2 most promising adaptation strategies that would be beneficial to adapt to the consequences of the selected Hazard at the on-farm production stage for the Selected Hazard

1	
2	

Question 17: What are the 2 most promising adaptation strategies that would be beneficial to adapt to the consequences of the selected Hazard at the post-harvest stage for the Selected Hazard

1	
2	

Question 18: What are the 2 most promising adaptation strategies that would be beneficial to adapt to the consequences of the selected Hazard at the output market stage for the Selected Hazard

1	
2	

Question 19: Please rank the selected most promising adaptation strategies in order of importance – with: 1 being the most important to you (8 being the least important to you (depending on the number of selected hazards)

Practices (based on selected practices in **question 15-18**)	Rank

Question 20: What is/are the factors/criteria you considered in your ranking

	Reason
1	
2	
3	
4	

Question 21: Do you have any additional comments? _________________ (1= Yes (Oui) 0= No (Non)

Question 22: Comment(s)

APPENDIX E: Cost-Benefit Analysis, Key Person Survey

General comments

Thank you for allowing us to speak with you. This questionnaire is intended to collect data that is aimed at helping us to identify innovations that sustainably increase agricultural productivity and incomes while helping farmers to adapt to changing climate conditions. Besides, these data will help farmers to adopt these practices. We are contacting you with the intent of collecting information that can help us to understand the costs and the benefits associated with the use of (the selected innovations in for example mango value chain will be entered here) the inputs, their cost, the length of the selected innovation since its implementation (start) to the end (i.e., when the innovation is changed or re-implemented again) and how profitable it is for farmers, and the role of community institutions in adopting this innovation.

As the respondent, we selected you with the help of Green Innovation Center to be a key resource person because you are more enlightened about innovation (the selected innovations for example mango value chain will be entered here). By agreeing to participate in this survey, you agree that you will do this activity voluntarily. Information obtained is strictly for academic and research purposes only and responses obtained will be treated with confidentiality. This interview will take approximately 45 minutes to 1 hour. Your participation is highly appreciated.

This questionnaire will only be used for research and will not in any way affect the respondents.

By signing this form, I agree that;

1. I am voluntarily taking part in this survey. I understand that I don't have to take part, and I can stop the interview at any time;
2. I don't expect to receive any benefit or payment (in monetary terms or otherwise) for my participation;
3. I have been able to ask any questions that I have at any time during the survey, and I understand that I am free to contact the researcher with any questions I may have in the future.

Participants name Insert your name.

Participant's Signature Choose an item..**Date** Insert the Date (Month/Date/Year

Value Chain: Select the VC you have been assigned to answer

Innovation: Select the Innovation you have been assigned to answer.

Identification Variables

Age: Enter your Age

Sex: Select your Sex

Questionnaire ID: Click or tap here to enter text.

Interview start time: In 24hrs format: 15:20

Interview end time: In 24hrs format: 15:20

Country Choose your country. Region/District Enter your region/ district

Phone number: Enter your Phone number

Section 1: General information about the Select the Innovation you have been assigned to answer. **for** Select the VC you have been assigned to answer

Question 1.1: Please describe the Select the Innovation you have been assigned to answer. in detail (in a way that enables non-user to understand it with ease). For example – to which crops is it applied and does it improve on another practice, and if it does, which practice is that?

Description.

Question 1.2: What is the main reason why Select the Innovation you have been assigned to answer. is used as opposed to another practice for Select the VC you have been assigned to answer or BAU (Business as Usual)

Main Reason

Question 1.3: Please list the crops (outputs) associated with Select the VC you have been assigned to answer that are affected by the Select the Innovation you have been assigned to answer.

Name of the crop (output) affected by the practice
1. **Enter the 1st Crop (Output)**
2. **Enter the 2nd Crop (Output)**
3. **Enter the 3rd Crop (Output)**
4. **Enter the 4th Crop (Output)**

Question 1.4: How many seasons can Select the Innovation you have been assigned to answer. in the Select the VC you have been assigned to answer » take, from its implementation until its optimal[20]? Number of Seasons.

---

[20] Season is dependent on the country and the value chain in question

Section 2 (a): Annual productivity changes (i.e., the average changes per year capturing both the short and long rainy seasons)

Question 2: Could you please provide information that can help us to understand the productivity changes associated with Select the Innovation you have been assigned to answer. for Select the VC you have been assigned to answer

	Please provide information for	Year (., year 1, 2 3, etc)
Q2.1a	How long does it take for Select the Innovation you have been assigned to answer. to start to have a physical impact on Enter the 1st Crop (Output)?	In which Year
Q2.2a	How long does it take for Select the Innovation you have been assigned to answer. to have a maximum physical impact on Enter the 1st Crop (Output)?	In which Year
Q2.1b	How long does it take for Select the Innovation you have been assigned to answer. to start to have a physical impact on Enter the 2nd Crop (Output)?	In which Year
Q2.2b	How long does it take for Select the Innovation you have been assigned to answer. to have a maximum physical impact on Enter the 2nd Crop (Output)?	In which Year
Q2.1c	How long does it take for Select the Innovation you have been assigned to answer. to start to have a physical impact on Enter the 3rd Crop (Output)?	In which Year
Q2.2c	How long does it take for Select the Innovation you have been assigned to answer. to have a maximum physical impact on Enter the 3rd Crop (Output)?	In which Year
Q2.1d	How long does it take for Select the Innovation you have been assigned to answer. to start to have a physical impact on Enter the 4th Crop (Output)?	In which Year
Q2.2d	How long does it take for Select the Innovation you have been assigned to answer. to have a maximum physical impact on Enter the 4th Crop (Output)?	In which Year

Section 2(b): The expected change in annual productivity (Kgs, Liters, Count, Bags)

	Please provide information for	Yield	Units kg, litres, bags, and count, etc
Q2.3a	For the Enter the 1st Crop (Output), what is the **business-as-usual yield before** the implementation of Select the Innovation you have been assigned to answer.	Yield	Select Unit
Q2.4a	For the Enter the 1st Crop (Output) what is the **new yield after the implementation** of Select the Innovation you have been assigned to answer.	Yield	Select Unit
Q2.3b	For Enter the 2nd Crop (Output) what is the **business as usual yield before** the implementation of Select the Innovation you have been assigned to answer.	Yield	Select Unit
Q2.4b	For the Enter the 2nd Crop (Output) what is the **new yield after the implementation** of Select the Innovation you have been assigned to answer.	Yield	Select Unit
Q2.3c	For the Enter the 3rd Crop (Output), what is the **business as usual yield before** the implementation of Select the Innovation you have been assigned to answer.	Yield	Select Unit
Q2.4c	For the Enter the 3rd Crop (Output) what is the **new yield after the implementation** of Select the Innovation you have been assigned to answer.	Yield	Select Unit
Q2.3d	For the Enter the 4th Crop (Output), what is the **business as usual yield before** the implementation of	Yield	Select Unit

	Select the Innovation you have been assigned to answer.		
Q2.4d	For the Enter the 4th Crop (Output) what is the **new yield after the implementation** of Select the Innovation you have been assigned to answer.	Yield	Select Unit

Section 2(c): Average annual price Prices per unit of the output

	Please provide prices per ***unit provided in section 2(b)*** for	Price per unit	Units (USD/ TSh /KSh etc.)
Q2.5a	For the yield associated with Enter the 1st Crop (Output)	Price per Unit	Unit
Q2.5b	For the yield associated with Enter the 2nd Crop (Output)	Price per Unit	Unit
Q2.5c	For the yield associated with Enter the 3rd Crop (Output)	Price per Unit	Unit
Q2.5d	For the yield associated with Enter the 4th Crop (Output)	Price per Unit	Unit

Price Unit

All the price you state are in Enter the Price Unit (. Ksh, Dollar)

Section 3: Costs for the Business as usual as compared with Select the Innovation you have been assigned to answer. **For** Select the VC you have been assigned to answer

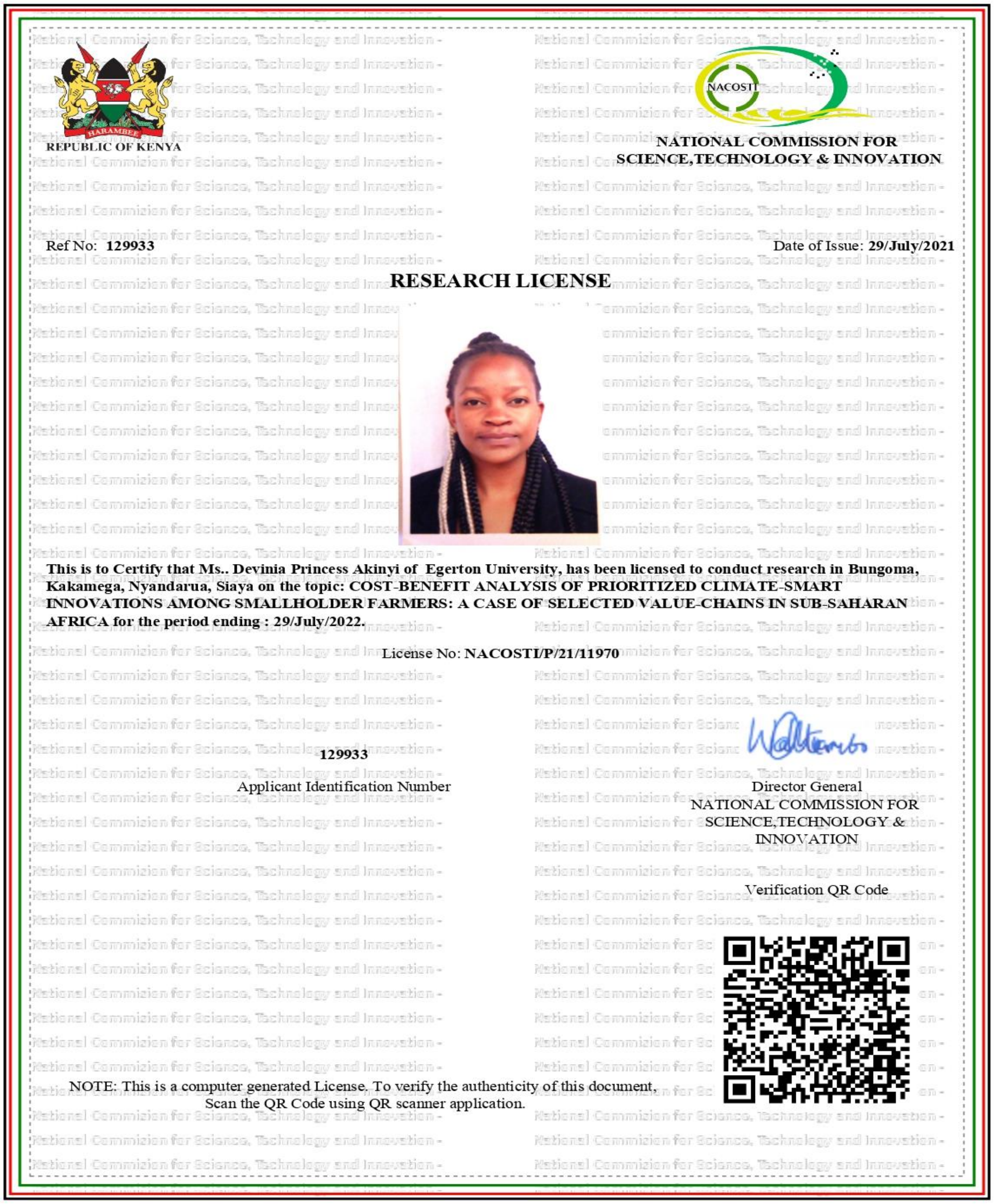
3a) Please list **MACHINERY AND EQUIPMENT** used for *List. tractor, wheelbarrows, etc.*	«BAU/farmers practice» *Number*	Select the Innovation you have been assigned to answer.	Units *, counts, number, man-days, kg, bags, cash-equivalent, etc.*	Price per unit	In which years
Example: Brouette	**1**	**2**	**Number**	**50000**	**Ex**amples: **Year 1** **Every year** **After 4 years, then yearly**
1. Machinery and Equipment	number	number	Unit	Price.	In which years
2. Machinery and Equipment	number	number	Unit	Price	In which years.
3. Machinery and Equipment	number	number	Unit	Price	In which years
4. Machinery and Equipment	number	number	Unit	Price	In which years
5. Machinery and Equipment	number	number	Unit	Price	In which years.
6. Machinery and Equipment.	number	number	Unit	Price t.	In which years
7. Machinery and Equipment	number	number	Unit	Price.	In which years
8. Machinery and Equipment	number	number	Unit	Price	In which years
9. Machinery and Equipment	number	number	Unit	Price	In which years

10. Machinery and Equipment	number	number	Unit	Price	In which years
3b) Please list **INPUTS** used for *List ., fertilizers, etc.*	«BAU/farmers practice»	Select the Innovation you have been assigned to answer.	Units	Price per unit	In which year.
1. *Input*	number	number	Unit	Price	In which years
2. Input	number	number	Unit	Price	In which years
3. Input	number	number	Unit	Price	In which years
4. Input	number	number	Unit	Price	In which years
5. Input	number	number	Unit	Price	In which years
6. Input.	number	number	Unit	Price	In which years
7. Input	number	number	Unit	Price	In which years
8. Input	number	number	Unit	Price	In which years
9. Input	number	number	Unit	Price	In which years
10. Input.	number	number	Unit	Price.	In which years

3c) Please list **SERVICES** used for *List ., transportation, greasing, etc.*	«BAU/farmers practice»	Select the Innovation you have been assigned to answer.	Units	Price per unit	In which years
1. Services	number	number	Unit	Price	In which years
2. Services	number	number	Unit	Price	In which years
3. Services	number	number	Unit	Price	In which years
4. Services	number	number	Unit	Price	In which years
5. Services	number	number	Unit	Price	In which years
6. Services	number	number	Unit	Price	In which years
7. Services	number	number	Unit	Price	In which years
8. Services	number	number	Unit	Price	In which years
9. Services	number	number	Unit	Price	In which years
10. Services	number	number	Unit	Price	In which years
3d) Please list **LABOUR** used for *List ., labour for land preparation*	«BAU/farmers practice»	Select the Innovation you have been assigned to answer.	Units	Price per unit	In which years
1. Labour	number	number	Unit	Price	In which years.

2. Labour	number	number	Unit	Price	In which years
3. Labour	number	number	Unit	Price	In which years
4. Labour	number	number	Unit	Price	In which years
5. Labour	number	number	Unit	Price	In which years
6. Labour	number	number	Unit	Price	In which years
7. Labour	number	number	Unit	Price	In which years
8. Labour	number	number	Unit	Price	In which years
9. Labour	number	number	Unit	Price	In which years
10. Labour	Number	number	Unit	Price	In which years

APPENDIX F: Research permit from NACOSTI



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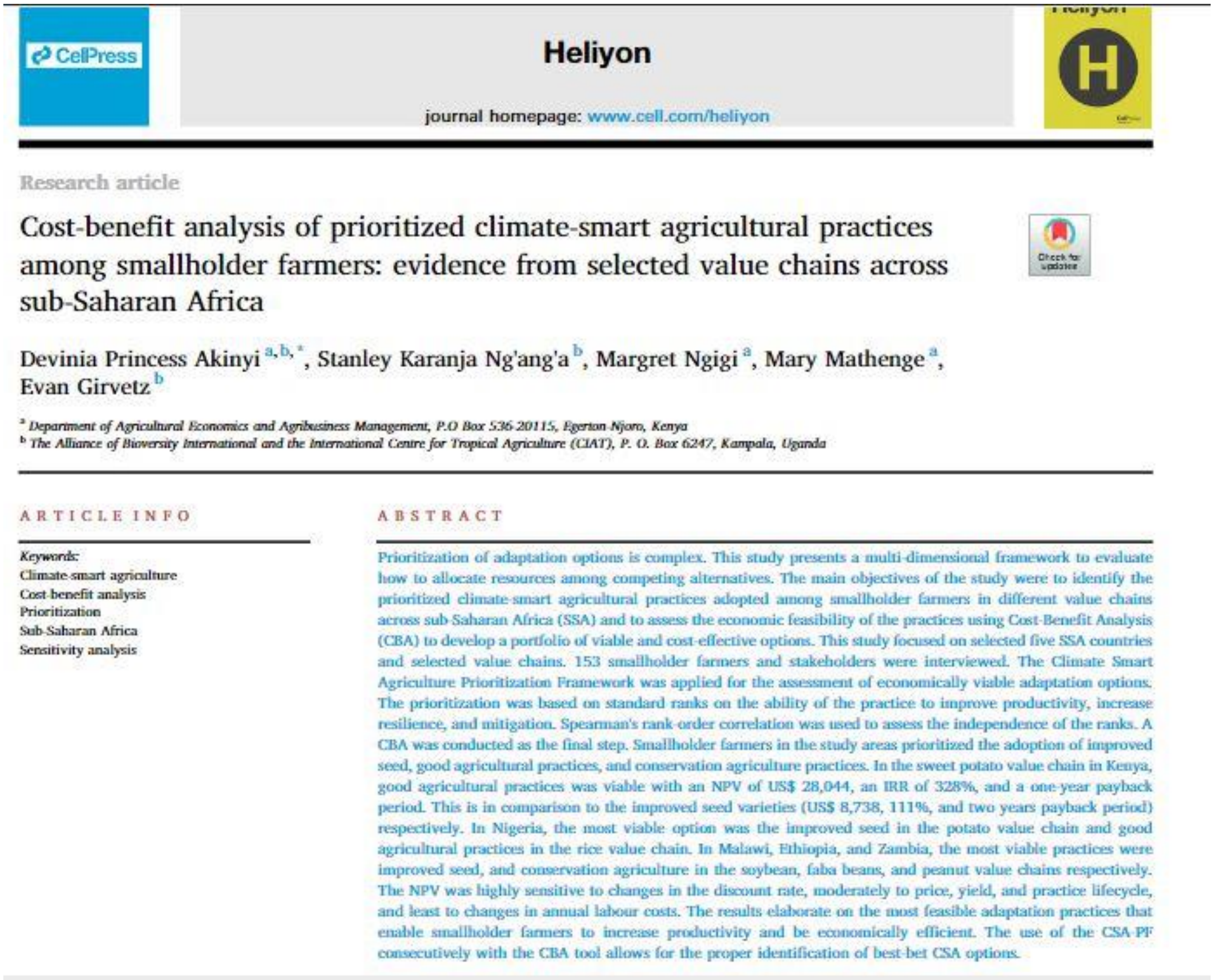
APPENDIX G: Abstract of publication on cost-benefit analysis



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Research article

Cost-benefit analysis of prioritized climate-smart agricultural practices among smallholder farmers: evidence from selected value chains across sub-Saharan Africa

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ARTICLE INFO

Keywords:
Climate-smart agriculture
Cost-benefit analysis
Prioritization
Sub-Saharan Africa
Sensitivity analysis

ABSTRACT

Prioritization of adaptation options is complex. This study presents a multi-dimensional framework to evaluate how to allocate resources among competing alternatives. The main objectives of the study were to identify the prioritized climate-smart agricultural practices adopted among smallholder farmers in different value chains across sub-Saharan Africa (SSA) and to assess the economic feasibility of the practices using Cost-Benefit Analysis (CBA) to develop a portfolio of viable and cost-effective options. This study focused on selected five SSA countries and selected value chains. 153 smallholder farmers and stakeholders were interviewed. The Climate Smart Agriculture Prioritization Framework was applied for the assessment of economically viable adaptation options. The prioritization was based on standard ranks on the ability of the practice to improve productivity, increase resilience, and mitigation. Spearman's rank-order correlation was used to assess the independence of the ranks. A CBA was conducted as the final step. Smallholder farmers in the study areas prioritized the adoption of improved seed, good agricultural practices, and conservation agriculture practices. In the sweet potato value chain in Kenya, good agricultural practices was viable with an NPV of US$ 28,044, an IRR of 328%, and a one-year payback period. This is in comparison to the improved seed varieties (US$ 8,738, 111%, and two years payback period) respectively. In Nigeria, the most viable option was the improved seed in the potato value chain and good agricultural practices in the rice value chain. In Malawi, Ethiopia, and Zambia, the most viable practices were improved seed, and conservation agriculture in the soybean, faba beans, and peanut value chains respectively. The NPV was highly sensitive to changes in the discount rate, moderately to price, yield, and practice lifecycle, and least to changes in annual labour costs. The results elaborate on the most feasible adaptation practices that enable smallholder farmers to increase productivity and be economically efficient. The use of the CSA-PF consecutively with the CBA tool allows for the proper identification of best-bet CSA options.