Climate-smart agricultural practices, productivity and food security among smallholder maize farmers in North West Province, South Africa

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Thesis accepted in fulfilment of the requirements for the degree *Doctor of Philosophy in Agriculture (Agricultural Economics)* at the North- West University

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Graduation ceremony: May 2024

General abstract

Various studies have shown that sub-Saharan Africa (SSA) is highly vulnerable to the impact of climate change due to its overreliance on rain-fed agricultural production. This sphere of production is highly susceptible to the vagaries of weather and climate. Climate change impacts are increasingly affecting farming households, resulting in socio-economic problems such as hunger, low productivity and reduced incomes. Consequently, its impact on agricultural production ranges from low outputs to fluctuations in market supply and the prices of food commodities. In South Africa, changes in rainfall and temperature patterns are endangering agricultural production and have increased the vulnerability of people whose livelihoods depend on farming by disrupting food markets, endangering the food supply for the entire population, reducing poor households' dietary diversity and increasing their food insecurity access score.

Climate-smart agriculture (CSA) is a strategy for transforming and reorienting agricultural systems to support food and nutrition security in light of the new climate change realities. By increasing the adaptive capacity of producers, and the resilience and resource use efficacy of agricultural production systems, climate change threats can be mitigated. While CSA adoption has been extensively studied in the literature, its impact on the food and nutrition security in SSA, especially South Africa, remains unclear. This study aimed to investigate the climate-smart agricultural practices, productivity and food security of smallholder maize farmers in South Africa. This entailed examining the complementary relationships among the adopted climate change adaptation strategies (CCAS) and the intensity of their adoption on smallholder maize farmers' productivity. It also entailed investigating the behavioural intentions of their adoption of the CSA practices and the associated impact on food-nutrition security (FNS).

Consequently, a multi-stage sampling procedure was adopted to select 316 smallholder maize farmers from 30 villages from the lists of all smallholder maize farmers available at the district extension officers of the four municipalities (Bojanala, Ngaka Modiri Molema, Dr Kenneth Kaunda, and Dr Ruth Segomotsi Mompati) that comprise North-West Province, South Africa. Primary data were acquired via a field survey of the smallholder maize farmers in the North-West Province over the 2022 farming season and analyzed through descriptive and inferential statistics. Multivariate probit regression (MVP) was used to model the complementarity among the adopted CSA, while a Negative Binomial Regression Model (NBRM) was employed to determine its adoption intensity. To understand the association between the behavioural adoption of CSA, food productivity and FNS of farming households, an endogenous switching regression model (ESRM) was employed, while household dietary diversity scores (HDDS) and household food security scores (HFIAS) were used to determine the FNS status of the households.

The socio-economic characteristics of the respondents revealed that the average age was 45 years, indicating that a large percentage were young and had the potential to contribute positively to agricultural productivity in the study area. The majority (79.00%) indicated that they had access to climate information, while about two-thirds (72.0%) had contact with extension agents, such advisory services being very important to disseminate information and encourage the adoption of new technologies for efficient production and improved farm outputs. Smallholder maize farmers in South Africa have devised a wide range of CSA strategies in response to the changing climate, including mulching (65.7%), mixed cropping (%), zero tillage (60.3%), planting cover crop (51.4%) and irrigation (52.8%). The ESRM showed that CSA had a significant impact on the net farm income of the smallholder maize farmers in North-West province. Furthermore, the MVP results revealed that the complementary relationships among the multiple CSA adopted by the farmers were influenced by institutional factors (e.g. access to extension training and climate information), socio-economic attributes (household size, age and educational status) and other farm variables (farm size and access to credit). Additionally, adoption of CSA had a positive and significant impacts on their FNS, resulting in increased in HDDS by 21.3% and decrease in their HFIAS by 30.7%. The study concluded that farmers who adopt positive behavioural intentions to CSA are more likely to enhance their desire to implement such practices, with a resulting improvement in agricultural productivity and responsive to FNS.

The study outcomes indicate that to achieve FAO’s sustainable agricultural goals and reduce global hunger by 2030, South Africa’s farmers need to develop resilience to climate change by adopting CSA to augment their food productivity. Policy interventions should therefore be focused on raising awareness among rural farmers to foster a more favourable attitude towards CSA practices. This could be enhanced through updated extension services and the integration of climate change sensitization into extension delivery methods through radio, smartphone, local newspapers as well as flyers/posters. Boosting the adoption of climate-smart practices is going to be essential to improve the resilience of farmers to climate change and FNS in the rural households.

Keywords: Climate change; Food policy; Food production; Risk of hunger; Shocks; Sustainability

DECLARATION

Student Number 43120075

I, Abeeb Babatunde Omotoso, solemnly declare here that this thesis titled "Climate-smart agricultural practices, productivity and food security among smallholder maize farmers in North West Province, South Africa," is my work. I declare that all literature sources and materials utilized have been adequately recognized and cited. I further declare that this thesis has not been submitted for an academic degree to any academic or research institution. This thesis is submitted to North-West University in fulfilment of the requirements for the degree Doctor of Philosophy in Agriculture with Agricultural Economics, in the Faculty of Natural and agricultural Sciences.

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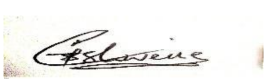

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DEDICATION

This dissertation is dedicated to Almighty Allah for making the programme a success.

ACKNOWLEDGEMENTS

I am most greatly indebted to Almighty Allah who has been there for me throughout my academic achievements, unfailing love and protection over me from my childhood days till date, especially throughout my stay in this citadel of learning. This research would not have been possible without the support of my Supervisory team (Dr A.O. Omotayo, Prof. S.S. Letsoalo and Dr Chris Tshwene). I would like to express my profound and sincere gratitude to my Promoter Dr. A.O. Omotayo for his technical inputs, mentorship, encouragement and constructive criticism throughout the conducts of this research work. May Almighty Allah give you good health and long life to achieve all your heart desires. My sincere gratitude also goes to Prof. S.S. Letsoalo and Dr Chris Tshwene for their support throughout the conduct of this research work. I really appreciate your efforts.

I extend my humble gratitude to my wife (Mrs. M.M. Omotoso) who has stood by me throughout my travails and absences. May Almighty Allah fulfill your heart desires. I acknowledge my kids (Hassan, Hussein and Atiyah) for their perseverance and moral support throughout my research study. May Almighty Allah be with you all. I also acknowledge the financial support rendered by the North-West University and Faculty of Natural and Agricultural Sciences, which helped in meeting my research needs during the study period. I would like to thank the Omotayo's family (Dr. O.P. Omotayo, Brian and Bennett) for their contributions and efforts in making my stay in South Africa comfortable as well as a cherished time spent together. May Almighty Allah give you good health and long life to reap the sowed seeds of your hard work.

Finally, I would like to thank my parent, Mr. S.A. and Mrs. R.O. Omotoso, and my siblings (Suraj, Teslim and Mrs. Z.T. Bello) for their support financially and morally during and after my programme. May Almighty Allah grant you a long life and good health so you can reap from what you have laboured for. I wish to appreciate the efforts of all my friends and colleagues at Oyo State College of Agriculture and Technology, Igboora, Nigeria, for their selfless assistance and all persons who read different sections of this thesis and made valuable editorial comments. I am indebted to you all. I also acknowledge the input of all the unknown reviewers for making this work a success. May the Almighty God be with you all. We also acknowledge the input of Carrin Martin for her professional English editing service on this thesis.

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LIST OF ABBREVIATIONS

ATT	Average Treatment Effect
BI	Behavioural Intentions
CCAS	Climate Change Adaptation Strategies
CH_4	Methane
CO_2	Carbon dioxide
CSA	Climate-smart Agriculture
DTMVs	Drought-Tolerant Maize Varieties
ESRM	Endogenous Switching Regression Model
FAD	Food Availability Decline
FAO	Food and Agriculture Organization
FAT	Funnel Asymmetry Test
FNS	Food-Nutrition Security
FSIN	Food Security International Note
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
HDDS	Household Dietary Diversity Score
HFIAS	Household Food Insecurity Access Score
IFAD	International Fund for Agricultural Development
IPCC	Intergovernmental Panel on Climate Change
JSTOR	Journal Storage
MRA	Meta-Regression Analysis
MESR	Multinomial Endogenous Switching Regression
MVP	Multivariate Probit
N_2O	Nitrous Oxide
NBRM	Negative Binomial Regression Model
NW	North-West Province
PCC	Partial Correlation Coefficient
PET	Precision Effect Test
PSM	Propensity Score Margin
SADC	Southern African Development Community

SE_PCC	Standard Error of Partial Correlation Coefficient
SSA	Sub-Saharan Africa
TPB	Theory of Planned Behaviour
UN	United Nations
UNEP	Unite Nations Environmental Programme
UNICEF	United Nations International Children's Emergency Fund
UT	Utility Theory
WoS	Web of Science
WHO	World Health Organization

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PUBLICATIONS

Omotoso et al., 2023. Climate change and variability in sub-Saharan Africa: A systematic review of trends and impacts on agriculture. *Journal of Cleaner Production 414 (2023) 137487*. https://doi.org/10.1016/j.jclepro.2023.137487 **(published)**.

Omotoso et al., 2023. The interplay between agriculture, greenhouse gases, and climate change in Sub-Saharan Africa**.** *Regional Environmental Change (2024) 24:1*. https://doi.org/10.1007/s10113-023-02159-3 (**published**).

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Omotoso et al., 2024. Impact of Concurrent Adoption of Drought-Resistant Maize Varieties and Organic Manure on Productivity and Welfare Outcomes. *Australian Journal of Agricultural and Resource Economics* **(in press)**.

Omotoso et al., 2024. Behavioural Intentions toward Climate-Smart Practices and Rural Farmers' Food and Nutrition Security? A Micro Economic-Level Evidence" *Climatic Change* **(in press).**

CONFERENCE OUTPUTS

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Omotoso et al., 2023. Enhancing Food Security through Climate-Smart-Agricultural Practices: Micro-Economic-level Evidence from Smallholder maize farmers in South Africa. Agri4D 2023: Building resilient food systems in uncertain times (26th September – 28th September 2023), Organized by SLU Global at the Swedish University of Agricultural Sciences (SLU) and the Swedish International Agriculture Network Initiative (SIANI), with support from the Swedish International Development Cooperation Agency (Sida) **(poster presentation).**

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POLICY BRIEF DISSEMINATION

Omotoso et al., 2023. Climate change and farming: economists warn more needs to be done to adapt in sub-Saharan Africa. The Conversation. November, 2023. Climate change and farming: economists warn more needs to be done to adapt in sub-Saharan Africa (theconversation.com)

CHAPTER 1: INTRODUCTION

1.1 Introduction

South African farmers produce a range of products, including maize, consequently, their productivity and distribution depending on issues such as soil quality, farm size, access to input and climate change. The adverse impacts of climate change on maize output are influenced by agricultural adaptations, farmer investment decisions, and policy choices (Abegaz et al., 2023; Fisher & Dodman, 2019; Galani et al., 2022). Being interrelated, these factors have had a detrimental impact on farming productivity if not well managed (Thothela et al., 2021; Traore et al., 2021). Various indicators of climate change, such as irregular rainfall, severe temperature stress, prolonged droughts, as well as flooding and temperature change, have been reported in the empirical literature, and have been shown to have varying impacts on South Africa's smallholder maize farming (Jennings et al., 2022). Smallholder maize farmers could directly perceive the effects of climate change on their enterprises, although the level of impact would vary according to their respective output levels and adaptation strategies (Abegaz et al., 2023; Fisher & Dodman, 2019; Fusco et al., 2020).

Maize farming is undertaken by farmers with a range of farm sizes, with smallholder farmers making a significant contribution to its production in many areas of the country, including the North-West Province, which borders with Botswana to the north, the boundary being the wide Orange River, which provides water for irrigation to many adjoining properties. Therefore, to achieve a sustainable output level and enhanced food security, smallholder maize farmers are expected to adopt various adaptation techniques to cope with the threats on their productivity posed by climate change. This study therefore aims to investigate impact of climate-smart agricultural practices on productivity and food security of smallholder farmers in South Africa. This chapter presents the background context to the study, the problem statement, Aim, objectives and hypotheses, as well as the structure of the following chapters. The study context is presented in three manuscripts in Chapter 2, with a brief summary to set the background to the study problem being indicated in this chapter.

1.2 Background

Achieving food security, addressing climate change and halting environmental and natural resource degradation are among the key challenges the agricultural sector faces in efforts to achieve various sustainable development goals. Globally, the number of people suffering from hunger has been on the rise, despite food production doubling in the last decades (Mullins et al., 2018). Thus, multiple pathways increase the number of food insecure people, such as poverty, disaster, migration patterns, culture, capital and environmental issues, among which is climate change (Maindi et al., 2020). Climate change is a universal environmental phenomenon that is being experienced across the globe, and cuts across all areas of life, from health and economics to the agricultural sector (Maindi et al., 2020). Climate change and agricultural productivity cannot be separated, its impact can negatively affect farm outcomes and food insecurity if not well managed (Maindi et al., 2020).

In sub-Sahara Africa (SSA), the effects of climate change are becoming increasingly severe, with approximately 45% of the population experiencing hunger or did not have regular access to nutritious and sufficient food as a result of the implications of climate change on food crop production (Outhwaite et al., 2022). The production of the three major cereal crops alone (maize, wheat and rice), on which many people in the region rely, will therefor need to increase by 80% by 2050 in order to feed its growing population (Cecil et al., 2021). However, climate change scenarios have shown that cereal production in SSA will be negatively affected if left unmanaged, and impede the ability to achieve the necessary gains for future food security (Aggarwal et al., 2019). This implies that the impact of climate change on maize production will be severe in SSA, particularly the southern region, due to poverty, multiple stresses and low adaptive capacity (Akano et al., 2022).

Maize is one of the most important crops being grown in South Africa, with yields having slowly declined over the years (Catherine et al., 2022). Low yields in this region are largely associated with climate change in the form of drought stress, coupled with low soil fertility, weeds, pests, diseases, low input availability and use, and inappropriate seeds (Brent et al., 2017). Bhandari et al. (2021), added that smallholder maize farmers in South Africa were amongst the most vulnerable farming households, as they are characterized by poor access to infrastructure, inputs and markets, and inadequate farming land (Outhwaite et al., 2022). Among the water-scarce countries of the world, South Africa ranks 30th from the top (World Health Organization (WHO), 2018), with the reliance on rainfall increasing the vulnerability of smallholder maize farming systems to climate variability and change (Akter et al., 2021).

Having sufficient rainfall gives smallholder maize farmers the ability to contribute positively to the country’s economic development and increase food security of rural households (Catherine et al., 2022). However, the contribution of smallholder maize farmers of North-West Province to food security and economy growth has been decreasing over the years due to climate change, and their vulnerability to the associated effects (Schreiner, 2018). For vulnerable households, a minor impact of climate change can lead to considerable losses of yields and severely impact the already non-diversified livelihoods and food security (Schreiner, 2018). Thus, smallholder maize farmers’ resilience and capacity to mitigate and recovered from the impact of climate change can go a long way in cushioning the effect on their productivity and food security (Imran et al., 2020).

Following International Panel on Climate Change (IPCC) meeting in 2018, the most effective way to combat the impact of climate change is regarded as being through climate-smart agricultural (CSA) practices. These practices ensure sustainable increments in agricultural productivity and food security by adapting to climate change through building resilience and reducing greenhouse gas emissions related to conventional practices (IPCC, 2018). Conversely, to attain a sustainable level of output, smallholder maize farmers are expected to adopt a variety of climate-smart adaptation strategies to combat the threats to their productivity posed by climate change (Gomes et al., 2020; Gramme et al., 2020). There are a variety of CSA techniques, but the farmer's perception of climate change will determine the type and extent of the methods they implement (Adego & Woldie, 2022). The CSA at the farm level to climate change can take many forms, such as agroforestry, soil water conservation, crop management modifications, and effective land-use management practices like crop diversification, mulching, and irrigation (Abegaz et al., 2023; Branca et al., 2013).

Consequently, identifying the complementary relationships among the adopted CSA and comprehending the dynamics of the adaptation decisions of the smallholder maize farmers is crucial for sustaining productivity in South Africa, particularly in the North-West province, which remains a key hub for maize production in the nation. However, the province is presently experiencing the negative effects of climate change as a result of a significant decrease in precipitation (Abegaz et al., 2023; Omotoso et al., 2023). Although maize plants are very adaptable, the extended decreased precipitation and drier environment would have a detrimental influence on production in the long term (Oguge & Oremo, 2017; Onyeneke, 2021). According to (Abegaz et al., 2023; Rosenstock et al., 2019; Zografos et al., 2016), the current drought due to rising temperature and unpredicted rainfall, forced South Africa's government to buy 934,000 metric tonnes of yellow maize from Argentina and Ukraine for $138 million between 2015 and the end of March 2016. Thus, significantly impacting the consumption power and food security of rural farming households in the Country (Rosenstock et al., 2019).

Against this backdrop, CSA could address/overcome this unfortunate outcome by integrating climate change with sustainable agricultural practices (Schreiner, 2018). This will provide a potential avenue for solving the challenges of declining productivity facing smallholder maize farmers in North West Province, and ensuring food sustainability by providing an opportunity for adapting and mitigating against climate change impact (Schreiner, 2018). The International Fund for Agricultural Development (IFAD, 2019) reported that the vulnerability status of smallholder maize farmers in South Africa is increasing due to low adaptive capacity and poverty. These farmers are struggling to mitigate the impact of climate change as a result of weak support institutions, limited incomes sources, decreasing education levels, as well as inadequate extension services and infrastructure to enhance their wellbeing (IFAD, 2019). The smallholder farmers therefore need to be better educated and supported to enable them to make timely and well-informed coping decision to adjust to the changes happening around them, to ensure adequate farm productivity and food secure households.

1.3 Problem statement

Despite its environmental challenges, maize farming continues to be the backbone for the majority of smallholder households in North-West Province, South Africa (Catherine et al., 2022). It constitutes approximately 80% of total grain produced nationwide, covers almost 65% of the cropping land area and plays a pivotal role in income generation, rural development as well as employment opportunities (Akanbi et al., 2021). Although the maize plant is quite hardy and adapts easily to harsh condition, a drier climate and lower precipitation could have detrimental effects on its productivity as well as the food security status of the farming households (Brosch et al., 2021). Rain-fed agriculture is the main agricultural practice of smallholder maize farmers in North-West Province due to limited access to irrigation facilities (Davies, 2019). These environmental challenges of harsh growing conditions and insufficient rainfall are increasing due to climate change, making it important for the stakeholders involved to understand fully the impact that they may have on the productivity and food security status of the smallholder maize farmers' household (Food Security International Note (FSIN), 2019). Many smallholder maize farmers are now faced with the choice of either falling casualty to the impact of climate change on their productivity or adapting to its impact by adopting various climate-smart agricultural (CSA) practices, these being important for economic improvement, poverty reduction and ensuring the food security of the grower and consumer (World Bank, 2018).

Despite the numerous benefits of CSA practices, as positioned by Abegaz et al. (2023) and Omotoso et al. (2023), there is inadequate information about the conditions and factors that hindered or motivate their use (Schreiner, 2018). There is little scientific knowledge about the vulnerability, adaptation strategies and food security impact of CSA practices on productivity and food security status among maize farmers in the North-West Province, South Africa. Schreiner (2018) noted that these farmers have the potential to create income for the majority of the households if there is sufficient rainfall, but that this is being hampered by the negative impact of drought and climate change. As the impact of climate change continues to have negative consequences, smallholder maize farming households are increasingly experiencing socio-economic problems, such as hunger, malnutrition, low productivity, reduced income and unemployment (Bahri et al., 2021). Focus on a national level has been limited due to lack of research findings to integrate support programs, policies and agricultural practices in improving rural food security (Kangogo et al., 2021). Understanding the behaviour of farmers regarding their food security is important for providing information to policy makers and other development agents who could lead the way in enhancing the effective use and practices of CSA among smallholder maize farmers in North-West Province, as well as other famers in the country.

1.4 Research questions

i. What is the climate change trends, its impact on agriculture and contribution of agriculture to greenhouse gas (GHG) emissions in sub-Saharan Africa?

ii. What is the impact of climate change adaptation strategies on productivity of smallholder maize farmers in the North-West Province?

iii. What are the impacts of adoptions of CSA practices on productivity and welfare outcomes of the smallholder maize farmers in the North-West Province?

iv. What are the impacts of CSA adoption on food and nutrition security of smallholder maize farmers in the North-West Province?

1.5 Research Aim and Objectives

The study assessed the impact of climate-smart agricultural practices on productivity and food security among smallholder maize farmers in the North-West Province. The aim was to fill the gap in understanding the impact of climate-smart agricultural practices in an effort to provide evidence to enhance productivity and food security among smallholder maize farmers in North-West Province of South Africa. The results, conclusions and recommendations from the study may serve as basis for policies regarding how to support smallholder maize farmers in North-West Province to the impacts of climate change.

The objectives of the study to achieve the aim/s were to:

1. Profile climate change trends, impact on agriculture production and contribution of agriculture to GHGs emission in sub-Saharan Africa[1].
2. Determine the impacts of climate change adaptation strategies on the productivity of smallholder maize farmers in the North-West Province, South Africa[2].
3. Examine the impacts of adoptions of CSA practices on productivity and welfare outcomes of smallholder maize farmers in the North-West Province, South Africa[3].
4. Analyze the effects of CSA adoptions on food and nutrition security of smallholder maize farmers in the North-West Province, South Africa[4].

[1] Objective 1 = Manuscript 1 -3
[2] Objective 2 = Manuscript 4
[3] Objective 3 = Manuscript 5
[4] Objective 4 = Manuscript 6

1.6 Hypotheses

The following hypotheses were set for the study, in their null forms (: β=0):

1. The smallholder maize farming households' socio-economic characteristics does not significantly influence CSA practices adopted in the study area.
2. The smallholder maize farmers' behavioural intention does not significantly influence the CSA practices adopted in the study area.
3. There is no significant relationship between the CSA practices adopted by the smallholder maize farmers in the study area and their farm productivity.
4. There is no significant relationship between the CSA practices adopted by the smallholder maize farmers in the study area and their food security status.

1.7 Motivation for the study

The impact of various climatic change scenarios, such as high temperatures, poor rainfall, variation in weathered condition, floods and high temperature increment on food security have been a major concern globally (Kangogo et al., 2021). According to IFAD (2019), there are serious concerns regarding the vulnerability of developing countries, including South Africa, as a result of the consequences of climate changes. This includes a negative effect on rural smallholder farmers who serve as the food basket for the nation, with those in South Africa not being exempt from the adverse effects of climate change on their productivity and household food security (Davies, 2019). Considerable research has been done to quantify the impact of climate change on smallholder maize farmers' productivity in the country but have not included their use of CSA practices to mitigate the effect on the productivity and food security of smallholder maize farmers in North-West Province (Paul et al., 2018; Akanbi et al., 2021).

Little has been done to understand the impact of CSA on productivity and household food security of smallholder maize farmers particularly in dry area of the country, where irrigation needs to supplement rainfall for optimal food production (Paul et al., 2018; Akanbi et al., 2021). Intriguingly, maize is a staple food for many families in SA, with poor families in particular using it as a staple food in various forms (Davies, 2019). Consequently, there are no policies regarding how to support smallholder maize farmer in North-West Province to the impacts of climate change, including the introduction of CSA (Paul et al., 2018; Akanbi et al., 2021). Many smallholder maize farmers in the province cannot afford to put in bore holes for water and do not have easy and affordable access to bulk sources, such as large rivers and dame, making it necessary to identify alternative ways for them to prevent their crops from drying out in the absence of sufficient regular and predictable rainfall at the right time of the year. Little is known about the extent to which CSA practices are being used among this population to grow maize, or the impact that it has had on productivity and household food security. Additionally, little is known about the role that the socio-economic variables of the farmers play in the adoption and successful application of CSA.

In the absence of this information, the study was necessary, given the potential of maize production in the South African food system. In order to remain aligned to the objectives of the NDP 2030, the needs of the smallholder maize farmers in North-West Province, and South Africa at large, must be met to feed the ever-increasing population. This study will assist by providing information that can be used in policy formulation to address the agricultural needs of smallholder farmers who do not have the capacity to undertake their own research. The results will also benefit development planners and policy makers to design and implement appropriate programmes to alleviate and mitigate the adverse impact of climate change on smallholder maize farmers' productivity and household's food security.

1.8 Overview of chapters

This study is presented in manuscript format, with the literature reviews being presented in each manuscript rather than as a separate chapter. The study is presented in the following chapters:

Chapter 2. Theoretical frameworks and literature review: This chapter outlines the theoretical and conceptual frameworks used to inform the study, followed by outlining the study context in three manuscripts. The first manuscript addresses Objective 1, and the other two manuscripts provide context to the study. The first paper reviews the available climate-change adaptive mechanisms, and the second details the interplay between agriculture and greenhouse gases emission, while the third provides the synergy between CSA and food-nutrition security in sub-Saharan Africa.

Manuscript 1: This review address Objective 1, profiling climate change trends and their impact in sub-Saharan Africa. The systematic review is titled "Climate Change and Variability in sub-Saharan Africa: A Systematic Review of Trends and Impacts on Agriculture", which has been published in Journal of Cleaner Production (Elsevier).

Manuscript 2: This manuscript is intended to provide context to the study by reviewing the contribution of agriculture and energy-use in agriculture to GHGs emission and climate change adaptive mechanisms relevant to SSA through a systematic review of "The interplay between agriculture, greenhouse gases, and climate change in sub-Saharan Africa", which has been published in Regional Environmental Change (Springer).

Manuscript 3: This is a meta-regression review of "Climate-Smart Agriculture in sub-Sahara Africa: A meta-analysis review of its Impact on food security", which is prepared for publication and already under review in Technological Forecast and Social Change (Elsevier).

Chapter 3. Research methodology: This study outlines the methods used to address the study Objectives, and reviews the study area and population, the data collection methods and processes, as well as the analytical techniques.

Chapter 4. Manuscript 4: This chapter addressed Objective 2 and provides empirical evidence on **"**Unravelling the complimentary interactions between climate change adaption strategies and smallholder maize (Zea mays L.) farmer's productivity in South Africa" which is under review in Ecological Economics (Elsevier).

Chapter 5. Manuscript 5: This chapter addressed Objective 3 and provides empirical evidence on "the Concurrent Adoption of Drought-Resistant Maize Varieties and Organic Manure Impact Productivity and Welfare Outcomes in South Africa" and already in press at Australian Journal of Agricultural and Resource Economics (Wiley).

Chapter 6. Manuscript 6: This chapter addresses Objective 4 and provides empirical evidence on "Behavioural Intentions toward Climate-Smart Practices and Rural Farmers' Food and Nutrition Security. A Micro Economic-Level Evidence from South Africa" which is already in press at Climatic Change (Springer).

Chapter 7: Summary, Conclusion and Recommendations: This chapter reviews the extent to which the aim was achieved by summarizing of the main findings of the objectives, outlines the study limitations, indicates the significance of the findings, and makes recommendations.

CHAPTER 2: THEORETICAL FRAMEWORK AND LITERATURE REVIEW

2.1 Introduction

Two theoretical frameworks were used to guide this study, the first being the theory of planned behaviour, which was used to identify the areas of interest and their associated variables. It addresses the complex interplay of factors that can lead to adoption of CSA and explores its consequences on productivity and overall well-being of the farmers. The second, the utility theory, contends that farmers would likely adopt climate change adaptation strategies if the expected benefit of adopting a CCAS outweighs non-adoption of it. Likewise, it provides a foundational framework for studying adoption choices, and making informed decisions in agricultural domain. The study context is presented in three manuscripts, each being presented in the format required for submission and submitted in high quality peer-review journals. They address the study setting on climate change trends in SSA and its impact on agriculture as well of contribution of agriculture to GHGs emission. The study conceptualizes on systematic review of literature which allows for the qualitative and quantitative synthesis of research results from multiple studies. This approach provides more precise estimates of the overall impact of climate change parameters, such as temperature, rainfall, and extreme weather events on agricultural production in SSA.

- Manuscript 1: Title “climate change and variability in sub-Saharan Africa: a systematic review of trends and impacts on agriculture” relates to objective 1 have been submitted and published in ***Journal of Cleaner Production (Elsevier)*.** https://doi.org/10.1016/j.jclepro.2023.137487

- Manuscript 2: Title “the interplay between agriculture, greenhouse gases, and climate change in Sub-Saharan Africa”, being part of objective 1 has been published in ***Regional Environmental Change (Springer)*** https://doi.org/10.1007/s10113-023-02159-3

- Manuscript 3: Title “climate-smart agriculture in sub-Sahara Africa: A meta-analysis review of its Impact on food security” relates with objective 1 was prepared and submitted to ***Technological Forecast and Social Change (Elsevier)*** **– under review**.

2.1.1 Theory of Planned Behaviour (TPB)

Climate change poses a serious problem to the productivity and food security of smallholder farmers, as most depend on agriculture as a source of livelihood, with the majority not having the means to cope with climate shocks (Brosch et al., 2021). As a result, many may find themselves diversifying into non-farm income due to the possibility of facing poverty and food insecurity, poor crop health and a decline in crop yields (Brosch et al., 2021). Consequently, the conceptual framework (TPB) is intended to provide an understanding of how the impact of climate change on the productivity and food security of smallholder maize farmers could be mitigated through the adoption of climate-smart agricultural (CSA) practices.

The theory of planned behaviour proposed by Atta-Aidoo et al. (2022) contends that adoption behaviour can be predicated by people’s intentions, which is determined by attitudes and behaviour intentions, which are affected by social norms and the level of controls (Boateng et al., 2019; Omotayo et al. 2020). It is based on the assumption that rational thinking influences people’s decisions, choices and actions, which are determined by three things: attitudes, subjective norms and perceived behavioural control (Figure 2.1). Attitudes refer to the perceived benefits, which are influenced by taking into account the consequences of an action (Omotayo et al., 2020). Subjective norms refer to people being influenced by what others think or the social attitudes to an action of family, friends and society at large. The perceived behavioural controls are the factors that affect their execution of an action or behaviour, with internal control relating to their knowledge, skills and ability, and external control being the opinions and actions of others that may enable or prevent a person from taking an action and affect the time it may require (Boateng et al., 2019; Omotayo et al. 2020).

These three factors collectively result in an intention to adopt (or not to adopt) and a resulting behaviour, with the intention not necessarily being the same as the final action, depending on the factors that have influenced the intervening decisions (Atta-Aidoo et al., 2022). The theory states that one’s intentions are the best drivers of one’s behaviour. The TPB maintains what the Theory of Reasoned Action (TRA) postulates about human behaviour being governed by one’s attitudes and behavioural intentions characterized by the presence of social norms and the exercise of volitional control.

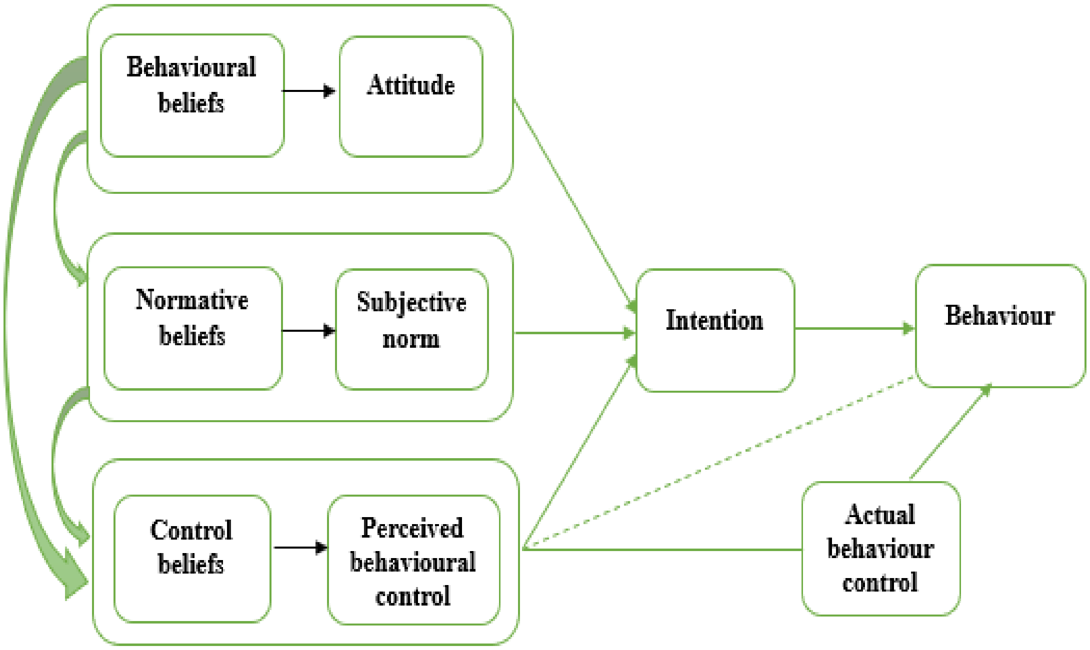

Fig. 2.1. Theory of Planned Behaviour (adopted from Atta-Aidoo et al., 2022)

The model consists of the following five sections:

1. Attitudes: this relates to individual's overall evaluation or appraisal of a particular behaviour. Attitude is composed of two components: the affective component (emotional response) and the cognitive component (beliefs and perceptions). A more favorable attitude toward the behavior leads to a stronger intention to perform/adopt it.
2. Subjective norms: these relate to perceived social pressure or influence that an individual perceives regarding the behaviour. It considers the expectations and opinions of important people or groups in an individual's life.
3. Perceived behaviour control: this deals with individual's perception of the ease or difficulty of performing the behaviour. It includes factors like self-efficacy (confidence in one's ability to perform the behaviour) and the presence of facilitating or inhibiting factors.
4. Intention: this relates to individual's purpose or resolve to perform an action, and it plays a central role in understanding and predicting human behaviour. Intentions are often seen as a key precursor to actual behaviour.
5. Behaviour: this refers to the actions, conduct, or reactions of an individual in response to internal or external stimuli. It encompasses a wide range of activities, both conscious and unconscious, of farmers to response to climate change.

The TPB was adapted for this study to understand the various ways in which CSA practices adoption have impacted on the productivity of smallholder farmers, and how such impacts mitigate their vulnerability and food insecurity status. The three goals of CSA practices are to promote a sustainable increase in agricultural productivity, adapt to the challenges of climate change, and reduce or remove greenhouse gas (GHG) emissions that emanates from agricultural practices (IPCC, 2019). The CSA in this modified framework (Figure 2.2) were intended to integrate these three goals to enhance agricultural productivity and food security among smallholder maize farmers under a changing climate (Akanbi et al., 2021). As indicated in Figure 2.2, the CSA practices require innovation to ensure the availability and accessibility of food (food security).

The new framework consists of the following eight sections:

1. CSA framework: to promote a sustainable increase in agricultural productivity, adapt to the challenges of climate change, and reduce or remove greenhouse gas emissions through positive attitude towards CSA practices.
2. Previous agricultural practices: farmers' perceptions of their ability to control and implement specific practices can be crucial. They can discontinue previous practices due to perceived barriers, lack of resources, or inadequate knowledge and skills. Identifying these control factors can help in addressing barriers to adopt new agricultural technology.
3. Food security: TPB can be applied to assess farmers' intentions to adopt sustainable and food-secure agricultural practices. It can help understand why farmers choose particular farming methods, crop varieties, or conservation techniques.
4. New CSA practices: in the face of farmers' positive attitudes and strong intentions to adopt these technologies, interventions can focus on providing training, access to resources, and support to facilitate their adoption.
5. Farmers' socioeconomic characteristics: play a significant role in influencing adoption behaviour, including the adoption of new practices, technologies, or innovations.
6. Adoption of CSA (extension services): the uptake of new technology, this being a reflection of the farmers having a positive attitude towards new technology through having had contact with and support from an extension officer.
7. Adoption level: subjective norms consider the influence of social factors on adoption behaviour. If individuals perceive that important other (e.g. peers, leaders, experts) support

the adoption of a specific behavior, it can positively impact adoption level. The endorsement of an innovation by trusted individuals or groups can encourage its adoption.

8. Maize farmers' productivity: the adoption of CSA practices offers substantial potential for improving maize productivity in the context of climate change and variability.

Figure 2.2. presents the adaptation of the theory of planned behaviour for this study regarding CSA adoption among smallholder maize farmers in North-West province and how it can influence their productivity and food security.

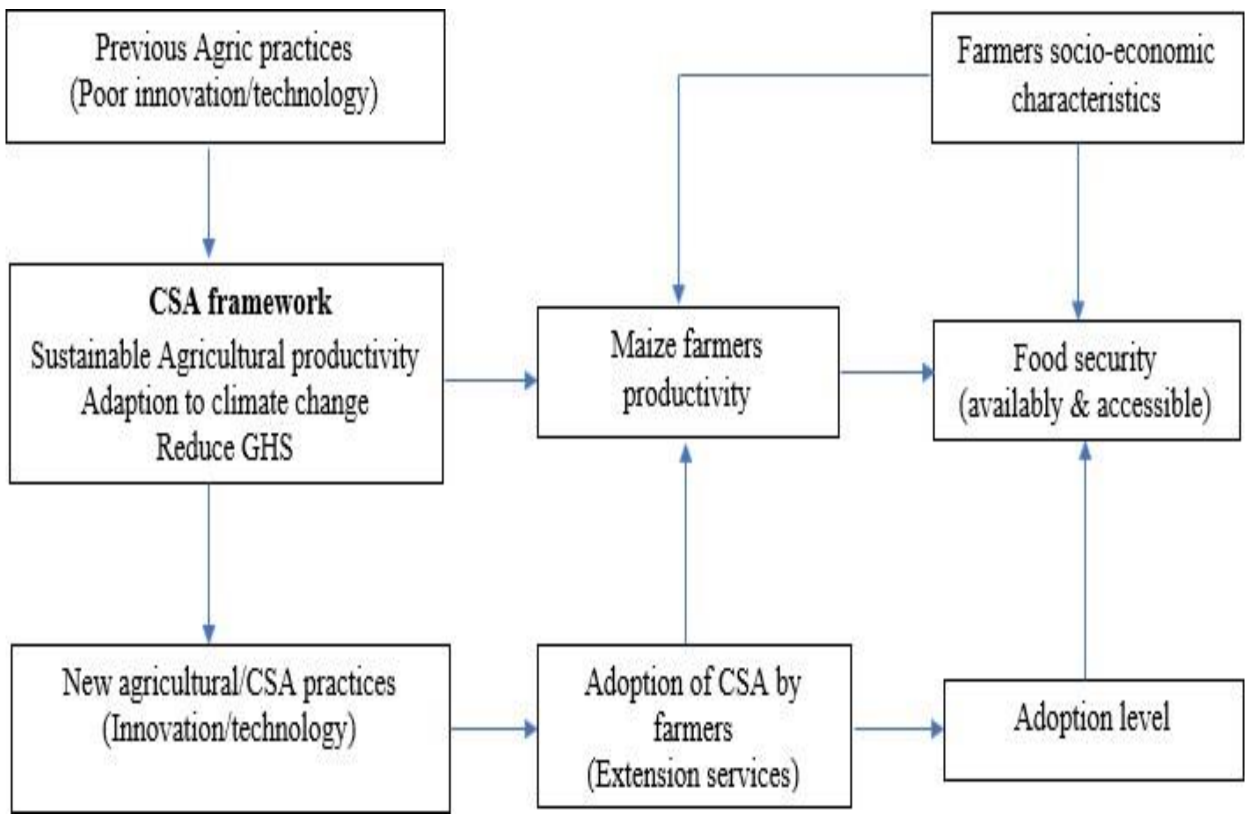

Fig. 2.2. Conceptual framework of the adoption impacts of Climate-Smart Agricultural Practices on smallholder's maize productivity and food security

In addition to the innovations and technologies that are being harnessed towards the implementation of CSA, agricultural practices that fit into the CSA framework were identified as CSA technologies (Sorgho et al., 2020). Therefore, this study conceptualizes agricultural practices such as zero tillage, soil and water conservation, agroforestry, crop rotation and diversification that have been identified to fit into the CSA framework based on the FAO's (2018) recommendation.

This involves identifying the choice that the farmers make about which CSA practices to use, and their level of adoption of these practices.

Consequently, the socio-economic characteristics (age, household size, education level and farm size) of the farmers, coupled with their CSA technological options and agents of information (extension agent), are factors that need to be considered in their implementation and adoption. Not only do these factors influence CSA adoption, but they can also influence the level of adoption or adoption intensity, which in the long-term affects their productivity and food security (Sorgho et al., 2020).

2.1.2 The Utility Theory

The theory of utility contends that individual behaviour will affect choices, these being based on their available options (Atta-Aidoo et al., 2022). The adoption or rejection of any CSA practice lies under the utility theoretical frameworks (Sorgho et al., 2020). The theory of utility evaluates the choice(s) being made, and establishes if one option has a higher utility than another. The choices being made by smallholder farmers about which agricultural practices to be adopted depends on the available options and the benefits they stand to gain from each (Sorgho et al., 2020). There is the assumption that smallholder farmers, adopt CSA practices when the expected utility or net benefits are higher than when they do not adopt them (Sorgho et al., 2020).

For example, a rational farmer whose aim is to maximize the proceeds from production over a specific period and has a set of CSA practice options to choose from will decide to adopt those for which the utility is perceived to be better than other options.

This relationship is expressed as Equation

$$U_{ij} = V_{ij} + E_{ij} \quad \text{.......} \quad 2.1$$

Utility (U) is examined as choices taken and relies upon on alternatives made from j CSA options assumed to have a utility function as follows;

$$U_{l} = V\,(X_{j}, Zi) \quad \text{.......} \quad 2.2$$

Smallholders' farmer choice of implementing certain CSA practices is a function of the relative advantage of using that specific practice. If a choice has no relative advantage for a farmer, then they are unlikely to adopt it. For this study, the synergy between socio-economic characteristics, vulnerability, awareness and choice of CSA practices adopted were explored.

Manuscript 1

Climate Change and Variability in Sub-Saharan Africa: A Systematic Review of Trends and Impacts on Agriculture

Abstract

Various studies have shown that sub-Saharan Africa (SSA) is highly vulnerable to the impact of climate change due to its overreliance on rain-fed agricultural production, this sphere of production being highly susceptible to the vagaries of weather and climate. Climate change impacts on agricultural production range from low outputs to fluctuations in market supply and the price of food commodities. In this study, various studies were systematically reviewed to highlight the trends in climate change in SSA and its impact on agricultural production. Our findings show that the impacts have been significant, as evidenced in the average temperature and rainfall fluctuations, as well as in the intensity of extreme weather events. Additionally, climate change is proving to be unpredictable, with its severity being reflected in the deceasing agricultural production of some crops in SSA. Ascribed to the current manifestations of climate change, resulted to decline in agricultural productivity due to reduced yields, attributed to the shorter length of the growing season, which affects the availability, accessibility and price of food products. Thus, this review sets out to verify the widespread belief that SSA is severely affected by climate change. It confirms that in order to improve agricultural productivity and sustainability, policymakers should prioritize the development and implementation of specific policies/programmes regarding adaptation strategies and promotions in the farming industry in an attempt to mitigate its effects of climate change. This makes it important to take steps to strengthen the resilience of agricultural production techniques, improve human adaptability and develop project-based early warning weather reporting systems.

Key words: Vulnerable region; Food production; Shocks; Risk of hunger; Sustainability

2.2.1 Introduction

The global agricultural production system is facing serious constraints in meeting the increasing demand for food, this being due to various political, economic and environmental challenges (Hisano, et al., 2018), including those associated with climate change (Food and Agricultural Organization (FAO), 2019). Climate change is among the more recent issues affecting the world and is recognized as the major environmental risk for the 21st century (Mihiretu et al., 2020). It affects the food production system in various ways, ranging from reduced productivity to the death of livestock, and in indirect effects such as fluctuations in food prices and market supply (Ado et al., 2019), as indicated in numerous sources in the literature (Khanal et al., 2021; Ado et al., 2019). However, most of these studies appear to concentrate on developed nations, where the economic consequences are less intense due to their widespread adoption of modern technology.

This stands in sharp contrast to developing countries, where the use of modern technology is still limited (Mihiretu et al., 2020; Makuvaru et al., 2020). The impacts of climate change, including both decreased and increased precipitation, as well as variations in the global average temperature, have already had an influence on ecosystems, biodiversity and human systems all over the world (Ricke et al., 2017; Hundera et al., 2019). It is anticipated that if temperatures continue to increase and precipitation becomes more erratic, or increases or decreases substantially, agriculture will be negatively affected if the farming systems cannot adapt to the new conditions (Imran et al., 2020; Mihiretu et al., 2020).

Agricultural production is susceptible to a change in atmospheric and weather conditions (Stern, 2017; Ado et al., 2019), which can negatively affect agricultural productivity (Imran et al., 2020). This is especially true for developing countries, as climate is the main factor affecting agricultural distribution and production, with many farmers having minimal capacity to adapt to new conditions (Badi and Murtagh, 2019). The economies of SSA countries depend heavily on a system of agricultural production that is weather and climate-sensitive, making them susceptible to these forces (Brugger, 2020; FAO, 2018).

Numerous researchers have demonstrated that the climate change impacts per country vary and cannot be similarly quantified (Goglio et al., 2020; Milesi & Churkina, 2020; Lezaun, 2021). These impacts tend to vary with respect to the adaptation and mitigation strategies in place, as well as with the resources available (Intergovernmental Panel on Climate Change (IPCC), 2020; Brugger et al., 2021; Ceci et al., 2021). According to Khan et al. (2021), climate change will make SSA more vulnerable than developed countries, thereby leading to an exacerbation of their income inequalities. In addition, temperature increases could have a limited impact on the market sectors of many of the more affluent countries, but a detrimental effect on many SSA countries (Dadzie, 2021; Koberg et al., 2019).

Additionally, this vulnerability arises from the fact that SSA has experienced the slowest rate of technological advancement to date than any other region, and is regarded as being information poor with respect to climate information (Mihiretu, et al., 2020). According to the IPCC (2020), SSA is predicted to become the region exhibiting the greatest level of vulnerability by 2100, with agricultural losses likely to range between 5%-15% of GDP. These impacts are also expected to be accompanied by rapid population expansion in the region, being anticipated to increase from approximately two billion in 2005 to over 3.2 billion by the year 2050 (FAO, 2019; Dadzie, 2021). As new studies on agricultural vulnerability emerge, it is important to review and assess them to identify common findings, trends and solutions, with this current study exploring three areas of interest.

Firstly, to review the synergic association between climate change and agriculture. Secondly, to highlight the trends of climate variability in SSA and identify ways to overcome them. Thirdly, to assess the impacts of climate change on the vulnerability of the agricultural industry to enable the processes and actions to be modelled. Understanding of the connections between climate change and agricultural production in SSA regarding the implementation of improved adaptation procedures will also be better understood. In order to guide effective interventions in respect of policy formulation in SSA, this paper set out to survey the literature on climate change, assess the scope and character of climate change challenge, and evaluate how the evolving patterns affect agricultural productivity.

2.2.2 Materials and methods

To find relevant articles, the literature search was conducted between October 2021 and February 2023 from online sources such as Web of Science (WoS), Scopus, as well as Journal Storage

(JSTOR). Furthermore, books, theses, and dissertations were taken out from the library of South Africa's North-West University (NWU). To find relevant publications, search terms and terminologies such as "climate variability," "severe weather," "agricultural," "temperature change," "rainfall pattern," "food production," "livestock production," "adaptation in SSA," "mitigation in SSA," and "sub-Saharan Africa" were employed. Bibliographic search processes were also employed to intensify the search for the precise location of the pertinent literature connected to climate change and agriculture, with a systematic method for approaching the literature study being applied. This was done by searching for "climate change in SSA" in the specified databases. Furthermore, a search was conducted to establish and save the bibliographies of the retrieved articles in the Endnote reference manager.

Study Area

SSA is Africa's southernmost region (National Geographic Society, 2019), and includes 47 African countries and territories that are located entirely or partially south of the Sahara Desert. The bioclimatic zones in SSA are diverse (National Geographic Society, 2019), with most of the region being located in the tropics and sub-tropics, with their associated climatological characteristics (National Geographic Society, 2019), although there is significant variation in its seasonal climates (Cervigni et al., 2019b). Various environmental factors, including high altitudes and a vast and extensive region of alternating plains and highlands, contribute to the continent's diverse climate. The Sahel and Savanna regions, positioned between the extensive and barren Sahara Desert and West Africa's lush tropical forests, experience temperatures and conditions usually characteristic of arid regions, but receive some rain during the monsoon season (Batumike et al., 2022). Africa's western and central rain forest regions receive an annual 70 inches of rainfall from air masses moving onto the land from the Atlantic and Indian Oceans (National Geographic Society, 2019). The southeastern coast, where humid tropical conditions dominate, receives the highest rainfall in Africa south of the equator (Mabogunje et al., 2017).

Data Sources

The methodology used in this systematic review of the literature followed that detailed by Ricart *et al*. (2022) in a number of steps:

1. Literature was sourced from two major scientific databases [Scopus (Elsevier) and Web of Science (WoS)] using relevant keywords and search phrases that were unique to each database. Using the Scopus and WoS electronic database, a keyword search using the words, [“agriculture” or “food production” or livestock production”] and [“climate change” or “global warming”] and [“sub-Saharan Africa”] was performed. Some articles, if not published in English or published prior to 2000, were excluded. The information from the different scientific databases provided 1,270 studies. (376 from Scopus and 894 from WoS).
2. It was initially found that searches of the bibliographic databases did not always produce content that was pertinent. To concentrate on the more relevant articles entailed concentrating on the title, employing duplicate elimination, and abstractly screening the reviews, with 303 articles being retained (Figure 2.1).
3. The full texts of the 303 studies were thoroughly reviewed and 147 discarded, including those review articles (systematic or literary) that were solely concerned with current agricultural management practices. Furthermore, the texts of those studies not modeling SSA as case studies on climate change, variability and agriculture were excluded (Table 2.1).
4. Finally, the results of the literature screening process resulted in 122 articles being included, which represented approximately 13% of the literature identified from the database.

Table 2.1. Criteria for article inclusion in the systematic literature review

Search result	Reason for acceptance	Reason for rejection
Initial look	Studies published in English	Studies published in other languages
	Articles on climate change and variability	Articles unrelated to climate change and variability (human evolution)
Title with abstract screening	Articles related to agriculture	Studies unrelated to agriculture
	Studies focusing on Africa	Global and continental studies
	Studies published from 2000 – 2023	Studies published subsequent to the 2000s
	Articles addressing climate change in SSA and relevant to the aims of the review	Articles addressing climate change but not relevant to the aim of this review and study area
Full paper review	Original studies	Qualitative literature reviews and analyses
	Articles that were not duplicated versions of other articles	Articles that were duplicated versions of other articles in the dataset
	Studies available on the ISI Web of Knowledge	Studies not available on the ISI web of knowledge
	Adaptation options under different climate variability scenarios	Adaptation options not related to climate variability

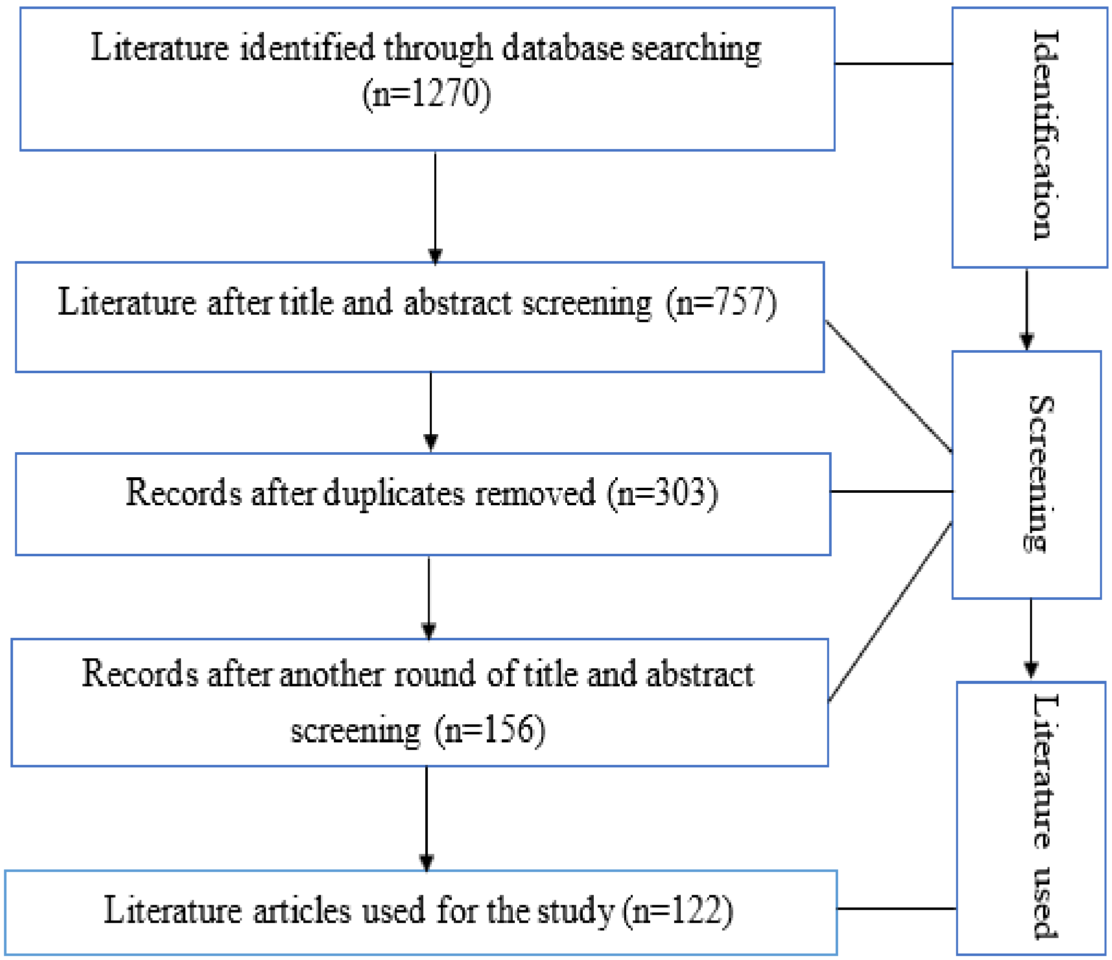

Figure 2.1. Flow chart for systematic review of article selection

2.2.3 Review synthesis on climate change and agriculture in SSA

Effective agricultural production and sustainability is critical to rural livelihoods, as well as to the economies of the majority of African countries (FAO, 2018; Omotayo et al., 2022). This sector constitutes 50% to 60% of Africa's GDP and approximately 75% to their total export value (World Bank, 2020). In addition, about 75% of the SSA population consists of rural dwellers, whose livelihood activities are based on rain-fed agricultural production (Oliveira et al., 2020). Agriculture in this region is therefore exposed to the impacts of climate change (Dadzie, 2021), with annual farm productivity having been declining over the last few decades (Diallo et al., 2020). Over the past 20 years, SSA's agriculture experienced the weakest growth in production worldwide

(Croijmans et al., 2021), while their counterparts in Asia and America saw a sharp growth in agricultural output (Howe et al., 2019; Akanbi et al., 2021). Persistent problems, such as inadequate irrigation schemes and market structures, as well as absent or ineffectual supporting institutions, poor incentives for modernization, unsuitable environmental conditions, poor soil quality and inadequate policy contexts can be blamed for the weak performance of the agricultural sector (Bagheri and Teymouri, 2022; Dietz, 2020; Omotayo et al., 2022). The armed conflicts occurring in many African countries are likely to affect agricultural production, with climate change and extreme weather events being expected to significantly exacerbate this situation (Table 2.2). The effects of climate change on agriculture could affect the livelihoods of rural dwellers, and likewise, the food security issues in the region (Charrua et al., 2020).

Since the 1980s, scientists have been making projections on the effects of climate change on agriculture in SSA. According to research (Hein et al., 2019; Oliveira et al., 2020), the mean temperature of the world has increased over the past 100 years by around 0.80º C. If nothing is done, temperatures will continue to rise to a point where it will be challenging for some areas to adapt to the new conditions (Oliveira et al., 2020). The threats posed by the negative consequences of climate change will affect those countries that rely heavily on resources that are climate-sensitive in the contexts of livelihood activities and general growth and could contribute significantly to their vulnerability status in the long-term (Abid et al., 2019).

Table 2.2. The variability of climatic impacts on agriculture in SSA

Climate variability	Impacts on Agriculture	Consequences
Frequent and prolonged droughts	• Reduced production of food crops, livestock losses, and the possibility of resultant famines (Bagheri & Teymouri, 2022) • Increased stress on crops which may in turn lead to declining yields (Khan et al., 2021; Omotayo, 2018) • Emergence of pests and diseases (Ceci et al., 2021) • Drying out of seedlings, crops and trees (Ceci et al., 2021) • Delays in the flowering of crops (Ricke et al., 2017)	• Seasonal shortages of food supply (Hasan & Kumar, 2020) • Water shortages for agriculture (Howe et al., 2019) • Loss of income (Abid et al., 2019) • Malnutrition and hunger (Brugger, 2020) • Proliferation of pests and diseases threatening crops and livestock (Ceci et al., 2021) • Lack of pastures and animal feeds (Badi, 2019) • Livestock dehydration leading to fatigue and diseases in livestock (Diallo et al., 2020)
Changes in the timing and amount of rainfall	• Increased frequency of flooding and landslides in cases of heavy rainfall, thus causing losses of farmland (Ceci et al., 2021) • Reduced water availability for crops and livestock (Koberg et al., 2019) • Heavy reliance on irrigation (Khan et al., 2021) • Poor quality crops owing to decreased volumes of water (Howe et al., 2019)	• Issues with planting dates, thus affecting harvests (Dadzie, 2021) • Reduced agricultural production and destruction of crops (Howe et al., 2019; Oderinde et al., 2022) • Occurrence of animal respiratory diseases and foot rot owing to increased rainfall (Badi, 2019) • Loss of income (Ceci et al., 2021) • Increased sedimentation in lakes and rivers resulting from heavy runoff water
Increased incidence of temperature	• Reduced agricultural yields and reduced reliability of product quantities (Koberg et al., 2019) • Increased heat stress in livestock (Abid et al., 2019) • Destruction of crops or reduction in crop productivity • Declines in certain aquacultural stock as a result of raised sea temperatures and sea level (Dadzie, 2021)	• Reduced agricultural production and destruction of crops (Badi, 2019) • Proliferation of pests/diseases in crops and livestock (Ceci et al., 2021)
Extreme weather events	• Manifestation of various diseases (Ceci et al., 2021) • Increased production costs owing to reliance on irrigation and pest/disease control measures • Death of aquatic life owing to a shortage of seawater	• Total loss of farm produce (Abid et al., 2019) • Poor agricultural market values (Dadzie, 2021) • Defoliation of food crops (Brugger, 2020) • Possible death of livestock (Howe et al., 2019) • Shortages of food supply all year round

Croijmans et al. (2021) contend that as a result of their geographic location, poor economic conditions and greater reliance on the agricultural and forestry sectors, which are based on the available renewable natural resources, many SSA countries are very susceptible to changes in climatic conditions These authors note that as a result of the complex linkages that prevail in this region between the farming, weather and climate components, as well as the intricate nature of its agrarian commerce, in conjunction with the prevailing inadequate regulations, to anticipate the negative influence of climate change on the future of agriculture is a complicated process. Numerous studies show that the increased frequency and severity of storms, as well as of flooding and droughts, have had an impact on agriculture, especially arable crop production in SSA (Goglio et al., 2020; Croijmans et al. 2021).

According to the report by IPCC (2019) as to how climate change affects agricultural productivity in SSA, food yields, especially in the poorer countries, where people are already at risk and vulnerable, are expected to diminish significantly over the next century (IPCC, 2019). The report concludes that despite technological developments, such as the implementation of improved crop types and irrigation systems, weather and climate are still important regulators in determining agricultural productivity (Batumike et al., 2022). Furthermore, the incidence of food emergencies, infrastructures for food distribution, frequency of extreme weather events and droughts, rising sea levels, and growing irregularities in rainy season patterns are already having an impact on these factors in both rural and urban areas (Dietz, 2020; Goglio et al., 2020). Thus, to address some of the long-term effects of climate change on agricultural production in sub-Saharan Africa, suitable policies measures must put in place.

2.2.4 Trends and impacts of climate variability in SSA

The unfavourable effects of climate change may include broad and unprecedented changes in the weather as well as unexpected conditions in terms of temperature, rain/precipitation yields and cloud density (Brugger et al., 2021). Seven distinct climate zones occur across Africa: mid-latitude dry, humid subtropical, tropical rainforest, mountain, wet and dry tropical, and tropical dry. Altitude and other geographical factors within the various zones are responsible for producing the variations in these regional climates (Bekele et al. 2018). Studies have demonstrated that there have been significant changes in SSA in terms of rainfall, temperature and extreme weather events, as well as in their frequency and patterns, this situation being likely to continue.

2.2.4.1 Temperature changes

The recent unprecedented global temperature increases are projected to continue, given that greenhouse gases are still present in the atmosphere, with severe restrictions on their emission only serving to reduce the rate of temperature increase (IPCC, 2020; Bedeke et al., 2018). Due to climate change, there is 0.8°C temperature increase over Africa in the past 30 years than the average global temperature increases over the previous 1000 year (IPCC, 2020; Batumike et al. 2022). Over the last century, the increase in the mean temperature over Africa, manifesting as a linear trend, amounted to approximately 0.74º C (Figure 2.2) (Brugger et al. 2021; IPCC 2021). Africa is known for its hot and dry conditions, and recent patterns indicate that it has seen warmer spells than it did 100 years ago (Batumike et al. 2022). Since the 1960s, temperatures in SSA have been increasing at a faster rate than than the rest of the world (IPCC, 2021). The 20th century saw warming at a pace of roughly 0.5ºC/annum, with the seasons of June - August and September - November being slightly warmer than those of December - May (Batumike et al. 2022).

Most SSA countries are located in the tropical latitudes (30° north to -30° south) (Batumike et al. 2022), where temperatures are high throughout the year, these countries also experiencing extreme temperature changes, particularly during the day (Figure 2.2), with increases in temperature being expected (Khanal et al., 2021). Although these trends seem to occur across the continent, the temperature changes are not consistent within and between countries and regions. For example, in 2019, the temperature rose by 0.2° to 0.3˚C in the Nile Basin's neighbouring nations of Sudan, Eritrea and Djibouti, while it rose by 0.7° to 0.9°C in Rwanda, Tanzania and Malawi (Crojimans et al. 2021).

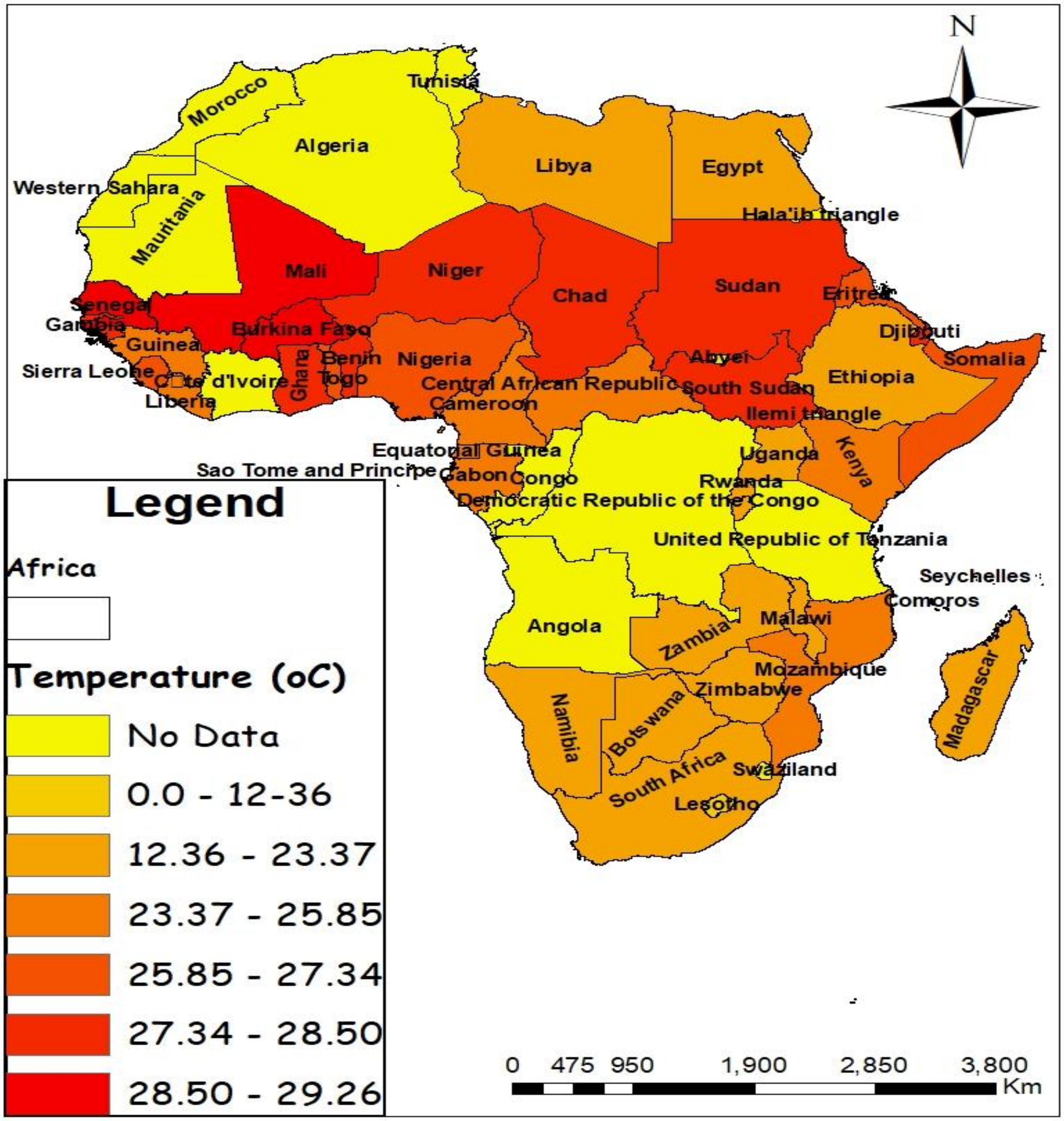

Fig. 2.2. Daily temperature variations in Africa (Author's modification from IPCC, 2022)

In Equatorial Guinea, Gabon, Congo and Angola, the average surface temperature throughout the 20th century increased by 0.2° to 0.6ºC (IPCC, 2020), the trend being anticipated to continue, with an increase of 1.4° to 5.8ºC by 2100 (IPCC, 2020). Regarding the anticipated changes, the entire SSA region is expected to become warner during the next 100 years (Behailu et al., 2021). Model-based forecasts of the continent's climate change that can be attributed to the concentration of greenhouse gases in the atmosphere overwhelmingly indicate that global warming will persist (Brussow et al., 2019). According to IPCC (2021) reports, the average temperature in western SSA will rise to around 5º C by 2100, which is roughly twice the average global temperature, with warming likely to be more severe over the semi-arid region and central SSA (Koberg et al., 2019; IPCC 2021).

2.2.4.2 Variations in rainfall patterns

Although temperature changes can have a considerable impact on the yearly variations in agricultural production, the yields tend to be influenced to a greater extent by rainfall (Behailu et al., 2021), which affects the economic and social well-being of the rural inhabitants in SSA (Lezaun, 2021). There are generally marked seasonal and annual variability in rainfall in SSA countries (Ceci et al. 2021), with climate change patterns being largely influenced by both inter- and intra-seasonal rainfall patterns, together with events such as flooding and droughts, which have direct implications for agricultural production and cause food shortages (Diallo et al. 2020).

The current trends in climate change indicate that rainfall patterns across Africa (Figure 2.3) vary considerably, and manifest on different scales in terms of both their temporal and spatial fluctuations (Behailu et al. 2021). Jamal et al. (2021) demonstrated the nature of rainfall variability in three African regions, namely: the Sahel, East and Southeast Africa. According to various findings (Hundera et al., 2019; Dadzie, 2021), the Sahel region exhibits strong multi-decadal variability, with its current climatic status classified as arid, while East Africa is characterized by a constant rainfall, with some long-term moisture indications, and Southeast Africa has a constant rainfall with inter-decadal variability (Figure 2.4).

While the current rainfall in some parts of SSA are unpredictable, the decreases are often more pronounced, with increased precipitation anomalies, extreme temperatures and natural disasters not being unexpected (Dadzie, 2021; UNDP, 2019). Hundera et al. (2019) and Dadzie (2021) assessed the socio-economic implications of climatic change in selected SSA countries (e.g. Zimbabwe, Botswana and Namibia), and reported that since the turn of the 21st century, the climatic effects have resulted in approximately US$ 6 000 million in direct economic damages and at least 1 000 annual deaths due to severe temperature increases, natural disasters and aberrant precipitation trends (World Bank, 2021). Furthermore, 13 million people have been seriously affected by these impacts (UNEP, 2021), and include those who are homeless, suffer from food insecurity, lack access to water and sanitation, and have been injured (Badi and Murtagh, 2019; Stern, 2017; UNICEF, 2020).

Several studies, particularly those of Badi (2019) and Akano et al. (2022), have shown that a long-term decrease in precipitation and severe weather events are the most important climate change impacts experienced in SSA. In particular, the average rainfall in the late 1990s fell by approximately 40% compared to the decline of approximately 25-30% across north Africa (IPCC, 2019). Rainfall in SSA has decreased over the last 25 years (Figure 2.4), with two or three severe droughts having occurred in the early 1990s (Afkhami et al., 2022).

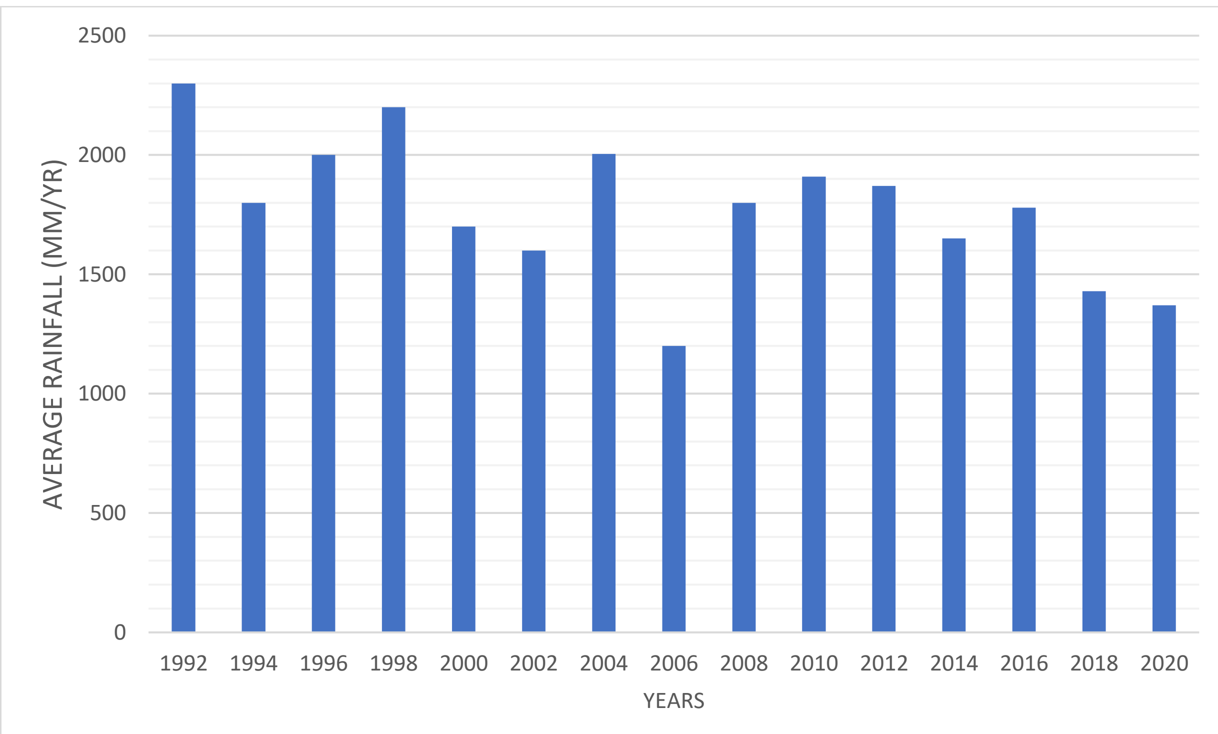

Fig. 2.3. Rainfall patterns in SSA over the past 30 years (University of East Anglia Climate Research Unit, 2020)

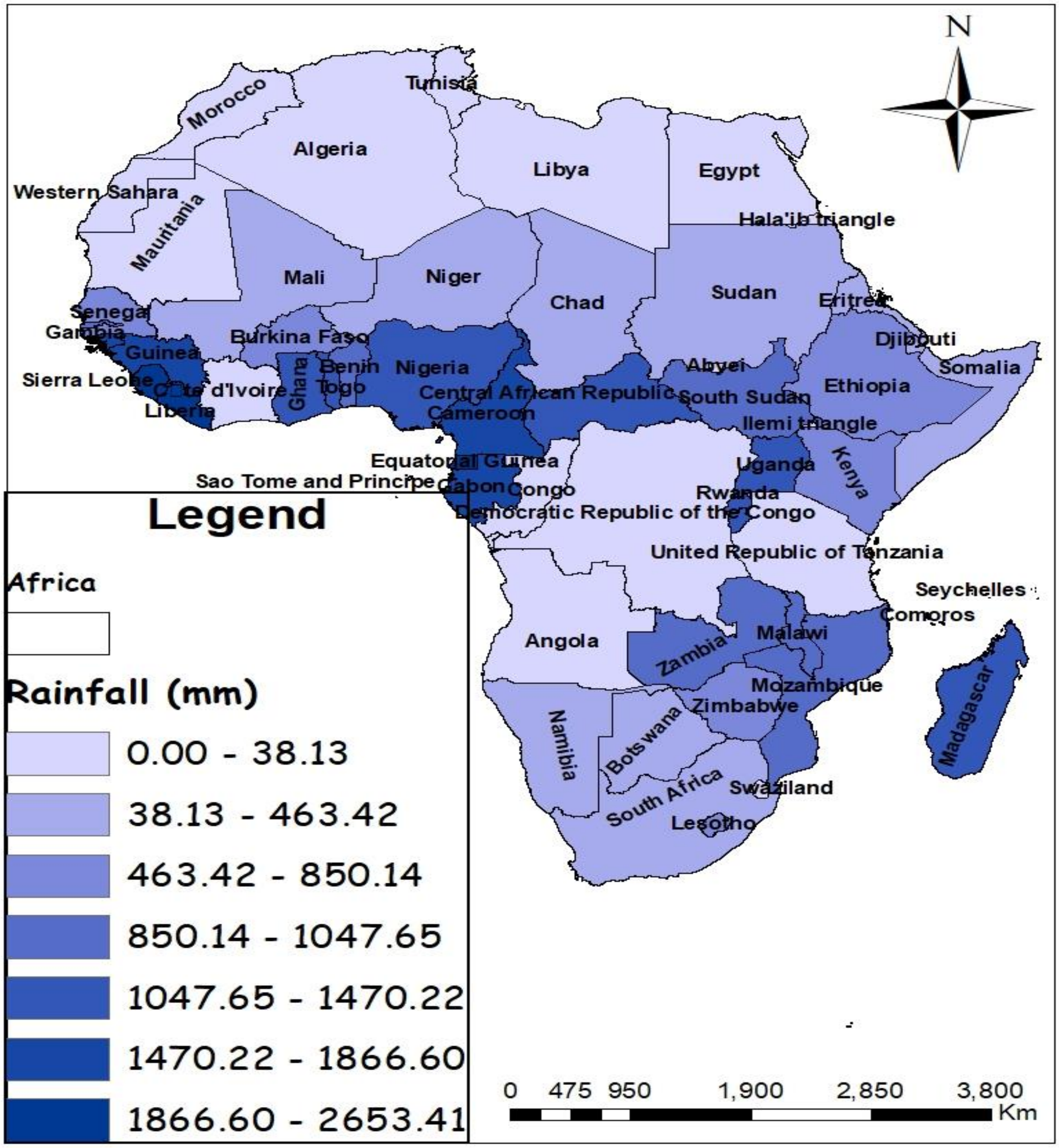

Fig. 2.4. Rainfall pattern in Africa

2.4.3 Extreme weather events

Natural disasters have always existed, such as earthquakes, volcanoes and extreme weather events, but there is clear evidence that the human-induced gradual temperature increases and changes in precipitation are causing a rise in sea level, as well as extreme droughts and desertification, fueling more frequent floods and storms, such as hurricanes and tropical cyclones (IPCC, 2020; Hounnoua et al., 2023; Teshome et al., 2021). Natural weather disasters, as increasingly seen in many parts of SSA, are characterized by either too much or too little rain (Jamal et al., 2021; Azadi et al. 2019). Heavy rainstorms, flooding and droughts are characteristic of extreme weather events, and are predicted to occur more frequently and with greater intensity as a result of rising temperatures and unstable atmospheric conditions (Milan-Garcia et al., 2021). Droughts have become common in most of SSA (Bedeke et al., 2018), these being natural events that manifest when the amount of precipitation is substantially lower than the recorded standard due to insufficient rainfall or excessive evaporation, thus causing the temperature to rise. This may lead to dryness/aridity, which adversely affects land resources and agricultural production systems (Azadi et al., 2019).

Droughts have been persisted over the last 20 years in many countries of the Sahel, southeast and southern Africa (Figure 2.5), and have drawn interest from numerous scholars (Brussow et al., 2019; UNDP, 2019; Duong et al., 2019). Generally speaking, SSA experiences most of the world's droughts, with the frequency of floods and storms increasing in this region with the onset of climate change (Figure 2.6). In the early 2000s, numerous countries in SSA suffered severe droughts as a result of insufficient rainfall, which in turn caused poor food crop yields that led to inadequate food supplies for the region's population (Brugger et al. 2021).

There has been a noticeable decline in precipitation in the driest regions of SSA, including the southern and southeast areas (Goglio et al., 2020; IPCC, 2021). Madagascar, Malawi, Ethiopia and Mozambique stand out as the most severely affected, with some areas experiencing short-lived droughts and others a significant increase in rainfall (Hasan & Kumar, 2019; WHO, 2019). Across the rest of SSA, the increased frequency of extreme rainfall episodes, which are detrimental to agricultural production, often outweigh the benefits of increased precipitation (Milan-Garcia et al., 2021). The supplies of surface water, which are essential for farming, fishing and the generation of hydroelectricity, are dwindling, especially in Central Africa (Foguesatto et al., 2020). The greatest toll on people's lives and livelihoods is being caused by the current droughts, which threaten to reverse the progress made over the past three decades in extending life expectancy and lowering infant mortality and malnutrition (Figure 2.6). The Sahel and southeast Africa are the most severely affected, with Mozambique, Ethiopia and Malawi feeling the effects most acutely. (Esayas et al., 2019; WESS, 2021).

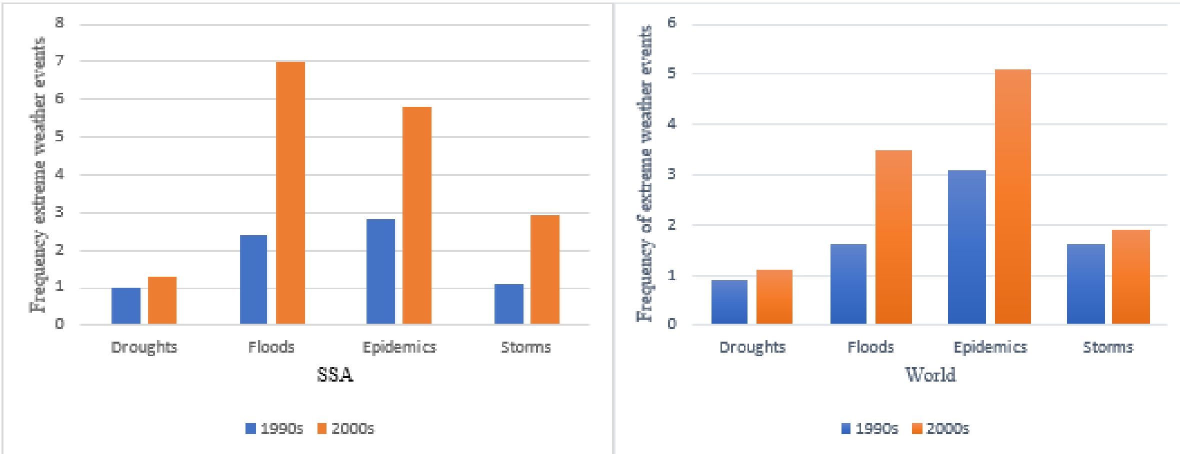

Fig. 2.5. Extreme weather events from 1990 to 2020 in SSA and the World (Source: Centre for Research on Epidemiology of Disasters, 2020)

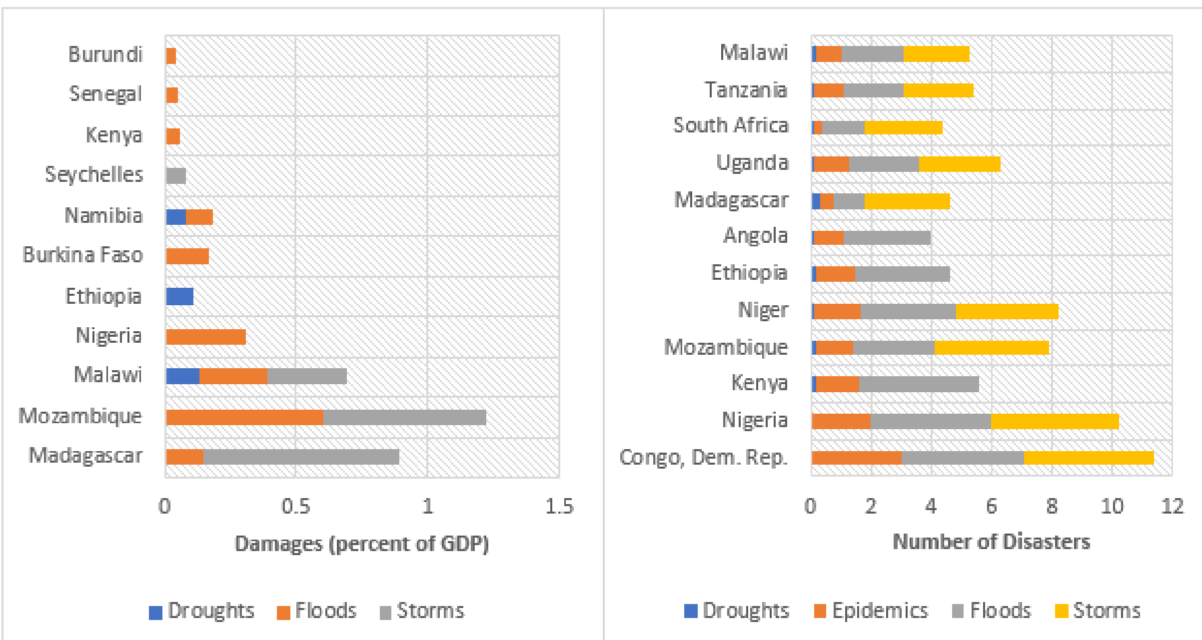

Fig. 2.6. Damage impact and number of disasters in SSA between 2000 and 2020 (Source: Centre for Research on Epidemiology of Disasters, 2020)

2.2.5 Impact of climate change on agricultural production in sub-Saharan Africa

Currently, fewer regions in SSA have the ability to feed their populations, implying a reliance on food imports of some products (Oliveira et al., 2020; World Bank, 2018). The majority of developing countries are vulnerable to the effects of climate change through their inability to achieve food security as a result of various factors, which in turn exacerbates their limited use of food production technologies and regional markets (Ayal et al., 2021; Oliveira et al., 2020). According to research (Ceci et al., 2021; Ricart et al., 2022; Badi, 2019), over the past century, the average global temperature has risen by 0.8°C, and unless something tangible is done to prevent it from rising further, it will continue to increase to degrees that will make life challenging and unbearable. Researchers have also place emphasis on the seriousness that climate change poses to societies that rely extensively on climate-sensitive assets for their livelihoods and overall development. Ceci et al. (2021) state that countries in SSA, including South Africa, are likely to struggle as a result of the low incomes, inadequate institutional frameworks, and their dependence on climate-sensitive natural renewable resource sectors such as agriculture.

2.2.5.1 Climate change and food crop production

The complex synergy between forestry, agriculture and climate change complicates the task of forecasting the overall impacts of climate change on agricultural production in SSA. The interactions between temperature, rainfall and crop production, as well as the intricacies of the SSA agricultural trade system and its associated policies, are complex (Ceci et al., 2021). Many studies (Tan et al., 2021; Tall et al., 2018; Khan et al., 2021) show that the agricultural production outputs, especially in the form of food crops in SSA, are impacted by the increased intensity and frequency of storms, droughts and flooding. According to Behailu et al. (2021), the climate change impacts on food crop farming can be divided into two categories, namely, bio-physical and socio-economic impacts, resulting to national food insecurity. Le Dang et al. (2019) projected that cereal production in SSA could rise to approximately five billion tons by the year 2100, provided there is adequate rainfall and appropriate temperatures.

Focusing on the current climatic conditions of this region, they predict that as a result of variations in the seasonal rainfall and extreme weather events, the agricultural outputs of SSA will undergo a drastic decline (Tall et al., 2018; Khan et al., 2021). For example, the decline in the rainfall in Mali has resulted in poor farm yields, thus causing high food price and a decline in household food security status (Macchi et al., 2019). Similarly, the decline in the rainfall over the continent has led to an increase in intra- and inter-state migration within SSA (Imran et al., 2020). It will therefore become increasingly important to pay more attention to the development of strategies to encourage enhanced agriculture and forestry, as well as the necessary infrastructure and institutions, to make SSA's agriculture sector function more efficiently and balance the growing disparities between the need for food and the lack of its availability (Khan et al., 2021).

With increasing pressure on the agricultural sector to meet the continent's rising population growth rate, individual countries need to embrace the impact of climate change. A similar study by IPCC (2019) on a number of SSA countries showed that grain yields, as well as those for other cash crops that serve as a means of foreign exchange, are destined over the next century to result in losses to the economies of the developing countries (e.g. Angola, Congo, Nigeria, Mali and Togo), where the people are already at risk and vulnerable. This study concluded that weather and climate continue to be important regulators/components in determining agricultural outputs, even in the face of technological advancements, such as the introduction of improved crop types and irrigation systems (Darabant et al., 2020; World Bank, 2021).

Various researchers (Barrios et al., 2019; Baek et al., 2020) have noted the possible economic impacts of unfavourable climatic events on agricultural production, especially in SSA. In Senegal (Figure 2.7), for example, poor harvests in cereal production, rubber and palm oil, as a result of a decline in the rainfall, have discouraged farmers in the affected regions from farming, thereby causing them to migrate to the country's urban areas in search of work, resulting in a population surge in the cities (Akano et al., 2022; UNEP, 2021). Similarly, in Nigeria, particularly in the rural areas, climate change has posed a great challenge to the farmers, resulting in low crop yields, the emergence of new insect pests, disease outbreaks, the drying up of rivers, raised soil salinity levels, and intensified precipitation, which has resulted in urban migration (Oderinde et al., 2022).

As a result of the impacts of climate change, trends in cereal production over the last few decades (Figure 2.7) have shown a decline in production across SSA. Further exploration of the level of impact indicated that a very high percentage of sampled respondents in western SSA claimed that as long as crop yields keep declining, and the availability of crop products keeps diminishing, there will be serious implications for the overall contribution of crops to household livelihoods. This includes the safety net function performed by the agricultural sector in the time of financial shortfalls or environmental crises being lost (Aggarwal et al., 2019).

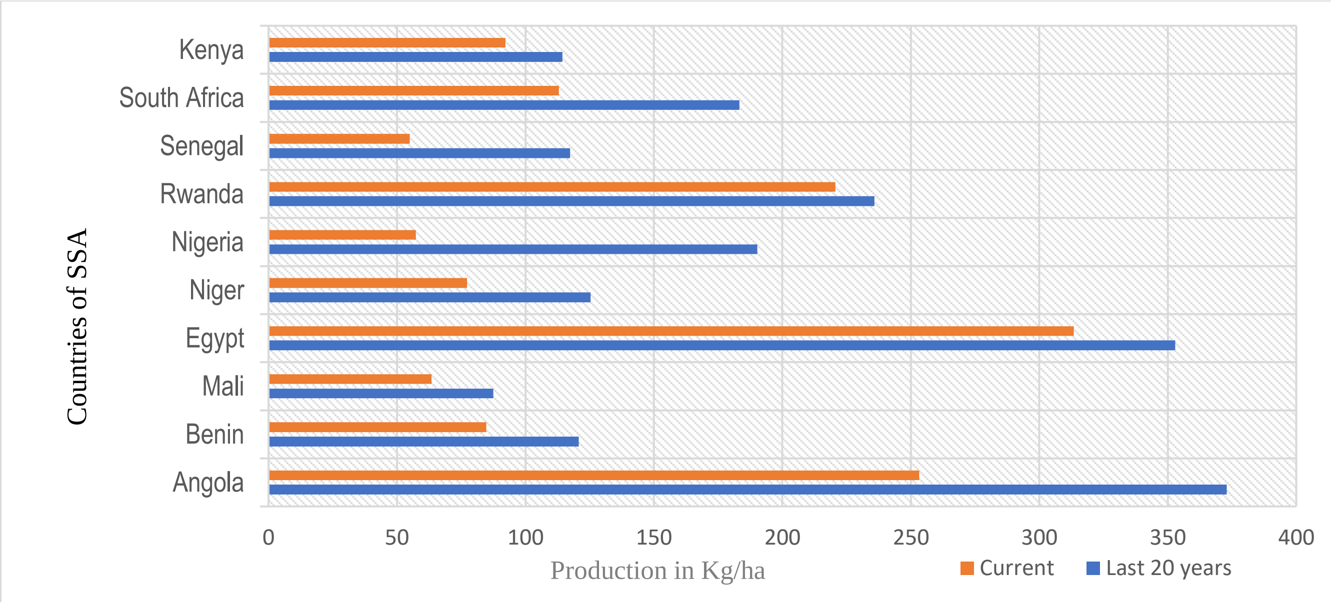

Fig. 2.7. Trends in cereal (including rice, millet, sorghum, maize and wheat) production in SSA over the last 20 years till 2022

2.2.5.2 Climate Change and Livestock Production

There are two main livestock production systems in SSA, large to medium-scale and village-to-backyard farming (Hulme et al., 2019). The production scale/level, size, management system and productivity are the distinguishing factors between the two systems of production (de Lonuelle et al., 2020). As temperatures rise in tandem with climate change, the production levels in terms of livestock farming have the potential to decrease, which leads to an increase in the probability that a farmer would choose climate-tolerant livestock species for his farming enterprise (Joshi et al., 2019). Addressing climate change in livestock production involves rearing animals that are heat and disease tolerant, robust and can be relatively adaptable to adverse conditions (Bedeke et al., 2018). From this empirical study, it is expected that if not well managed, livelihoods that are natural resource-based (e.g. farming, forestry and aquaculture) will be severely depleted as a result of the impacts of climate change (Brugger et al., 2021), the impacts being categorized into indirect and direct impacts (Alemayehu and Woldeamlak, 2017).

1. **Indirect Impacts**

Climate change in SSA affects livestock production through the availability and quality of feeds and water, and the presence of pest and disease infestations (Ceci et al., 2021). Climate change has also impacted on crop yields (e.g. pastures) (Ceci et al., 2021). Feed components, such as grasses, forage, wheat offal and rice bran, which are some of the essential components of animal husbandry, are sourced from agronomic activities (de Lonuelle et al., 2020; Omotayo, 2018). Owing to the low and irregular rainfall patterns affecting this region, harvests will be affected. In the long-run, the low feed crop harvests could serve to trigger the already high prices of feeds for poultry and for other livestock species, thereby increasing the competition between livestock and humans for food resources. This would be the expected scenario, unless a mitigating approach to the impacts of climate change and feed crop production were to be employed (Stern, 2017). Manifestations of climate change are to be observed in the reduced water levels of ponds, lakes, streams and rivers, usually as a result of the higher evaporation levels throughout SSA (Alemayehu & Woldeamlak, 2017). As a result of various climate change scenarios, variations in infestations of diseases and pests are to be expected, which will negatively affect livestock outputs in that the animals might die, or high costs incurred in providing the necessary immunizations and treatment.

2. Direct Impacts

The direct impact of climate change on livestock production involves the imposition of stress in the form of extreme climatic conditions, such as high temperatures, floods or droughts, and water scarcity (Hasan & Kumar, 2020), the most common being the raised global temperature (Kaganzi et al., 2021). Most of the losses around livestock production include reduced growth rates and diminished egg production in the poultry industry (Gbegbelegbe et al., 2018), other losses being increased morbidity and mortality of ruminants (Alemayehu & Woldeamlak, 2017; Omotayo, 2018). In spite of the mechanisms intrinsic to the strategies for coping with the extreme environmental conditions that livestock are subjected to, nutrient losses may also occur. For example, nutrients meant for the metabolic functions of the body may instead be diverted to regulate body temperature (de Longueville et al., 2020; Aria & Cuccurullo, 2017).

With the exception of those livestock farmers living in the mid-latitudes, where the temperatures are conducive to richer pastures and increased production levels, livestock farmers are generally amongst the most susceptible to the impacts of climate change, which is largely due to their limited adaptive capacity (FAO, 2018). Methods to counter the effects of climate change on livestock farming are primarily focused on maintaining the good health of the livestock and their production levels, promoting biodiversity, and maximizing the volume and quality of the feed products supplied (de Longueville et al., 2020). However, a reduction of approximately 25% in livestock production in SSA (Figure 2.9) is expected as a result of the reduced feed volumes produced and increased heat stress (FAO, 2020). In addition, livestock productivity, in terms of carcass weight, reproductive function, milk and egg production, may be negatively affected by the higher temperatures caused by climate change, and in turn lead to diseases, sickness, uterine infections and the reduced intake of feeds (Alemayehu & Woldeamlak, 2017).

The FAO (2020) has indicated that climate change in the form of higher temperatures and decreased annual rainfall will have severe implications for both crop and livestock production in SSA. Furthermore, extreme weather events, such as rising sea levels, drought and fluctuations in rainy season patterns, are already severely impacting food and livestock production as well as distribution channels, the incidence of food emergencies, livelihood assets, and human health in both rural and the urban areas (de Longueville et al., 2020; Malhi et al., 2020).

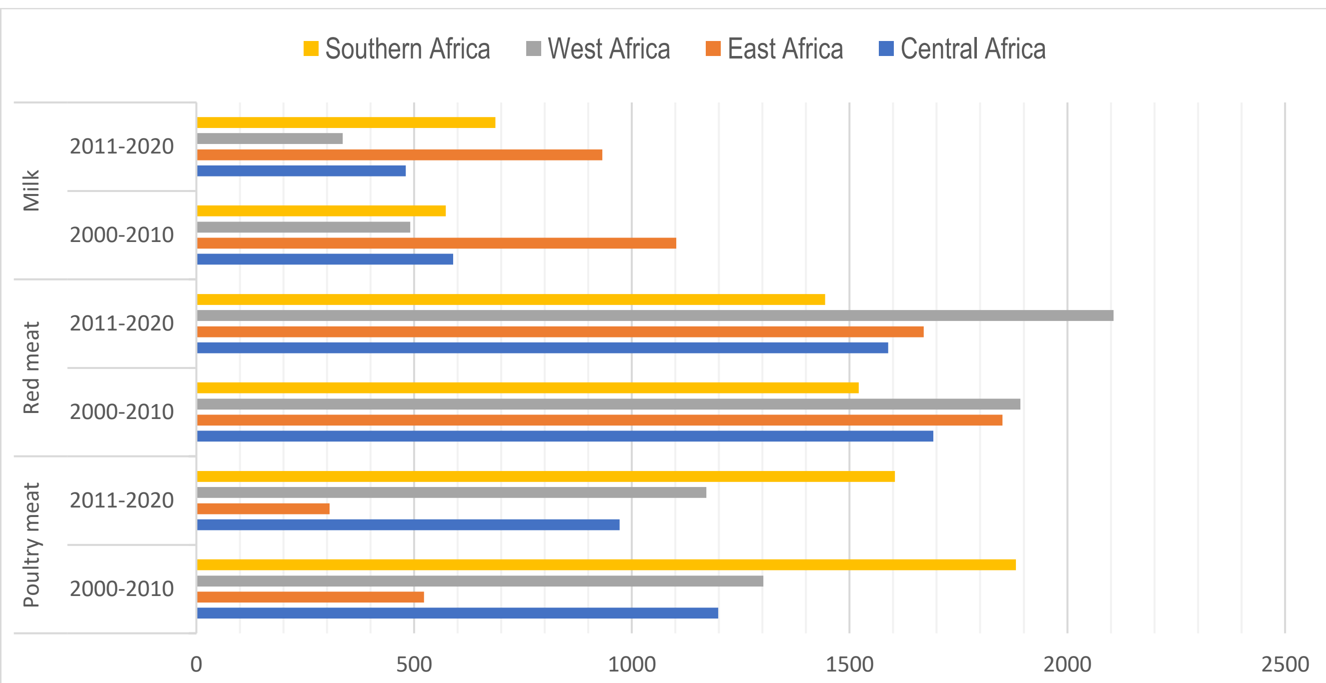

Fig. 2.9. Comparative values (in $ million) of livestock produce between 2000/2010 and 2011/2022 in SSA region (Author's modification from FAO, 2022)

The overall impacts of climate change (Figure 2.10) on agricultural production, particularly on the frequency and severity of adverse weather events, remain uncertain, with the expectation that in many developing countries they will be negative (Hein et al., 2019). There is therefore a need to ensure that appropriate policy responses are made regarding some of the anticipated longer-term impacts.

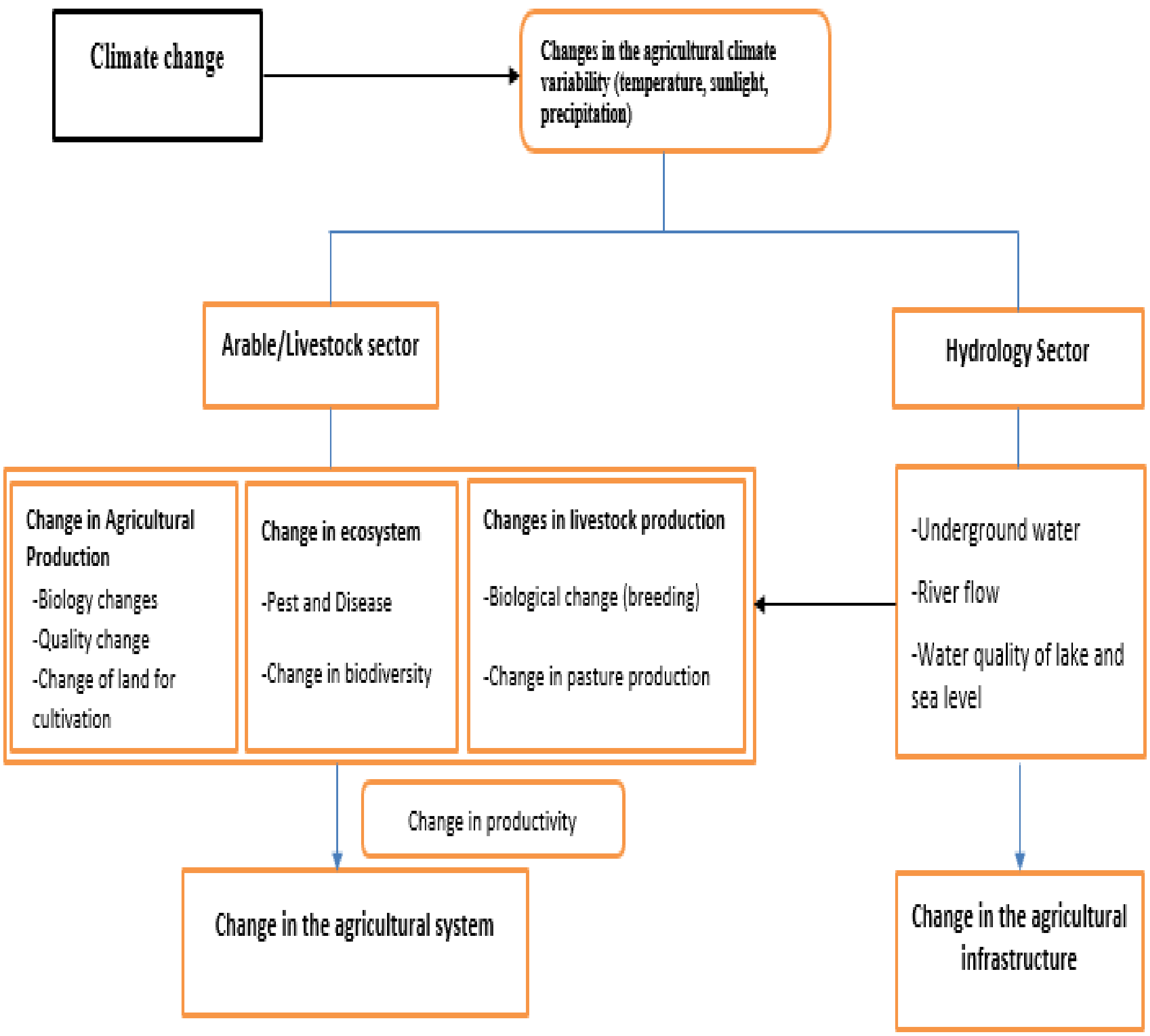

Fig. 2.10. Flow chart of impacts of climate change on the agricultural system in SSA

2.2.6 Novel approach to mitigating climate change and adaptation strategies in SSA

There is a need to find insightful solutions ways of adapting to and mitigating the impact of climate change for the well-being of future generations, especially vulnerable households. There is therefore an urgency to address the issue of adaptation to changing climatic conditions, as well as to implementing associated mitigatory strategies (Aggarwal et al., 2019). The concept and practice of adaptation to climate change poses a threat to agricultural development, with interventions being made by government to ensure that every household supports agricultural sustainability. Smith et al. (2019) noted that farmers in SSA are acclimatized to controlling for, as well as adjusting to climate change in order to achieve their agricultural goals, which would depend on the geographical region in which they practice agriculture (Table 2.3).

Adaptation measures have been indicated in numerous Scopus sources (Baudoin et al., 2018; Akanbi et al., 2021; Hein et al., 2019) to dramatically cushion the negative impacts of climate change. A review of studies by Behailu et al. (2021) focused upon those adaptations that serve to boost cereal crop yields (e.g. millet, maize, and rice) in different temperate and tropical locations in SSA by an average of 10% - 17%. Several ground studies (Van de Steeg et al., 2019; Smith et al., 2019) corroborated this trend in West Africa, and demonstrated the favourable influence of climate-smart practices, as well as technology, on agricultural outputs.

Furthermore, acquiring weather-predicting information promotes adaptation (Vitousek et al., 2017), whereas the experience of the farmers impacts more on adaptation techniques use (Smith et al., 2019). According to Tabari (2020), farming households with at least a primary school level of education seem to use adaptation techniques efficiently, and would generally be able to participate in various developmental and resource management activities and programmes. The most significant impediment to climate change adaptations is inadequate access to additional water resources, finance and extension services (Teshome et al., 2021). Some researchers (Tabari, 2020; Ricart et al., 2022; Hounnou et al., 2023) have concluded that climate-tolerant and improved planting dates result in increased yields, often offsetting the detrimental impacts of climate change on crops. However, the impacts of adaptation approaches regarding crop responses to climate change vary greatly and can sometimes be harmful (Hein et al., 2019). By adopting climate-resilient crop types and changing planting dates to mitigate the impacts of climate change, the maximum crop potential could be attained in only a few situations. The provision would be that these measures would be conducted in conjunction with the application of improved fertilizers and more effective methods of irrigation management (Sorgho et al., 2020; Etana et al., 2020).

Researchers (Batumike et al 2022; Ceci et al., 2021) contend that farmers in SSA generally implement a number of diverse adaptation strategies, which are grouped into five main categories, namely, crop management, water and soil resources, livestock and crop diversification. The favoured adaptation measure is the introduction of drought-resistant crops (65%), followed closely by changes to the planting date (52%), water-saving strategies and the collection of rainwater (45%). Furthermore, farmers are more inclined to use drought-resistant crop varieties, as well as to implement irrigation practices when they expect that the temperature will increase (Ceci et al., 2021; Malhi et al. 2020; Omotayo, 2018). When they decide to move away from cultivating soil-water-intensive plants, such as rice, maize, cotton and sunflower (Batumike et al 2022; Esayas et al., 2019), farmers are also encouraged to cultivate those crops that absorb limited amounts of water/moisture (e.g. fruit, vegetable, cash crops, pulse crops e.g. beans and peas).

Likewise, their choice to change the timing of the planting season cushions the severe impacts of extreme weather events, including seasonal floods, droughts and storm surges (Akter & Ahmed 2021). If it is not possible to change the planting dates to ensure the envisaged adaptation procedures, the farmers should then work towards crop diversification. In so doing, they will be able to enhance an integrated crop-livestock farming system that would be less risky than a specialized or monoculture system (Sorgho et al., 2020; Batumike et al 2022). To develop a "climate-smart agricultural system" that can endure climate change, a strategy shift is required, which should include the development of drought and heat-resistant crops, as well as novel tillage practices that limit the release of carbon from the soil. Furthermore, additional steps should be taken to ensure that all trade, investment and development policies prioritize a 'climate-smart' agricultural food system.

Table 2.3. Adaptation strategies to deal with climate change in agricultural production in SSA

SSA Region	**Climate phenomenon**	**Adaptation strategies in crop production**	**Adaptation strategies in livestock farming**
Southern Africa	Changing climatic conditions and seasonality	• Optimization of planting schedules such as sowing dates (Dietz, 2020) •The use of short-duration cultivars (Azadi et al. 2019) •Increased diversification of varieties or crops (Jamal et al. 2021) •Changing post-harvest practices (Mihiretu et al. 2020)	• Breeding of stock that can resist drought, heat and harsh conditions (Ceci et al., 2021) • Changing breeds and production systems (Badi, 2019) •Selective breeding/for genetic improvement (Vitousek et al. 2017)
	Change in rainfall and water availability	• Water-saving measures, such as rainwater collection and the sinking of boreholes (Dietz, 2020) • The use of marginal and wastewater resources (Akanbi et al. 2021) • The planting of cover crops (Bhandari et al. 2021)	• Water conservation management (e.g. the sinking of boreholes; the harvesting of rainwater) (Imran et al. 2020) • The rearing of heat-resistant animals (Badi, 2019) • Improved breeding strategies (Dietz, 2020)
	Increased frequency of droughts, floods, wildfire events, rise in sea level	• The use of flood, drought and/or saline-resistant varieties (Badi, 2019) • Improved drainage, farm design and soil organic matter content (Joshi et al. 2019) • Insurance cover against extreme events (Azadi et al. 2019)	• Cooling systems and the provision of shade (Brugger et al. 2021; Sorgho et al., 2020) • General water conservation measures (Dietz, 2020) • Insurance cover against extreme events (Ceci et al. 2021)
	Pests and diseases; disruption of ecosystem services	• Participation in risk monitoring and prevention schemes (Dietz, 2020) • The use of pesticides and herbicides (Ricke et al. 2017)	• Changing the breeding and rearing calendars • Agroforestry (Ceci et al., 2021) • Efficient animal husbandry practices

		• The natural regulation and strengthening of ecosystem services (Badi, 2019)	(Hundera et al. 2019)
Western Africa	Changing climatic conditions and seasonality	• The planting of several crop types or cultivars (Akano et al. 2022) • Mixed farming and inter-cropping (Mihiretu et al. 2020) • The planting of indigenous crop varieties (Jamal et al. 2021)	• Animal diversification (Ceci et al., 2021) •Selective breeding/and genetic improvements (Badi, 2019) • The use of covers to reduce radiation loss at night (Ceci et al., 2021; Talanow et al., 2021)
	Change in rainfall and water availability	•Intercropping/mixed cropping (Bento, 2020; Cervigni et al., 20219a) • Reduced tillage to reduce water loss (Ricke et al. 2017) • The use of plant nurseries (Ricke et al. 2017)	•The proclamation of laws to reduce/ban/control open grazing (Akano et al. 2022) •Irrigation/the sinking of boreholes, dam/ditch construction for collecting water (Imran et al. 2020)
	Increased frequency of droughts, floods, wildfire events, rise in sea level	• The planting of cover crops (Jamal et al. 2021) • Afforestation (Akano et al. 2022) • Taungya farming (Akanbi et al. 2021)	•Reforestation/afforestation (Ceci et al., 2021) • Reliance on weather information (Brugger et al. 2021) • Setting up windbreaks/shelter belts (Akano et al. 2022)
	Pests and diseases; disruption of ecosystem services	• The planting of resistant varieties (Thomas et al., 2021) • The development of natural regulation methods and the strengthening of ecosystem services (Hasan and Kumar, 2019) • Ecological pest management (Hundera et al. 2019)	• The application of disease control measures and animal health management practices (Mihiretu et al. 2020; Budhathoki et al., 2020)
Central Africa	Changing climatic conditions	•The use of integrated systems involving livestock and/or aquaculture to improve resilience	• The sensitization of the public as to ways in which to reduce GHG emissions in

	and seasonality	(Mihiretu et al. 2020) •The control of bush burning through the implementation and enforcement of prohibition measures (Vogel and O'Brien, 2018)	farming activities (Zezza & Tasciotti, 2016; IFAD, 2020) •Financial aid/the subsidization of agricultural inputs (Bento, 2020)
	Change in rainfall and water availability	• Minimal tillage operations (Ricke et al. 2017) •The planting of drought and heat-resistant varieties (Azadi et al. 2019) • Changing planting depth (Azadi et al. 2019)	• Grazing management (Akano et al. 2022) • Reduction in flock size (Badi, 2019) • The digging of wells or boreholes to supply water (Haile, 2020)
	Increased frequency of droughts, floods, wildfire events, rise in sea level	• The planting of cover crops (Tarfa et al. 2019) •Avoidance of deforestation/ tree felling (Ouhamdouch et al., 2019) • The retention of crop residues in the field (Ibe et al. 2018; Haile, 2020)	• The setting up of windbreaks/shelter belts (Tan et al., 2021) • The construction of elevated homesteads and farmsteads • The infrastructure renforcement of pens/paddocks (Ceci et al., 2021 ; Jagermeyr, 2020)
	Pests and diseases; disruption of ecosystem services	• Regular weeding to prevent some insect pests from breeding (Ibe, 2017; Eriksen et al., 2018) • The proper conservation of seeds (Habtemariam et al. 2016) • The planting of disease and heat-resistant crops	• Farm insurance (Salmeron and Manzano, 2017) • Adequate ventilation and sanitation (Dietz, 2020) • Selective breeding (Dietz, 2020)
Eastern Africa	Changing climatic conditions and seasonality	• Changing plant and harvesting dates (Denton et al. 2020) • Increased applications of fertilizers (Ricke et al. 2017) • Establishment of food grain reserves (Ibe, 2017)	• Cross breeding with exotic animals (Vitousek et al. 2017) • Introduction of anti-stress medications (Vitousek et al. 2017; Kabote et al., 2017)
	Changes in water availability and rainfall	• The planting of cover cropping (Deoll et al., 2020) • Mulching (Hundera et al. 2019) • Mixed cropping practices (Dakurah, 2021)	• The rearing of heat-resistant animals (IFPRI, 2019) • Water harvesting (Akano et al. 2022)

	Increased frequency of droughts, floods, wildfire events, rise in sea level	• The use of water channels as drainage systems (Dietz, 2020) •The construction of drainage channels on wetlands, as well as sand filling and the construction of culverts (Demiroglu & Hall, 2020)	• Migration from climate-risk areas (Dietz, 2020) • Farm insurance (Hasan & Kumar, 2020) • The building of embankments to control flood water drainage (Azad et al., 2019)
	Pests and diseases; disruption of ecosystem services	• Crop rotation, bush fallowing and shifting cultivation (Dietz, 2020; Haile, 2020) • The use of short-duration cultivars (Azadi et al. 2019) • Cultural methods for pest control (Ricke et al. 2017).	• Quarantine and veterinary services (Limuwa et al., 2018) • The introduction of disease-resistant breeds (Ricke et al. 2017) • The use of vaccines and antibiotics (Limuwa et al., 2018).

2.2.7 Conclusion and recommendation

This review examined the existing knowledge on climate change and its impacts on agricultural production in SSA, with the magnitude of the changes experienced and their implications for agriculture being highly uncertain. Despite all of the uncertainties around climate change and the forecasts of its impacts, the countries of the SSA region that are suffering the effects of climate change have found themselves in an extremely vulnerable position due to the ineffectual adaptations that have already been attempted and the inadequate mitigation programmes in place. Furthermore, while projections regarding the degree, magnitude and sectorial, as well as the regional pattern of climate change are unpredictable, its impact on vulnerable households would prove to be extreme if adequate measures are not implemented timeously. Numerous adaptation practices employed by farmers in SSA are evidence to this effect, but have been inadequate and unsuccessful in mitigating the severe effects of climate change on their productivity levels. Thus, incentives such as institutional strengthening, improvements to the rural infrastructure, and public welfare programmes (e.g. improved access to finance, markets, educational programmes, and climatic information) need to be established and incorporated into the ongoing development programmes in such a manner that they will contribute to diminishing the vulnerability of the rural farmers. To ensure that adequate measures are in place to reduce the impacts of climate change, there is a call for more indigenous forest to be established and to maintain the existing ones to assist with acting as shock absorbers to mitigate the adverse impacts of climate change.

Manuscript 2

The interplay between agriculture, greenhouse gases, and climate change in Sub-Saharan Africa

Abstract

Agriculture is the leading sector that is responsible for global climate change through its significant contribution to greenhouse gas (GHG) emissions. Intriguingly, sub-Saharan Africa (SSA) is experiencing higher temperatures and lesser rainfall due to climate change enhanced by anthropogenic GHG emissions. Agriculture and energy-use in the SSA predominantly influence the anthropogenic GHG leading to global warming. Therefore, reducing agricultural GHG emissions (such as carbon dioxide, nitrous oxide, and methane) plays a significant role in climate change adaptation. This paper reviews the potential implication of agriculture and energy-use on climate change and its implications on environmental sustainability in SSA. Herewith, we explored various GHGs emitted through agriculture-energy-use, their effects on climate change, as well as several climate change adaptation mechanisms, and gaps in existing knowledge that necessitate more research, were also explored. We found that agriculture had negative implications on climate change impacts in the SSA countries and that a more focused strategy that is both economically and technically feasible in terms of preferences for land-use, effective energy-use and food supply would aid in GHG emission reduction and environmental sustainability. Adapting to the projected changes in the short term while investing in long-term mitigation strategies might be the only way toward a sustainable environment in this region.

Keywords: Energy-use; Climate-smart practices; Global warming; Land-use; Sustainability; Urban Agriculture

2.3.1 Introduction

Human-induced climate change is a significant environmental issue that affects people all around the world with its implications cutting across a variety of different industries, ranging from the energy sector to the health industry and the agricultural industry (Scott et al., 2023; Tongwane and Moeletsi, 2018). The world's climate is getting warmer and various studies (Chabbi et al., 2017; Outhwaite et al., 2022) confirmed that it is due to various human activities emitting planet-warming gases, called Greenhouse Gases (GHGs). GHGs such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are emitted by a variety of human activities, including deforestation, disrupting the natural use of land, industrial operations, unsustainable agriculture (such as excessive application of pesticide and fertilizer), and the use of fossil fuels such as coal, oil, and petroleum products (Borrelli et al., 2020; Scott et al., 2023).

Regrettably, a continuous increase in GHG concentration across the globe creates the greenhouse effect, which leads to global warming and climate change (Gopalakrishnan et al., 2019; Tongwane and Moeletsi, 2018). Globally, there is a 75% increment in GHG emissions in the last 30 years (Chabbi et al., 2017; Outhwaite et al., 2022). Assessing the present total source of GHGs, carbon dioxide (CO_2) contributes about 76%; methane (CH_4) is around 16%, while nitrous oxide (N_2O) is around 6% (Crippa et al., 2021). The synergy between GHG emissions and human activities (like agriculture, fossil fuel burning, and energy-use) is crucial and well-known to people (Lungarska and Chakir, 2018; Rao et al., 2016). According to various literature (Omotoso et al., 2023; Outhwaite et al., 2022), the effects of GHG emissions on ecological and socioeconomic vulnerabilities are severe and will continue to increase regionally and globally in the coming years if human-induced activities such as agriculture and its energy-use are not well managed.

In Africa, GHG emissions as a result of various human activities, have grown with about 84% increment between 1970 and 2020 (Mullins et al., 2018; Robinson, 2020). It is due to an increase in the global radiative force of CO_2, CH_4, and N_2O rising more rapidly presently than at any other period in the last 1000 years (Adusah-Poku, 2016; Boateng et al., 2019). In SSA, climate change and agriculture are two entities that cannot be separated, which can result in negative impacts on each other if not well managed (Robinson, 2020). According to (Leitner et al., 2020; Robinson, 2020), temperature changes in the SSA as a result of high continuously changing anthropogenic GHG emissions, have led to increased scrutiny of the role all sectors can play in climate change adaptation, with a particular focus on agriculture. Management of agricultural land in SSA coupled with forestry and land-use changes has a significant influence on GHG concentration in the atmosphere (Praveen and Sharma, 2019). The primary contributors to GHG emissions within the agricultural sector are agricultural energy consumption, including activities such as food processing and the utilization of farm inputs, as well as land use for agricultural purposes (Chalise and Naranpanawa, 2016). Apart from the CO_2 emitted during crop burning and animal waste, livestock production and rice fields contribute significantly to methane emissions (Outhwaite et al., 2022). Understanding GHG emissions from agricultural sources like enteric fermentation from livestock, and CO_2 emitted during energy-use in farming operation is critical for developing appropriate mitigation and adaptation strategies such as sustainable farming and minimal GHGs emission from energy-use in agriculture.

Intriguingly, the impact of agriculture and energy-use on climate change can vary significantly depending on geographic locations, climatic conditions, agricultural practices, and energy sources adopted in farming system (Ngarava et al., 2023). Conducting context-specific studies can provide valuable insights into the unique challenges and opportunities for mitigating climate change in SSA through GHGs emission reduction. While general adaptation strategies are obvious (Abernethy and Jackson, 2022; Petersen et al., 2023), but there is still literature gap in the evaluation of the effectiveness of adaptation practices in SSA's agriculture and energy-use sector. Furthermore, there is need for research that focus on assessing the impact, scalability, and sustainability of various adaptation measures and technologies in agriculture and energy-use in SSA. This evaluation can provide insights into the success factors, challenges, and opportunities for enhancing adaptive capacity in the region.

In this paper, different agriculture and energy-use influence on climate change were outlined, how their reporting could be improved was considered, as well as exploring the overall potential implications on climate change adaptation practices. The existing knowledge of the impact of agriculture and energy-use on climate change is numerous in data-rich regions, such as Europe and America but inconsistence in SSA (Graham et al., 2022; Lungarska and Chakir, 2018). In SSA, some research (Chalise and Naranpanawa, 2016; Rao et al., 2016), has been done to understand the synergy, but the findings are incoherent and disparate. This article reviews the findings of peer-reviewed studies undertaken over the last decade on the impact of agriculture and energy-use on climate change and variability in the SSA. Therefore, the paper provides an overview of the observed climate change and variability trends, as well as highlights the contribution of agricultural production and energy-use to climate changes in SSA. Additionally, it identifies the adaptation strategies implemented to control GHGs emissions by farmers, outlines various policies as well as the role of institutions to support adaptations in ensuring a sustainable environment. Finally, the paper provides an overview of the state of the knowledge on the impact of GHG emissions from various land-use and energy-use in agriculture on climate change in SSA, highlighted the structures and trends of various GHG emissions as well as knowledge gaps, and identified priority areas for future research.

2.3.2 Materials and Methods

2.3.2.1 Literature Search

The related literature on the impact of agriculture and energy-use on climate change in SSA was searched from the three accessible scholarly electronic databases (Web of Science (WoS), Scopus and google Scholar). These databases were used because it has an advanced search function, multidisciplinary, and scholarly-quality control. Some pre-defined keywords were used to search these databases (see Table 2.4). The identification of keywords (such as climate change, GHG, carbon, methane, nitrogen and urban agriculture) were first initiated for proper literature screening. To ensure that the literature used are recent and wide enough to draw reasonable conclusions, data timeline from 2000 to 2023 were used. Following (Omotoso et al., 2023) setting a specific time frame for data search helps maintain methodological consistency throughout the literature review. By focusing on studies published within years 2000 to 2023, this research was able to apply consistent criteria for inclusion and exclusion in order to reduce potential bias in the review process.

The full texts of the 346 articles were reviewed, from which 284 articles were discarded; this includes review articles solely concerned with contemporary agricultural practices, or those where its impact on climate change was not the subject of the study. Furthermore, studies on climate change and agriculture energy-use not modeling SSA as a case study were excluded. Finally, the literature-screening process reduced the results to 80 articles, representing approximately 22% of the identified literature from the database.

Table 2.4. Search string used for the SLR

Database	Keywords used for searching
Scopus	((“agriculture*” impact*” OR “GHG*” OR “land-use*” OR “energy-use*”) AND (“strategy*” OR “measure*” OR “mitigate*”) AND (“crop*” OR “agriculture*” OR “livestock*” OR “farm*” climate*”) AND (“urban agriculture*” OR “sub-Sahara*”))
Web of Science	((“agriculture*” impact*” OR “GHG*” OR “land-use*” OR “energy-use*”) AND (“strategy*” OR “measure*” OR “mitigate*”) AND (“crop*” OR “agriculture*” OR “livestock*” OR “farm*” climate*”) AND (“urban agriculture*” OR “sub-Sahara*”))
Google Scholar	((“agriculture*” impact*” OR “GHG*” OR “land-use*” OR “energy-use*”) AND (“strategy*” OR “measure*” OR “mitigate*”) AND (“crop*” OR “agriculture*” OR “livestock*” OR “farm*” climate*”) AND (“urban agriculture*” OR “sub-Sahara*”))

2.3.2.2 Systematic Literature Review (SLR)

Systematic literature review is the way of identifying, analyzing as well as interpreting scholarly studies relevant to a research interest (Omotoso et al., 2023). This technique was adopted because of its systematic, transparent, and reproducible processes of selecting databases for the review. This study was guided by the methods outlined in the study of (Omotoso et al., 2023; Pradhan et al., 2023; Praveen and Sharma, 2019). Literature was gathered from three major scientific databases [Google scholar, Scopus and Web of Science (WoS)]. Relevant keywords and search phrases (Table 2.4) was used to screen out the search output. Initial information from the search of the scientific databases yielded a total of 3891 studies. Articles not published in English or published prior year 2000, were screened out. The data from the different scientific databases provided a total of 1427 studies [Scopus (517), Google scholar (95) and WoS (815)]. It was discovered that searches of the bibliographic databases did not always generate material that was relevant. To focus on the most essential articles, we concentrate on agriculture and energy use, to apply duplicate removal, and to abstractly filter the evaluations. As such, 346 items were maintained.

The entire texts of the 346 studies were extensively scrutinized; and 170 studies were rejected, including those review articles (systematic or literary) not focusing on present agriculture and energy-use impact on climate change. Furthermore, the texts of those papers not modeling SSA as case studies on climate change, variability, and agriculture were omitted. Finally, the findings of the literature screening procedure were limited to 77 articles, which constituted roughly 6% of the literature identified from the database.

2.3.3 Agriculture and Greenhouse Gas emissions

The 6th assessment report of Intergovernmental Panel on Climate Change stated emphatically that a drastic approach to limit change in climate impact to 1.5 degrees Celsius is needed (Kanitkar et al., 2022; Robinson, 2020). This approach requires limiting the cumulative carbon budget in the atmosphere to 570 Giga tonnes of carbon dioxide ($GtCO_2$ eq/yr) by significantly reducing the emissions of other gases like nitrous oxide and methane (Leitner et al., 2020; Robinson, 2020). Intriguingly, agriculture is one of the major contributors of methane (CH_4) and nitrous oxide (N_2O) (non-CO_2 GHGs), which have a greater global warming potential (Robinson, 2020). In the last 20 years, about two-thirds of SSA's GHG emissions are majorly from agriculture, forestry, and land-use change (Ogunbode et al., 2020).

Likewise, the food system of SSA (crop production and livestock farming) is responsible for about 40–60% of annual emissions of GHG. Also, (Ogunbode et al., 2020; Robinson, 2020), reported that in 2014, agriculture in SSA comprised 15% of primary energy consumption, while in 2018, methane emissions from livestock production, carbon dioxide emissions from soil carbon loss and fossil fuel use, and nitrous oxide emissions from nitrogenous fertilizer application on farmland accounted for 60% of total GHG emissions (Chabbi et al., 2017; Chalise and Naranpanawa, 2016). If not actively addressed, these emissions will probably rise by 60% as the population rises due to being highly dependent on agricultural production in terms of food needs (Henry, 2020; Thornton et al., 2018).

Furthermore, limiting climate change impacts in SSA to 1.5 degrees Celsius requires major changes to agriculture in this region, from how we plant, to land and energy-use as well as forests management (Davis-Reddy, 2018). Implementing these changes could be a serious challenge for agriculture than for other sectors (Masson-Delmotte et al., 2021). However, understanding these variations is critical not just for understanding what various gases emission might do in the context of mitigating climate change via agriculture, but also for informing policy decision-makers in SSA.

2.3.3.1 Agricultural Land-use Change and Degradation in the Context of Climate Change

Land-use change significantly contributes to climate change in SSA (Borrelli et al., 2020; Popp et al., 2017). Large-scale changes in land-use like deforestation and soil erosion or machine-intensive farming methods contributed to increased contents of carbon concentrations in the atmosphere (Ngarava et al., 2023). Likewise, soil erosion through water, wind, and excessive tillage practice affects both agriculture as well as the natural environment (Robinson, 2020). Soil loss, and its associated impacts, are one of the most important but least well-known environmental problems (Ebhota and Tabakov, 2021). Generally, land degradation occurs from various land use, including forestry and agriculture, accounting for about 23% of all human GHG emissions (Robinson, 2020). GHGs have been part of humanity since agriculture was widely adopted and the associated population increase (Ngarava et al., 2023). There are indications that levels of GHGs in the atmosphere, particularly carbon dioxide (CO_2) and methane (CH_4), have already begun to rise over decades as a result of expanding agriculture, forest clearing, and animal domestication (Maindi et al., 2020). Land degradation is a serious driver of climate change through the emission of GHGs and the reduced rates of carbon uptake in soil (Tione et al., 2022).

Since the 1990s, the forest area in SSA has decreased by approximately 4% as a result of various agricultural land-use changes, resulting in net decreases in the tropics and net increases outside the tropics (Powlson et al., 2016). Furthermore, lower carbon density in re-growing forests compared to carbon stocks before deforestation results in net land-use change emissions (Ntinyari and Gweyi-Onyango, 2021). Forest management that reduces forestland carbon stocks causes emissions, but overall estimates of these emissions are uncertain (Ntinyari and Gweyi-Onyango, 2021). Out of all the land degradation processes in SSA, deforestation as a result of indiscriminate felling of trees, increasing wildfires, degradation of organic soil, as well as biomass fire contributed majorly to climate change through the release of GHGs and the reduction in soil carbon sinks (Tione et al., 2022).

The processes of land degradation have substantial impact on CO_2 exchange with the atmosphere because of their direct influence on soil and terrestrial biota (Ackerl et al., 2023). The most common kind of land degradation, erosion, results in the loss of topsoil, which typically contains the highest concentrations of organic carbon, and hence increases mineralization and CO_2 release to the atmosphere (Chabbi et al., 2017; Outhwaite et al., 2022). Complementary processes like carbon burial may compensate for this impact, turning soil erosion into a long-term carbon sink (Adusah-Poku, 2016). Conversion of primary land to unmanaged forests, illicit logging, and unsustainable forest management all resulted in GHG emissions and would have further effects on regional climate, including albedo changes (Kim et al., 2021). These interactions call for serious integrative climate impact assessments.

2.3.3.2 Agricultural Energy-use in the Context of Climate Change

In SSA, agricultural energy-use is an intriguer aspect of modern farming practices which contributes significantly to climate change (Ebhota and Tabakov, 2021). It encompasses the energy consumed for various agricultural activities, including land preparation, irrigation, planting, fertilization, pest control, harvesting, processing, transportation, and distribution of agricultural products (Maino and Emrullahu, 2022; Mirzabaev et al., 2023). Agricultural energy-use is primarily dependent on fossil fuels, such as diesel for tractors and machinery as well as natural gas for irrigation, food processing and other agricultural activities (Ngarava et al., 2023). Notably, the combustion of these fossil fuels release GHGs, particularly carbon dioxide (CO_2) and methane (CH_4), into the atmosphere which contribute to greenhouse effect which impacts climate change (Robinson, 2020). The exact proportion varies depending on regional agricultural practices and the level of mechanization (Kim et al., 2021).

In many regions of SSA, especially semi-arid regions, agricultural practices rely heavily on irrigation to for crops propagation (Cockx et al., 2019). For instance, approximately 75% of food crop farmers in Southern Africa (countries like South Africa, Botswana, Malawi, Lesotho, Namibia and Zimbabwe), relies heavily on irrigation as alternate source of water for their farms due to unpredictable rainfall and rising temperature (Davis-Reddy, 2018). Therefore, the pumping and distributing water for irrigation can be energy-intensive, especially when using groundwater sources (Ackerl et al., 2023). The energy required for irrigation can lead to additional GHG emissions if it comes from fossil fuel-based sources (Ebhota and Tabakov, 2021).

Likewise, the transportation of agricultural products and the processing of crops and livestock in Western African countries (such as Ghana, Senegal, Nigeria and Togo) into various food products also consume energy, much of which comes from fossil fuels (Leitner et al., 2020). This adds to the carbon footprint associated with the agriculture energy-use in SSA (Ogunbode et al., 2020). According to (Outhwaite et al., 2022; Robinson, 2020), understanding the impact of agricultural energy-use on climate change is crucial for achieving sustainable agricultural practices and mitigating global warming. Addressing these consequences requires transitioning to more sustainable and climate-friendly farming practices. Encouraging the adoption of renewable energy sources, promoting efficient use of resources, implementing agroecological practices, and enhancing carbon sequestration in soils are some of the strategies that can help mitigate the negative impacts of agriculture energy-use on climate change.

2.3.3.3 Food Crop Production and Climate Change

The overall compositions of GHGs emitted through the food crop production in SSA doesn't reflect the overall emissions balance, notwithstanding, it contributed actively to generating around half of all methane emissions and about three-quarters of nitrous oxide emissions (Robinson, 2020). In SSA, large emissions of methane and nitrous oxide occurred directly via crop cultivation, through urea and lime applications to farms as well as residue burning which also constitutes in CO_2 emissions but in small portions (Leitner et al., 2020). Nitrous oxide emissions mainly occur during the application of nitrogen-rich fertilizers to farmland (Sánchez-Rodríguez et al., 2018). It could also originate from manure application or the burning of fossil fuels in engines (Liu et al., 2019).

Likewise, carbon dioxide emission occurs through the burning of fossil fuels used in powering agriculture machinery for tillage (Liu et al., 2019). However, direct emissions via agriculture are comparatively enough to influence climate change coupled with other human-induced emissions (Ackerl et al., 2023). Energy-use CO_2 either from agricultural operation practices (tractor fuels) or embedded agricultural inputs (fertilizer manufacture), could be included as a food system emission source, but are highly uncertain (Gopalakrishnan et al., 2019). The routes in emission reductions from all these sources are likely to be the overall decarbonization of energy generation sources, rather than specific agricultural mitigations (Boateng et al., 2019). In addition, research (Legg, 2021; Omotayo et al., 2022), reported that the food system of western and southern Africa, is one of the major causes of GHG emissions through ongoing land-use change, primarily from clearing land for crop cultivation and pasture. Specifically, about 15% of annual emissions are attributed to net land-use related GHG emissions in five African countries: Niger, Uganda, Malawi, Cape Verde, and

Zambia. Of this total, 10% can be traced back to crop cultivation, while the remaining 5% comes from pasture, crop residue burning, and deforestation (Chabbi et al., 2017; Outhwaite et al., 2022).

The reports of (Praveen and Sharma, 2019; Tongwane and Moeletsi, 2018), on GHG emission in some selected nations of SSA showed that other GHGs apart from CO_2 emitted from food crop production have increased from the observed trend of 5.82 Gt.CO_2eq/yr in 2018 to projected emission of around 6.95 Gt.CO_2eq/yr by the year 2030. Given the central importance of food in our lives, crop production activities have increased and will continue to increase the concentration of anthropogenic GHGs emissions in SSA (Ackerl et al., 2023). In addition to its contribution to various anthropogenic GHG emissions in SSA, agriculture is also responsible for varying negative impacts on the environment (Borrelli et al., 2020). Nitrogen-rich Fertilizers could pollute the water body as well as threaten the aquatic ecosystems through surface runoff. Likewise, pesticides, herbicides, and excessive tillage would lead to a loss of biodiversity (Outhwaite et al., 2022).

As the population increases, agricultural production must expand and be more efficient and sustainable to meet the population surge (Chabbi et al., 2017; Outhwaite et al., 2022). Increasing land area for crop cultivation offers one option for increasing production but has its setback (Ackerl et al., 2023). Land preparation for farming purposes could destroy natural ecosystems, which would have a devastating impact on wildlife and biodiversity (Kim et al., 2021). Notwithstanding, constant exploitation of soils due to crop farming could lead to erosion as well as compaction, thereby leaving the land useless for future generations and in long run influencing climate change in the location (Borrelli et al., 2020).

2.3.3.4 Livestock Production and Climate Change

Livestock production contributes both directly and indirectly to climate change through the emissions of GHGs such as carbon dioxide, methane, and nitrous oxide. In SSA, this sector contributes around 18% (7.1 billion tonnes CO_2 equivalent) of GHG emissions (Graham et al., 2022). It also generated more than 3 billion tonnes of CO_2eq/yr while post-farm transport and processing account for only a few fractions of the GHG emissions, linked to livestock production (Ackerl et al., 2023). GHG emissions through livestock production are generated from either the digestive system of livestock through the production of a by-product called enteric fermentation or from livestock dungs which contains organic compounds such as methane and nitrous oxide (Chabbi et al., 2017).

In a collaboration effort investigating GHG emissions across the livestock value chain in selected regions of SSA, researchers (Petersen et al., 2023; Robinson, 2020), found that enteric fermentation is the primary contributor to GHG emissions, along with feeding, animal dung, and energy consumption. Additionally, (Henry, 2020; Mirzabaev et al., 2023) stated that the generation of methane is a significant problem in cattle production in SSA since it accounts for about 18% of the total GHG emissions (Robinson, 2020). In addition to environmental and climate goals, the agricultural sector should include biodiversity, nutritional needs, food security, rural farmers' livelihoods, and rural communities as important issues (Graham et al., 2022). Agriculture has addressed humanity's greatest challenges throughout its history (Davis-Reddy, 2018). This sector has raised food production to levels that many thoughts were unattainable (Borrelli et al., 2020). The sector now faced the task to make another significant contribution to humanity's progress by lowering GHG emissions. It is conceivable and desirable to create management techniques to reduce methane emissions from ruminant and non-ruminant livestock to adjust to total GHG contributions to climate change.

2.3.3.5 Urban Agriculture and Climate Change

Over the last few decades, urbanization has spread fast and steadily around the globe (Ogunbode et al., 2020). More than half of the world's population lives in cities, and this ratio is expected to climb to almost 70% by 2050 (Pradhan et al., 2023). Cities use up to 80% of the energy generated globally and contribute for more than 70% of energy-related global GHGs emission, with both statistics predicted to rise (Esmail and Oelbermann, 2022). It is anticipated that emerging nations, particularly fast-growing cities in SSA, would account for about 60% of the increase in CO_2 emissions from agriculture and energy usage by year 2050 (Robinson, 2020). Additionally, inadequate waste management and agricultural debris in many cities leads to nitrous oxide and methane emissions (Hanif, 2018).

As a result of population surge that comes with urbanization, urban agriculture plays a viable solution to meet the high demand for food in the cities (Pradhan et al., 2023). According to (Esmail and Oelbermann, 2022; Pradhan et al., 2023), urban agriculture is the practise of cultivating land inside city or suburb, community gardens, rooftop farms, hydroponic, aeroponic, and aquaponic facilities, as well as vertical production, for agricultural purposes (Thornton et al., 2018). This urban land use pattern can also pose problems for environment and climate change if not well managed (Pradhan et al., 2023). Due to networking commerce and increased globalization, food now travels great distances from farm before reaching their plates (Robinson, 2020). This has prompted worries about GHGs emission from the transportation sector in relation to food value chain in urban areas (Hanif, 2018).

Furthermore, (Crippa et al., 2021; Hanif, 2018), reported that negative environmental impacts of GHGs on climate are also brought on by the subsequent stages in urban agricultural food production such as propagation, processing, consumption, disposal, digestion, and water reuse. This constitutes about 50% of the overall GHG emissions attributed to the food industry in SSA (Tongwane and Moeletsi, 2018). In addition, the increased usage of land for agriculture to meet the urban food needs has had far-reaching consequences (Davis-Reddy, 2018). When these factors are taken into consideration, it is estimated that food production in form of home-garden, and community farm are responsible for about 30% of the SSA cities total carbon footprint (Ebhota and Tabakov, 2021).

As (Pradhan et al., 2023; Praveen and Sharma, 2019) noted, urban community farms serve to lessen the biodiversity loss that comes with industrial farming. It has also been brought to light that community farms can lessen our environmental impact by diverting trash from landfills via agricultural practices such as usage of little packaging, on-site recycling of commonly used appliances, and composting of organic scraps (Cockx et al., 2019; Kumar et al., 2021). This kind of urban land use is growing in popularity, and it may affect GHG emissions through the use of fertilizers, herbicides and agrochemicals unsustainably (Ngarava et al., 2023). There is currently limited quantitative evidence on the associated contribution of urban agriculture projects like community farms, despite (Abernethy and Jackson, 2022; Esmail and Oelbermann, 2022) proposal that local production of fruit and vegetables reduced GHG emissions associated with food transport, distribution, and retail. According to (Abbass et al., 2022; Scott et al., 2023), laws are being passed, advisory organizations like the Rural and Urban Climate Change Forum are being funded, and road maps for more sustainable supply chains are being developed as part of government strategy to reduce greenhouse gas emissions associated to food production in urban regions.

2.3.4 Various GHG Sink: Impact on Climate Change

Climate change has a significant impact on human habitat as well as livelihood conditions, likewise, our ways of life had a significant influence on climate change (Henry, 2020). As changes increase larger and faster, there is a chance that adverse outcomes may continue to dominate. GHG emissions in SSA have grown due to increased population, rapid industrialization, and intensive agriculture practices (Robinson, 2020). The use of fossil energy, deforestation, biomass burning and decay, as well as land degradation have all contributed to rising atmospheric CO_2 concentrations, which are now at (0.04%) 421 ppm and expected to rise to around 500 - 600 ppm by 2050 (Liu et al., 2019).

Following (Abbass et al., 2022; Tongwane and Moeletsi, 2018), different sectors contributed significantly to GHG emissions in SSA. The energy sector contributes the most, closely followed by industrial, deforestation (through tree felling, burning, and hacking) as well as intensive agricultural practices, and transportation. The waste from commercial and residential buildings is the least polluting sector (Legg, 2021; Masson-Delmotte et al., 2021). All of these sectors contribute to the overall anthropogenic activities that lead to climate change.

2.3.4.1 Methane (CH_4) Emissions

In 2020, methane accounted for around 15% of all GHG emissions from human activities in SSA (Robinson, 2020). The various human activities emitting methane are leaks from natural gas systems, the raising of livestock, and natural wetlands (Robinson, 2020). In addition, about 65% of overall CH_4 emissions also come from energy, industry, agriculture, land use, and waste management activities, as described below (Robinson, 2020).

Agriculture: Domestic livestock (such as cattle, swine, sheep, and goats) generate CH_4 naturally as part of their digestive process (Robinson, 2020). Since these animals are raised by human for food and other purposes, their emissions are deemed human-related (Smith et al., 2016). The agriculture sector is the leading source of CH_4 emissions in the SSA, although emissions can also occur as a result of land conservation and management activities as well as forestry management through forest and grassland fires, organic matter decomposition in coastal wetlands (Chalise and Naranpanawa, 2016).

Energy and Industry: Natural gas and petroleum systems are also significant contributors to CH4 emissions in SSA (Davis-Reddy, 2018). Methane is released into the atmosphere via natural fossil fuel extraction, as well as crude oil production, refining, transportation, and storage. Coal mining also contributes to CH4 emissions (Legg, 2021).

Waste from Homes and Businesses: Methane gas is generated from landfills when garbage decomposes, during home and industrial wastewater treatment as well as during composting and anaerobic digestion (Boateng et al., 2019). Methane is also emitted by a variety of natural sources, including wetlands, which produce CH_4 from microorganisms that decompose organic compounds in the absence of oxygen. Termites, seas, sediments, volcanoes, and wildfires are examples of smaller methane emission sources (Borrelli et al., 2020; Popp et al., 2017).

2.3.4.2 Carbon dioxide (CO_2) Emission

The primary GHGs emitted by human activities is carbon dioxide (CO_2) (Bakshi et al., 2019; Ogunbode et al., 2020). CO_2 accounts for almost 80% of total SSA greenhouse gas emissions from human-related activities in the year 2020 (Boateng et al., 2019). According to (Ngarava et al., 2023), CO_2 is found naturally in the atmosphere as part of the Earth's carbon cycle (the natural circulation of carbon among the atmosphere, oceans, soil, plants, and animals). Human-related activities are influencing the carbon cycle, both by releasing more CO_2 into the atmosphere and by altering natural sinks' ability (such as forests and soils) to take and store CO_2 from the atmosphere (Davis-Reddy, 2018). While CO_2 emissions come from varieties of natural sources, human-related emissions are responsible for the rise in atmospheric CO_2 during the industrial revolution, which has a relatively large impact on the climate (Robinson, 2020). Aside from agriculture and land-use, burning fossil fuels for energy-use and transportation purposes are part of human activities that generate CO_2 in SSA (Crippa et al., 2021). CO_2 is also emitted by some industrial activities (Tione et al., 2022). The following sections detail the major sources of CO2 emissions in the SSA.

Transportation: In the 1990s, the combustion of fossil energy such as gasoline and diesel to transport people and goods was the major source of CO_2 emissions, accounting for around 16% of total CO_2 emissions and 22% of total greenhouse gas emissions in SSA (Scott et al., 2023). This includes domestic transportation sources like highway and passenger vehicles, air travel, marine transportation, and rail (Kanitkar et al., 2022).

Electricity: Electricity is a significant energy source in the SSA, used in powering homes, businesses, and industries (Adams and Acheampong, 2019). The combustion of fossil fuels to generate electricity, constitutes the major source of CO_2 emissions in SSA, thereby accounting for around 16% of total CO_2 emissions (Adams and Acheampong, 2019). The kind of fossil fuels used in generating electricity emit different amounts of CO_2 (Henry, 2020). Therefore, by producing a certain quantity of electricity, the burning of coals will produce more CO_2 than natural gas or oil (Ackerl et al., 2023).

Industry: Numerous industrial processes emit CO_2 through fossil fuel combustions as well as through chemical reactions such as the production of mineral products, cement, and metals (like iron and steel) that do not involve combustion (Liu et al., 2019). In addition, many industrial processes also make use of electricity for energy generation; therefore, indirectly complement CO_2 emissions through the industrial source (Adams and Acheampong, 2019).

2.3.4.3 Nitrous Oxide (N_2O) Emissions

Nitrous oxide (N_2O) accounted for around 17% of all SSA GHG emissions through human-related activities (Abbass et al., 2022). Human-related activities like agriculture, industrialization, energy-use, and wastewater management, increase the amount of N_2O in the atmosphere (Ogunbode et al., 2020). N_2O is also present naturally in the atmosphere being part of the Earth's nitrogen cycle and has a variety of natural sources (Chabbi et al., 2017; Outhwaite et al., 2022). N_2O is emitted from other various sources such as agriculture, land use, transportation, and industry, as described below (Scott et al., 2023).

Agriculture: Various agriculture soil management activities in SSA like the application of synthetic or organic fertilizers and other cropping practices, the management of manure, or the burning of agricultural residues generate N_2O (Borrelli et al., 2020; Popp et al., 2017). Agriculture soil management is the largest source of N_2O emissions in the SSA, accounting for about 64% of total N_2O emissions in 2020, closely followed by the application of synthetic nitrogen fertilizers to urban soils (lawns, golf courses) and forest lands (Adams and Acheampong, 2019).

Fuel Combustion: N_2O is emitted through the combustion of fuels (Gopalakrishnan et al., 2019). The amount of N_2O emitted to the atmosphere from fuel combustions depends on the type of fuel combusted, combustion technology, maintenance, as well as operating practices (Robinson, 2020).

Industry: N_2O is generated as a by-product during the production of chemicals like nitric and adipic acid which is used in making synthetic commercial fertilizers, nylon, and other synthetic products

(Robinson, 2020).

Waste: N_2O is generated during nitrification, which involves the treatment of domestic wastewater and the denitrification process of nitrogen present urea, ammonia, and proteins (Leitner et al., 2020).

2.3.4.5 Stylised facts on agriculture-energy-use as a true contributor to climate change

Land changes and agricultural energy-use have a significant influence on carbon sequestration and GHG emissions in SSA (Mullins et al., 2018). Plants absorb CO_2 from the atmosphere, plants, forests, and many other natural ecosystems that have evolved over thousands of years could store enormous amounts of carbon (Outhwaite et al., 2022). The transformation of uncultivated land from a carbon sink and store to a source of GHG emissions owing to burning plant material or crop cultivation has a detrimental influence on the emission balance and climate (Tione et al., 2022). Similarly, maintaining and expanding plant biomass aids in the sequestration of carbon and reduces the concentrations of atmospheric CO_2, CH_4, and N_2O (Tongwane and Moeletsi, 2018).

According to (Abbass et al., 2022; Tongwane and Moeletsi, 2018), the main driver of climate change in Ethiopia, Sudan, Chad, and Niger is deforestation (for agricultural expansion and fuel wood). Similarly, intense tillage is a traditional land-use technique in Mali, Guinea, and Mauritania that contributes significantly to climate change by continually disrupting the topsoil (Tongwane and Moeletsi, 2018). These practices increase CO_2 and CH_4 emissions by inducing soil organic matter decomposition and soil erosion (Ngarava et al., 2023). As a result, forestry and woodland management have also influenced the concentration of GHGs in the atmosphere, resulting in climate change (Robinson, 2020).

Various research (Gopalakrishnan et al., 2019; Omotayo et al., 2022; Pradhan et al., 2023), have found that unsustainable contemporary agricultural practices in some SSA regions constitute a substantial source of GHGs that exacerbate climate change. Agriculture practice varies across SSA, resulting in a diverse range of agricultural contributions to climate change (Omotoso et al., 2023). GHG emissions from agriculture are severe in Eastern African nations (such as Kenya, Ethiopia, Uganda, and Djibouti) due to large numbers of cattle and inadequate waste management, inefficient use of agro-chemicals, and mismanagement of farmland (Robinson, 2020). Furthermore, energy use in agriculture, such as a tractor for land clearing, fertilizer application machinery, and tillage practices in some Southern African nations like Zambia, Zimbabwe, Namibia, and Botswana, significantly altered the nitrogen and carbon cycles, contributing to GHG emissions and climate change (Davis-Reddy, 2018).

In addition, organic farming in Western Africa (such as Nigeria, Ghana, Togo, Burkina Faso, and Senegal) contributes significantly to GHG emissions due to a lack of crop residue management, since most agricultural wastes in these countries are publicly burnt or left for animal grazing (Ngarava et al., 2023). Likewise, savanna or grassland fires, which seem to be prevalent in the region, are a significant contributor to GHG emissions (Legg, 2021; Masson-Delmotte et al., 2021). Because of the large contribution of GHG emissions to ecosystems, agriculture has emerged as an integral sector that SSA and the entire world should focus on to manage emissions and preserve current and future generations from devastating climate change (Robinson, 2020).

2.3.5 Economic Impacts of Climate Change in Various SSA Nations

The SSA is one of the world's poorest regions, with an estimated 421 million people living on less than $1.20 a day (Robinson, 2020). They are recognized as the most susceptible to climate change because they have the fewest financial and technological means to deal with its impact (Omotoso et al., 2023). Climate-related disasters, particularly droughts and floods, are the most prevalent types of natural disasters in SSA (Omotoso et al., 2023). As a result, they account for around 80% of the casualties and around 70% of the economic losses as a result of natural disasters in SSA (Omotoso et al., 2023). Flooding and droughts are projected to become more frequent and intense in the future, due to poor institutional structure, weak infrastructure and adaptive measures (Chalise and Naranpanawa, 2016; Davis-Reddy, 2018).

Climate change is expected to influence agricultural activity in SSA by shortening the growing season, increasing water stress, and raising the prevalence of disease, insect, and weed outbreaks (Robinson, 2020). Heat and water stresses are regarded as the most severe environmental factors resulting from climate change that affect agricultural production systems (McCarthy et al., 2022; Robinson, 2020). However, in regions with excessive water and heat (due to climate change), disease, weed, and insect infestations, are expected to wreak further havoc on agroecosystems (Maino and Emrullahu, 2022). Moreover, the carbon-cycle distortions are anticipated to have an impact on livestock and food crop production such as rice, maize and sorghum (Robinson, 2020).

Furthermore, climate-related shocks are predominantly hitting SSA, a subcontinent that contributes 2% of global GDP in 2021, is home to about 15% of the present world's population, and will account for more than half of the anticipated global population by 2100 (Abbass et al., 2022). This is largely due to the region's geographic vulnerability, low income, increased reliance on climate-sensitive industries, and inadequate ability to adapt to weather shocks (Ngarava et al., 2023). Droughts in the Sahel, for example, would have an impact on economic growth and, in particular, agricultural productivity (Ngarava et al., 2023). Droughts and flooding can result in a huge number of casualties (Robinson, 2020). For example, the 2018-19 rainy season in SSA inflicted unprecedented amounts of disaster, displacing about 2.2 million households in Malawi, Mozambique, and Zimbabwe (Kim et al., 2021; Mirzabaev et al., 2023).

Mozambique's economic losses have resulted in a slowing of GDP growth to 2.5 percent in 2019, as opposed to the anticipated rise of up to 4.7% (Kim et al., 2021). Because of the sensitivity of their key engines of growth, such as agriculture, forestry, pastoralism, energy, tourism, and water resources, empirical findings show that African economies are very vulnerable to changes in climatic variables and climate-related events (Borrelli et al., 2020). Numerous researchers (Abernethy and Jackson, 2022; Bakshi et al., 2019; Davis-Reddy, 2018; Petersen et al., 2023), investigated the impacts of rising temperatures on economic growth in SSA from 2000 to 2019, utilizing panel data from 26 SSA nations. They discovered that a 1.0°C increase in temperature in a given year reduces economic development by 1.3% points on average in poorer nations, whereas the impact is minimal in wealthier countries. Their findings indicated that higher temperatures have a big impact on poorer regions since they rely excessively on climate-sensitive industries (such as agriculture and forestry) and have few resources (low income and savings) to adapt to weather shock (Omotayo et al., 2022).

In addition, (Abbass et al., 2022; Henry, 2020; Thornton et al., 2018) evidenced that prolonged changes in climatic conditions (like variations in precipitation, temperature, and sunlight) had a long-term negative impact on economic growth per capita in SSA countries. Also, (Boateng et al., 2019; Tione et al., 2022), discovered that following a natural disaster, difficulties in economic growth are exacerbated by bigger current account deficits, mounting fiscal and debt vulnerabilities, as well as pressures on international reserves. Remittances, foreign aid, and reconstruction can assist in minimizing the negative growth implications in the short term (Maino and Emrullahu, 2022).

Renovations of damaged infrastructure can assist in minimizing physical capital losses (Thornton et al., 2018). Human capital loss from disaster-related mortality, starvation, or decreased school attendance, on the other hand, is irreversible (Bakshi et al., 2019).

2.3.6 Climate Change Adaptation Practices and Agriculture in SSA

It is crucial to reduce agricultural GHG emissions and that of the net food system. CO_2 emissions must be abolished, and lowering agricultural CH_4 and N_2O emissions is climatically beneficial and should be advocated (Robinson, 2020). Climate change adaptation is a continuous activity that necessitates site-specific responses (McCarthy et al., 2022). Adaptation strategies should end up making agricultural systems more sustainable by adopting contemporary farming technologies that minimize GHG emissions (Robinson, 2020). Differentiated adaptation approaches and enhanced climate-risk management assistance for agricultural and farming households are crucial ways to cushion the impact on climate (McCarthy et al., 2022). These adaptation strategies involve, in particular, the choice and substitution of species and varieties, the adaptation of fieldwork to seasonal changes, the modification of plant production practices (efficient fertilization and irrigation practices), along with the adoption of plant production techniques that preserve soil organic matter content, manure management, and agroforestry practices (McCarthy et al., 2022).

2.3.6.1 Key Roles of Adaptation Practices on Agriculture and Energy-use Impacts

The impacts of agriculture on climate change can be sustained through climate change adaptation processes which involve the recognition of carbon (C) as a tradable commodity and the reduction in GHG emissions for agriculture and its energy use (Chalise and Naranpanawa, 2016). These processes entail focusing on ways of adjusting to emissions of GHGs from the agriculture sector by employing natural resource conservation measures without compromising food production in terms of meeting the growing population's demands (Boateng et al., 2019). This will be a triple win given that it will enhance adaptation while also increasing food security and sustainability in the country (Abernethy and Jackson, 2022; Ackerl et al., 2023).

The forestry sector which is the ideal conservation measure holds the key to successful adaptation techniques by trapping carbon through various forest management such as deforestation, degradation, afforestation and reforestation (Ackerl et al., 2023). Other ways of GHG emissions adaptation in agriculture include enhanced crop and pasture land management (e.g., improved agronomic methods, fertilizer usage, tillage, and residue management), increased input usage efficiency, organic manure restoration of degraded lands, improved livestock and manure management, and agroforestry (Ngarava et al., 2023). In addition, GHG emission intensity from consumption would be reduced through the adoption of a diet that is plant-based (Davis-Reddy, 2018). Numerous scholars (Chabbi et al., 2017; Omotoso et al., 2023; Outhwaite et al., 2022; Robinson, 2020), pinpointed that agricultural emissions eliminated in some selected states of SSA are achieved through more efficient agricultural techniques, such as smarter livestock handling, zero/minimal tillage, crop rotations, agroforestry, monitoring fertilizer application using technology and making adjustments to farm configuration during propagation.

Interestingly, imposing a carbon fee on agricultural operations would enhance the adaptation process which will result in the reduction of GHG-intensive agricultural commodities (Chalise and Naranpanawa, 2016; Mirzabaev et al., 2023). Researchers (Omotoso et al., 2023; Robinson, 2020), positioned that meeting the food need of SSA given the increasing populations while simultaneously adapting to GHG emissions, requires drastic changes in production structure and energy-use intensification. This could be done through a carbon offset program organized by the government for measuring carbon emitted during agricultural production as well as drastically enhancing energy efficiency in the food production process (Maino and Emrullahu, 2022). These initiatives will greatly decrease GHG emissions from agricultural and energy usage, significantly lowering the rate of climate change, improving environmental sustainability, reducing pollution, and better human health (Robinson, 2020).

Land-use for climatic advantages, like sequestering carbon or biomass for energy, is emphasized as vital for ambitious adaptation approaches (Kanitkar et al., 2022). Acknowledging that agricultural land is used for more than just these uses, but primarily for food production, will go a long way toward assisting adaptation efforts (Chalise and Naranpanawa, 2016). Measures to reduce agricultural emissions may thus be connected to initiatives to sequester carbon through land use (Robinson, 2020). Greater emphasis must be placed on alternate land-use and energy-use in agriculture since agricultural emission adaption solutions could either support or interfere with other Sustainable Development Goals in SSA (Crippa et al., 2021).

2.3.6.2 Climate Change Adaptation Practices in some Selected Countries of the SSA

A significant issue in SSA is farmers' improper management of soil nutrients and land use (Tione et al., 2022). Most farmers don't know how to use resources effectively to cut back on GHG emissions that contribute to climate change (Robinson, 2020). Enhancing nutrient usage efficiency offers a significant chance of lowering indirect carbon dioxide emissions from fertilizer businesses as well as N2O emissions from crops, which are normally produced by soil microorganisms from nitrogen surpluses (Leitner et al., 2020). According to (Leitner et al., 2020; Sánchez-Rodríguez et al., 2018), some recommended farming techniques include using the proper resource (higher-efficiency fertilizer) at the proper rate, time, and location.

Improved nutrient management is seen as a more effective and realistic option for overcoming the challenges connected with GHG emissions' implications on climate change in SSA (Omotoso et al., 2023). Adopting enhanced agronomic techniques can result in higher yields and the creation of more carbon, which can be utilized to increase soil carbon storage, resulting in fewer losses to the environment (Ebhota and Tabakov, 2021; Robinson, 2020). Other strategies proposed include lengthening crop rotations, utilizing better cultivars, and employing mixed cropping with perennial crops, which will result in higher underground carbon storage.

2.3.7 Climate Change Adaptation Practices: A Panacea to the GHG Emissions

Agriculture, forestry, and other land use accounted for major anthropogenic GHG emissions in SSA, mostly from non-CO_2 GHGs (CH_4 and N_2O) and indirect CO_2 emissions from induced deforestation (Outhwaite et al., 2022). Reducing these emissions is key to achieving net-zero objectives of GHG adaptation IPCC (Emenekwe et al., 2022; Kanitkar et al., 2022). Also, (Bahri et al., 2021; Ngarava et al., 2023), estimates that the adaptation potential for agriculture (excluding forestry and fossil fuel offsets from biomass) will be between 10.5 and 16.0 $GtCO_2$-eq/yr by 2030, where around 89% are assumed to be from carbon sequestration in soils. Therefore, the assessment of adaptation potential and prospects remain a major tool for priority setting at the national and regional levels in SSA (Ogunbode et al., 2020; Robinson, 2020).

Many of these agriculture-enhanced options, particularly those that involve soil carbon (C) sequestration also increased adaptation potentials, food security, and economic development (Borrelli et al., 2020; Popp et al., 2017). These strategies entail enhancing soil organic matter levels and reducing GHG emissions from agriculture, land-use, and energy-use (Boateng et al., 2019). However, some of these options in the long run resulted in poor trade-offs, with mitigation advantages but severe effects on food security and economic development (Malla et al., 2022). Biofuel production, for example, provides a clean substitute for fossil fuels but may displace or compete for water and land resources required for food production (Davis-Reddy, 2018; Kim et al., 2021).

Planting of cover crops which might also be useful in biofuel production, helps in organic soil restoration but it may lower the amount of land suitable for food production (Kim et al., 2021). Rangeland restoration may boost carbon sequestration but also reduce herder income in the near term by decreasing the number of cattle. Some trade-offs can be regulated by efficiency measures or through the offering of incentives/compensation which may be beneficial for agricultural development but not adaptation strategies (Robinson, 2020). However, complementing climate-smart agricultural practices with climate friendly policy implementation (such as afforestation, agroforestry and use of solar energy to fossil fuel) can limit the impact of climate change to 1.5 degrees Celsius from GHG emission (Ogunbode et al., 2020). In reality, would lead to substantial impacts on food availability, cleaner air, and overall economic development of a nation (Mirzabaev et al., 2023).

2.3.8 Conclusion and Policy Recommendation

Management of land and energy-use in agriculture has a significant impact on GHG concentrations in the atmosphere. Apart from CO_2 emissions via combustion of agriculture and animal waste combustion in SSA reported in literatures, livestock production significantly contributes to CH_4 emissions. Meeting the food demand of the world's growing population while combating climate change is a difficult task that cannot be accomplished overnight. Similarly, achieving a 1.5°C pathway (as recommended by IPCC) will necessitate an industry-wide effort and collaboration of consumers, farmers, investors, and regulators to significant shifts in how we farm. Without swift action, emissions of GHGs in agriculture, land, and energy-use will continue to rise and lead to the overheating of the ozone layer. Understanding GHG emissions by sources and removal by sinks in agriculture is essential for devising effective GHG reduction and adaptation strategies. The international bodies and stakeholders involved in climate change has urge the agricultural communities to limiting GHG emissions to safeguard the environment while still meeting the demands of a growing population and food supply. This complicated issue necessitates a coordinated and consistent policy approach to climate change, agricultural growth, and energy-use. In the face of climate change and competition for scarce resources, the entire food system will have to reform and become more resource efficient, while also consistently reducing its environmental impacts, including GHG emissions. We must boost yields whilst having little or no influence on climate change by minimizing our agrochemicals, eliminating food waste, and reducing our consumption of greenhouse gas-intensive foods through adequate investments from governments and all stakeholders in SSA. Therefore, policies and incentives that promote sustainable land use such as agroforestry and conservation tillage and energy-efficient practices in agriculture, including carbon pricing and subsidies for green technologies should be implemented. Enhance research and innovation in sustainable agriculture and renewable energy to develop more efficient and climate-friendly solutions is necessary.

Manuscript 3

Climate-smart agricultural practices in the sub-Sahara Africa: A meta-analysis review of its impact on food and nutrition security

Abstract

In light of the emerging climate change realities, climate-smart agriculture (CSA) is a strategy for reforming and reorienting agricultural systems to ensure food and nutrition security. Widespread changes in rainfall and temperature patterns endanger agricultural productivity and make people whose livelihoods rely on agriculture more vulnerable. Climate change disrupts food markets, endangering the food supply for the entire population. By increasing the adaptive capacity of producers, the resilience and resource use efficiency of agricultural production systems, these threats can be mitigated. Although CSA adoption has been extensively studied in the literature, its significant impacts on the food and nutrition security in sub-Saharan Africa (SSA) remains unclear. This study contributes to the existing body of knowledge by employing a meta-regression analysis of 114 systematically selected primary studies published on CSA and food-nutrition security in SSA between the years 2001 and 2023. These sampled primary studies were peer-reviewed and filtered by 3 professionals before being eligible for the Meta-regression analysis (MRA). In general, the empirical findings from the MRA revealed that the adoption of CSA positively and significantly influenced food and nutrition security in SSA. More so, the impacts of CSA adopted on food and nutrition security of the households increases as the year of sampled primary study increases. However, the extent of the influence is relatively high, indicating a strong tenuous association between the adoption of CSA and households' food and nutrition in SSA. Additionally, Southern Africa has the highest study attributes and partial correlation coefficient estimates (0.38), which denotes the highest impacts of CSA on food and nutrition security than other regions of SSA. This research recommends that by investing in CSA, SSA countries can enhance their food and nutrition security, build resilience to climate change impacts, and ensure sustainable agricultural development.

Keywords: Climate change; Food policy; Partial correlation coefficient; Primary studies; Sub-Sahara Africa

2.4.1 Introduction

Climate change threatens global food systems especially food and nutrition security in sub-Saharan Africa (Omotoso et al., 2023). As a result, an increase in sustainable food production is necessary for fulfilling the growing food demands while also managing the impacts of climate change on farmers' output in sub-Saharan Africa (Akpan & Zikos, 2023; Anuga et al., 2022). Sub-Saharan Africa (SSA) is one of the most vulnerable regions to the consequences of climate change due to its limited adaptation and reliance on rain-fed agriculture (Gebre et al., 2023; Kichamu-Wachira et al., 2021). Climate change in SSA is manifested in diverse dimensions including rising temperatures, floods, arid periods, frequent droughts, and erratic precipitation, leading to poor agricultural productivity, and food and nutrition security (Nantongo et al., 2023; Omotayo & Aremu, 2021; Omotoso et al., 2023).

Studies (Abegaz et al., 2023; Keshavarz & Sharafi, 2023; Muñoz & Sandoval-Díaz, 2023) have shown that the current population of SSA stands at approximately 1.2 billion and is projected to reach a staggering 2 billion by the year 2050. Meanwhile, (Cockx et al., 2019) argued that the rapid population expansion and urbanization in SSA will inevitably lead to an increased demand for food. This surge in population will place significant pressure on the existing agricultural systems and necessitate the development of sustainable strategies to meet the rising food requirements (Cockx et al., 2019). To fulfill the rising demand for both quality and quantity of food in the face of climate change, SSA must quadruple its food production (Abegunde et al., 2022; Ado et al., 2020; Zheng et al., 2023). Meanwhile, considering the multiple-stressor environment in which agriculture is done in this region, SSA has a monumental struggle to achieve food and nutrition security (Bazzana et al., 2022; Thakur & Uphoff, 2017; Traore et al., 2021).

Over the years, climate change-induced disruptions[1] have been identified as one of the major contributors driving low agricultural output in SSA and other developing nations (Mutengwa et al., 2023; Omotoso et al., 2023) which consequentially impact the food and nutrition security of the farming household. Studies (Adesete et al., 2022; Mutengwa et al., 2023), have suggested that some of the challenges posed by climate change to rural farmers' productivity, food and nutrition

[1] Disruptions due to extreme weather events, such as erratic precipitation, heat stress, frequent droughts, floods, temperature increases, and pest invasions, are all components of climate change that have a significant influence on SSA agriculture. (Abegaz et al., 2023; Traore et al., 2021).

security could be addressed through climate-smart agriculture (CSA), which is increasingly been recognized widely as a sustainable solution to enhance inclusive, resilience and vibrant food systems.

Specifically, CSA seeks to address some underlying challenges induced by climate change while promoting national food and nutrition security and strategic development goals by increasing agricultural outputs and incomes sustainably, strengthening resilience, and lowering greenhouse gas emissions (Adesete et al., 2022; Issahaku & Abdulai, 2020). CSA promotes the development of climate-friendly agricultural technologies as well as the creation of more sustainable policies that embrace environmental stewardship (Kangogo et al., 2021; Paul et al., 2018). Interestingly, it enhances the resilience of agricultural systems to climate change impacts, such as droughts, floods, and erratic rainfall patterns (Ewunetu et al., 2023). This resilience helps ensure stable and reliable food production despite changing climate conditions. Adoption of CSA practices such as conservation agriculture, agroforestry, and crop diversification, would lead to increased crop yields (Omotoso et al., 2022; Omotoso et al., 2023). Likewise, diversifying crops helps mitigate the risks associated with climate variability, providing a more stable and varied source of food-nutrition security (Omotayo et al., 2020; Omotoso et al., 2023). Although, CSA is extensively discussed in SSA, its promotion and implementation are still in its infancy, leaving farmers in this region vulnerable to the negative impacts of climate change (Bahri et al., 2021; Lipper et al., 2014; Mutengwa et al., 2023).

Interestingly, several studies (Akpan & Zikos, 2023; Kombat et al., 2021; Omotayo et al., 2022) have made an effort to combine literature linking CSA adoptions to food and nutrition security to discover the synergy between the two key variables of interest. However, the results have been varied, inconsistent or have a narrow scope (Bai et al., 2019; Batisani et al., 2021). Studies (Abegaz et al., 2023; Nantongo et al., 2023) have raised concerns that variations in the results are likely to influence agricultural research funding and policies which could also have an impact on the adoption of new technologies in nations or regions where the impacts of climate change have been extremely severe

Although these attempts are commendable, a qualitative review of the literature is frequently subjective and may not provide a comprehensive understanding of the underlying causes that lead to the full realization of CSA potential (Adesete et al., 2022). Consequently, it is becoming more prevalent in research to incorporate estimates from disparate but related studies into a cohesive analysis (Bjornlund et al., 2022). Such methodologies would provide more insight into variations in CSA impacts literature, as well as an avenue for future research assessing the impact of its adoption on food-nutrition security in SSA (Ahmed et al., 2019; Leisner, 2020). Following (Abegaz et al., 2023; Araujo et al., 2023; Ogundari, 2022), considering the benefit of quantitative synthesis of empirical research over qualitative synthesis, we employed a meta-regression analysis (MRA) of primary studies in the SSA to investigate the influence of implementing CSA practices in agricultural production on food and nutrition security in the SSA. The meta-analysis method aided in answering the following research questions:

[2]RQ1. Does the adoption of CSA practices have a significant impact on food and nutrition security in SSA?

RQ2. What study-specific attributes account for the differences in the reported estimates of the impacts of CSA on food and nutrition security reported in the sampled primary studies?

Therefore, this review is significant for two reasons, both of which stem from the research questions described above. First, it provides details on the current status of the impacts of CSA practices on food and nutrition security metrics in SSA. Second, this kind of analysis helps identify study attributes that are essential for assessing the effect of implementing further agricultural innovation and technology in the context of future research.

2.4.2 Materials and methods

2.4.2.1 Research design and data collection

To ensure the comprehensiveness of our literature review, we conducted a systematic and thorough search of peer-reviewed research articles published between January 2001 and August 2023 across three major databases (Scopus, Google Scholar and Web of Science). To find the relevant publications from these databases, search keywords such as ‘Climate-smart’, ‘Agriculture’,

[2] RQ = Research Question

‘Climate change’, ‘HDDS[3]’, ‘HFIAS’ and ‘SSA’ were employed. Following (Li et al., 2022), bibliographic search procedures were used to enhance the search for the precise location of relevant literature related to climate-smart and food-nutrition security, using a systematic approach to the study of literature. The search was conducted by querying the provided databases using the keywords "climate-smart agriculture in SSA". In addition, a search was performed to construct and save the bibliographies of the retrieved articles in the Endnote reference manager.

2.4.2.2 Data Sources

For this review, 114 primary research studies were selected based on the inclusion and exclusion criteria (Table 2.5) from diverse backgrounds and their relevance to the topic to enhance the validity of the research outcomes. The sampled research studies were peer-reviewed and filtered by 3 professionals[4] before being eligible for meta-regression analysis (MRA). These studies were obtained from the database via the search of relevant keywords and search phrases that were unique to each database employed. These keywords were used in various combinations to find various articles used for the study. We began by narrowing our search to research the "CSA impact on food and nutrition security in SSA”. Using the Scopus, Google Scholar and WoS electronic databases, a keyword search using the keywords, [“agriculture” or “food-production”] and [“climate-smart” or “adaptation practices”] and [“HDDS” or “HFIAS”] and [“sub-Saharan Africa”] was performed. Articles not published in English or published before 2001, were excluded (see Figure 2.11). Additionally, we included in our final sample for MRA, those studies that published standard errors and t-values of the variable indicating the influence of CSA adopted in agricultural production on food and nutrition security. The data from the qualifying studies was retrieved and entered into an Excel database.

A meta-analytic review research strategy was chosen for this investigation. This strategy has been discovered to have been employed in various contexts relevant to the transformation of food systems (Ahmed et al., 2019; Araujo et al., 2023; Ogundari & Bolarinwa, 2019) and has aided the researcher in documenting basic problems linked to the examined topic that the evaluated studies have offered (Yuan et al., 2020). Furthermore, statistical results were obtained using such an

[3] HDDS = household dietary diversity score used as a proxy for food-nutrition security; HFIAS = household food insecurity assess score
[4] Using inclusion and exclusion criteria presented in Table 1

approach, which can inform policymakers and strategists for decision-making (Anderson et al., 2020; Araujo et al., 2023; Osinubi & Apanisile, 2021).

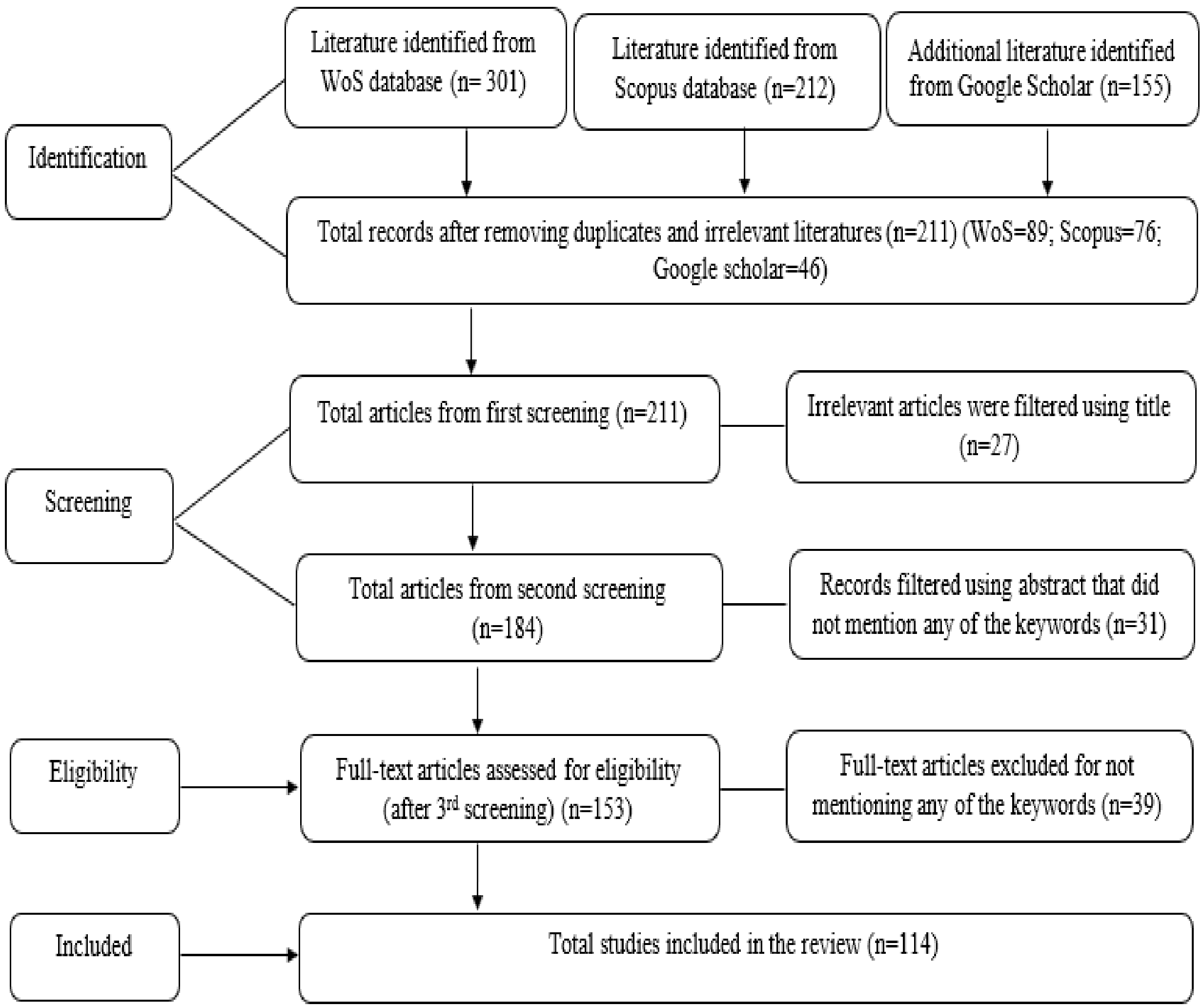

Fig. 2.11. Flowchart of article selection for meta-analysis (n = number of primary studies selected)

Table 2.5. Criteria for the article Inclusion and Exclusion in Meta-analysis

Search result	Reason for acceptance	Reason for rejection
Initial look	Articles published in English	Articles published in other languages
	Articles on climate-smart agriculture	Articles unrelated to climate-smart agriculture
	Articles related to agriculture	Articles not related to agriculture
	Articles that adopt household dietary diversity and household insecurity access score as a proxy for food-nutrition security	Articles that use unconventional food-nutrition security measures such as household per capita expenditure and depth of food deficit were excluded
Title with abstract screening	Articles focusing on sub-Saharan Africa	Articles focusing on Global issues
	Articles published from 2001 – 2023	Articles published before the year 2001
	Articles addressing CSA in SSA and relevant to the aims of the review	Articles addressing contemporary climate change adaptation practices but not relevant to the aim of this review and study area
Full paper review	Quantitative literature reviews and analyses	Articles without quantitative analysis
	Articles that were not duplicated versions of other articles	Articles that were duplicated versions of other articles in the dataset
	Studies that published standard errors and t-values of the association between CSA and food-nutrition security	Studies that did not publish standard errors or t-value

2.4.2.3 Meta-analytic procedures

The sampled studies were analyzed using a meta-analysis procedure, which allows us to quantitatively summarize and assess the dataset and generate statistically synthesized results (Lieber et al., 2022). Meta-analysis is a common method in environmental studies and ecological economics due to its flexibility and advantages (Gardezi & Arbuckle, 2020; Li et al., 2022; Ogundari & Bolarinwa, 2019). We estimated our results using three different procedures:

- Creating Effect size based on Partial correlation coefficient

The effect size of the research was determined based on the estimated elasticity reported in primary studies (Abegaz et al., 2023; Askarov & Doucouliagos, 2020). However, the partial correlation coefficient (PCC) is often advocated for MRA because it provides a single value which quantifies the strength and direction of a linear relationship between the dependent and independent variables (Branca et al., 2011; Bwambale et al., 2023). PCC is commonly used when the focus is on examining how changes in one variable are associated with changes in another (Branca et al., 2011; Bwambale et al., 2023). Following (Araujo et al., 2023; Egger & Smith, 1998; Sugerman et al., 2021), this study made use of PCC as effect size because most sampled studies reported correlation coefficients making them readily available for meta-regression analysis. For assessment, PCC requires the t-ratio and the degree of freedom (df) associated with the estimate (Araujo et al., 2023; Mullins et al., 2018).

Following (Ogundari & Bolarinwa, 2019; Zhou et al., 2020), the PCC equation is computed as;

$$\text{PCC} = \frac{\text{tj}}{\sqrt{\text{tj} + df}} \qquad \text{(2.1)}$$

where t_j and df denote the t-vale and degree of freedom j-th estimates, respectively.

The standard error of the partial correlation coefficient (SE_PCC), is given by:

$$\text{SE\_PCC} = \sqrt{(1 - PCC)/df} \qquad \text{(2.2)}$$

Where PCC = partial correlation coefficient of the study

PCC is being used in the context of this study to assess the strength of the association between CSA adopted and food and nutrition security in sampled primary studies. Following (Ahmed et al., 2019; Saddique et al., 2022), an absolute value of PCC; less than 0.10, between 0.10 - 0.25, and greater than 0.25 was used to stratify the estimates obtained from the sampled primary studies into small, medium, and large impacts of CSA adopted on food and nutrition security in SSA.

- Meta-regression analysis (MRA): Test of publication bias and genuine empirical effect

A significant application of meta-analysis is to detect the presence of publication bias and, in the absence of publication bias, to estimate the actual empirical impact size (Ogundari & Bolarinwa, 2019). Publication bias occurs when authors or reviewers have an explicit or implicit preference for statistically significant results, leaving research with relatively modest and non-significant estimates unreported (Bai et al., 2019). Empirically, publication bias can also occur when the association between the study effect size or PCC and its standard error is statistically significant (Jennings et al., 2022; Scridel et al., 2018). This implies that, in the absence of publication bias, the effect size of primary studies will not correlate significantly with the standard error (Acharyya, 2020; Adesete et al., 2022; Araujo et al., 2023). The consequence is that publication bias could overwhelm the genuine impact size, leading the reported effect size (PCC) distribution to be skewed (Ahmed et al., 2019; Araujo et al., 2023).

Interestingly, the emphasis on publication bias in meta-regression analysis does not imply neglect of other biases. Rather, publication bias is often emphasized because it can significantly impact the validity of meta-analysis results (Ahmed et al., 2019; Araujo et al., 2023). However, researchers are also aware of and recognize the importance of addressing other forms of bias. This research employs a range of strategies, such as quality assessments, clearly defining inclusion and exclusion criteria in a systematic review protocol, as well as assessing the methodological quality of included studies to help identify and address other potential biases. A thorough and transparent approach to bias assessment is critical for ensuring the reliability and validity of meta-analytic results (Ahmed et al., 2019; Araujo et al., 2023)

Following (Egger & Smith, 1998; Lieber et al., 2022), the funnel plots, funnel asymmetry test (FAT) and the precision effect test (PET-PEESE) approaches were adopted to test for the presence of publication bias in the sample primary studies, which are expressed as Univariate MRA (FAT-PET) thus:

$$PCC = \beta_0 + \alpha_0 SE\_PCC_i + \mu_j \quad \text{...} \quad (2.3)$$

Where SE_PCC_i denotes the standard error of PCC while β_0 and α_0 are the parameters estimated; μ_j is the error term. There is evidence of publication bias when α_0 is statistically significant, regardless of the sign of its value. Examining whether or not $\beta_0 = 0$, provides insight into the existence of a true empirical effect that is unaffected by publication bias.

- Multivariate MRA: identify sources of heterogeneity

Another important use of MRA is determining the sources of variation in reported effect size in primary research (Abler, 2023; Ogundari & Bolarinwa, 2018). Multivariate MRA, are used to discover the origins of heterogeneity or changes in population effect size (Ahmed et al., 2019; Ogundari & Bolarinwa, 2019).

The equation is expressed thus;

$$PCC = \beta_0 + \alpha_0 SE\_PCC_j + \sum_{K=1}^{K} \lambda X_{kj} + \mu_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.4)}$$

where X_{kj} is the vector of study attribute to explain variations in PCC; while β_0 and α_0 are the parameters estimated.

2.4.3 Results and discussion

2.4.3.1 Description and summary statistics of study attributes used in MRA

Table 2.6 summarizes the data used in MRA and provides an overview of how primary studies' moderator variables (study attributes) were grouped into categories based on data type, publication outlet, sampling method, methodology, model type, agricultural product, type of CSA adopted, and geographical location. Following (Popoola et al., 2022; Saj et al., 2017; Thakur & Uphoff, 2017), the wide range of CSA adopted in the primary studies sampled were classified into the following five groups (Figure 2.12): management of natural resources; zero tillage; integrated farming system; integrated pest management and high-yielding varieties.

The PCC represents the MRA dependent variable while the SE_PCC was also included in the table to account for potential publication bias in the sampled primary studies. The influence of the publishing outlet is captured by the dummy variable "journal," and it is crucial to include panel data in the MRA to take into consideration the long-term effects of the relationship between CSA and food and nutrition security. Notably, following (Neufeldt et al., 2013; Tione et al., 2022), sampled primary studies on household dietary diversity and house food insecurity access scores were used as a proxy for food-nutrition security. The following variables such as non-experimental design, parametric, endogenous switching regression, and difference-in-difference techniques were also included in the MRA to keep tabs on how the sampled primary studies varied in terms of methodology, study design, and econometric techniques.

Table 2.6. Summary of study-attributes used in MRA from the sampled primary studies in SSA

Category	Variables	Description	Mean	Std. Dev.
	PCC	Partial Correlation coefficients of the primary study	0.2251	0.1852
	SE_PCC	Standard error of PCC of the primary study	0.0271	0.0151
Publication outlets	Journals	Dummy, 1= Primary study published in journal, 0=Otherwise	0.9120	0.4236
Types of Data	Cross-sectional data	Dummy, 1= Primary study is CS data, 0=Otherwise	0.7953	0.3711
	Panel data	Dummy, 1= Primary study is panel data, 0=Otherwise	0.2047	0.1078
Types of CSA	Management of natural resources	1= Adopted management of natural resources, O= otherwise	0.3400	0.0974
	Zero tillage	1= Adopted zero tillage, 0= Otherwise	0.1500	0.0561
	High-yielding varieties	1= Adopted high-yielding varieties, 0= Otherwise	0.6000	0.1201
	Integrated farming system	1= Adopted integrated farming system, 0= Otherwise	0.0400	0.0335
	Integrated pest management	1= Adopted integrated pest management, 0= Otherwise	0.0600	0.0151
Research design	Non-experimental method	1= Primary studies use non-experimental method, 0= Otherwise	0.4871	0.2191
Methodology	Parametric	1= Primary data used parametric method, 0= Otherwise	0.4142	0.2094
Econometric methods	Instrumental Regression	1= Instrumental Regression was employed in the PS, 0= Otherwise	0.5316	0.1382
	Endogenous Switching regression	1= Endogenous Switching regression was used in the primary studies, 0= Otherwise	0.2710	0.0923

	Difference-in-difference technique	1= DD was employed in the primary study, 0= Otherwise	0.2217	0.1100
Product	Crop	1= Primary study focused on crop, 0= otherwise	0.9349	0.5912
Region	Western Africa studies	1= Primary studies were carried out in Western Africa, 0= Otherwise	0.2619	0.1491
	Eastern Africa studies	1= Primary studies were carried in Eastern Africa, 0= Otherwise	0.2318	0.0913
	Central Africa studies	1= Primary studies were carried in Central Africa, 0= Otherwise	0.1178	0.1102
	Southern Africa studies	1= Primary studies were carried in Southern Africa, 0= Otherwise	0.3975	0.0962

2.4.3.2 Type of CSA adopted in the sampled primary studies

The nature and distribution of CSA practiced adopted in SSA found in the sampled primary studies are shown in Figure 2.12. The adoptions of contemporary varieties, often known as high-yielding varieties and crop diversification, were shown to predominate the estimate in Figure 2.12. This accounts for around 52% of the overall estimations. The management of natural resources (such as agroforestry, crop rotation and bush fallowing) comes in second, which contributes around 23% to the overall estimations. Furthermore, it is estimated that soil and water conservation (such as mulching, minima/zero tillage practice and water harvesting) accounts for approximately 16%, while integrated pest management accounts for about 6%, and integrated farming system accounts for about 4%, respectively, of the total estimations. The findings revealed the various efforts that have been made over the years by national and international organizations to enhance the food and nutrition security in SSA through the adoption of agricultural innovations and technologies such as CSA practices, seems to be more concerned with the propagation of high-yielding varieties.

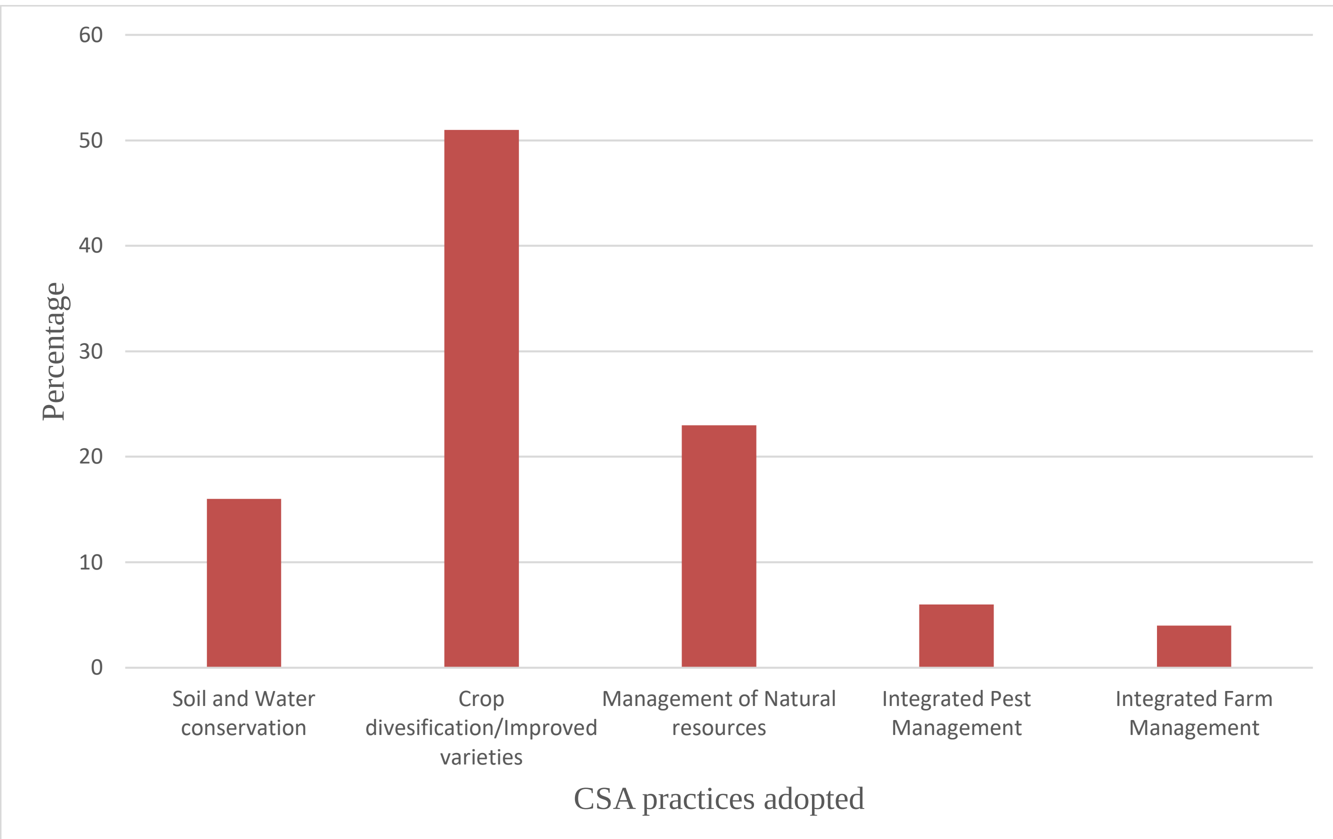

Fig. 2.12. CSA practices adopted in SSA evidenced from primary studies sampled

Other production strategies that are essential to complement yield-increasing technologies have been disregarded, despite their importance for achieving the objective of reducing poverty and ensuring food and nutrition security (Atta-Aidoo et al., 2022; Maindi et al., 2020). Notably, the use of climate-friendly technology such as zero tillage practices, would reduce greenhouse gas emissions, and increase the efficiency with which water is used in soil, thus, enhancing crop productivity (Adesete et al., 2022). According to (Chompolola & Kaonga, 2016; Steenwerth et al., 2014; Thothela et al., 2021), the combination of these technologies will both reduce the amount of environmental disruption caused and raise the level of soil production, increase farming output and enhance the food and nutrition security status. CSA promotes biodiversity conservation through practices like agroforestry and crop diversification (Mutengwa et al., 2023). Maintaining a diverse range of crops and species contributes to ecosystem health and provides a variety of nutrient-rich foods (Akano et al., 2023).

2.4.3.3 Impact of CSA on food-nutrition security status: Evidence from Partial Correlation Coefficient (PCC) on the sample primary studies in SSA

The partial correlation coefficient of the impacts of CSA practices adopted on food and nutrition security status is shown in Table 2.7. We took into consideration the average estimations of the correlation derived from the sampled primary studies. The distribution of PCC for the whole sample studies is shown in Figure 2.13 which depicts the observations ranging from -0.17 to 0.41. It is critical to highlight that the mean PCC observed in the sampled research indicates that the impacts of CSA adoption on food and nutrition security status in SSA are highly significant and have lots of potential for improvement and economic implications. Following (Abegaz et al., 2023; Tilahun et al., 2023; Tione et al., 2022; Zhou et al., 2020), the findings suggest that there is a need to concentrate emphasis on investments that would drive SSA agriculture closer to the present threshold to enhance productivity which will improve the food-nutrition security in SSA.

Similarly, the distribution (Figure 2.14) of the reported mean PCC differs throughout the study locations (regions) where the sampled primary studies were conducted. The findings highlight the variation in the strength of the correlation across different regions in SSA. For example, the figure reveals that studies from Southern Africa reported the highest PCC estimations, with a mean score of 0.38, followed by studies from West Africa (0.31), Central Africa (0.24), and Eastern Africa

(0.13). This implies that Southern African regions appear to have the strongest association of CSA adoption with food and nutrition security in SSA. This suggests that the impacts of CSA on households' food and nutrition security may be more significant or better established in Southern Africa compared to the other regions. Furthermore, these findings provide insights into the varying strengths of the correlation and highlight potential differences in the implementation and effectiveness of climate-smart practices in promoting food nutrition and security across the different regions in SSA.

Furthermore, following (Ahmed et al., 2019), we employed an average fixed effect and random effect model to estimate the association between CSA adoption and food-nutrition security, taking into consideration the heterogeneity in the correlation coefficient of the model used in the sampled primary studies. From the studies, the PCC of the association between CSA practices adopted and the food-nutrition security status revealed that the average fixed effect and the random effect as shown in Table 2.7 have the values 0.295, and 0.265, respectively, for the coefficient of determinant. Following (Abegaz et al., 2023; Araujo et al., 2023; Zizinga et al., 2022), the guideline for the interpretation of correlation, this indicates a magnitude that falls somewhere in high (high significant association). These findings imply that the association between the CSA practices adopted and food and nutrition security from the sampled primary studies is high, regardless of the guidelines employed to interpret the data. Following (Awaworyi Churchill & Yew, 2018; Churchill & Mishra, 2018), we further examined whether the coefficient of the association of the relationship differs after the primary studies have been adjusted for publication bias.

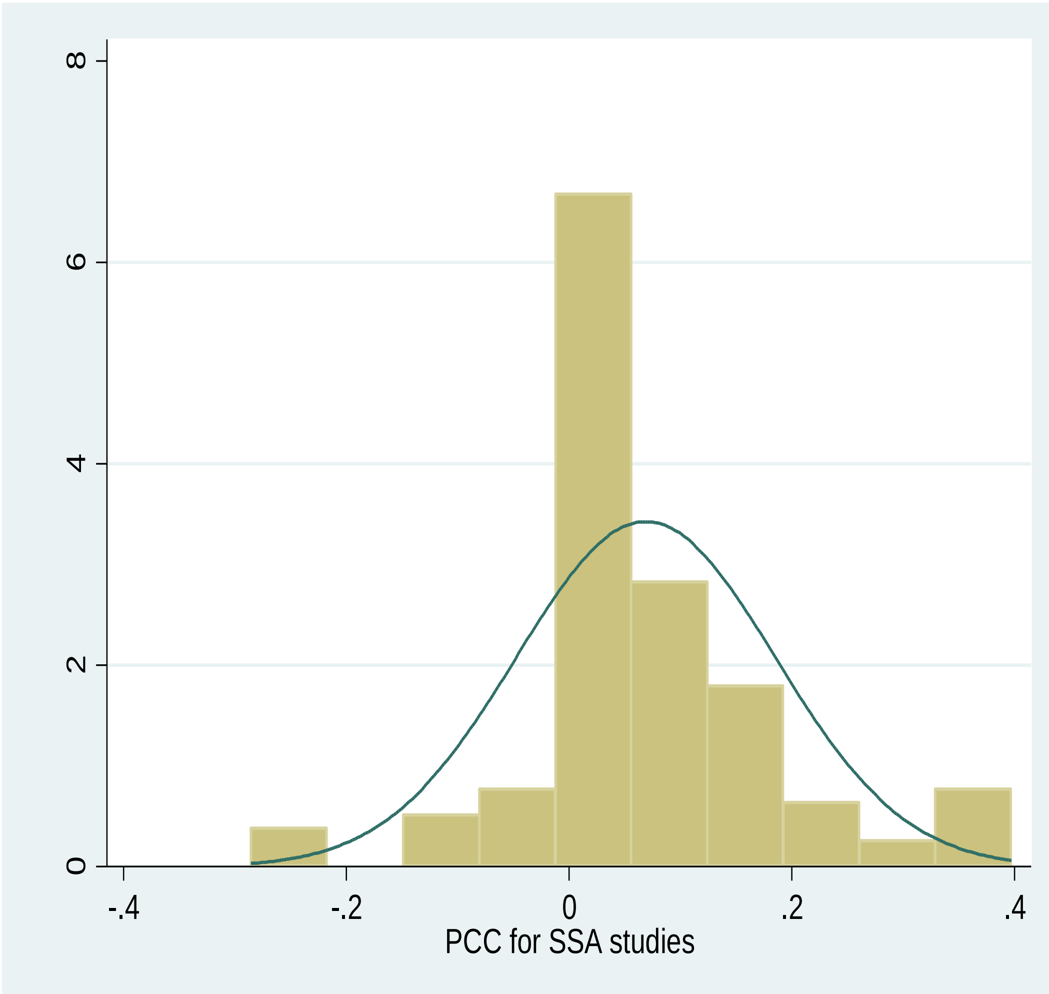

Fig. 2.13. Distribution of mean PCC of the impacts of CSA adopted on food and nutrition security across the whole sample data in SSA

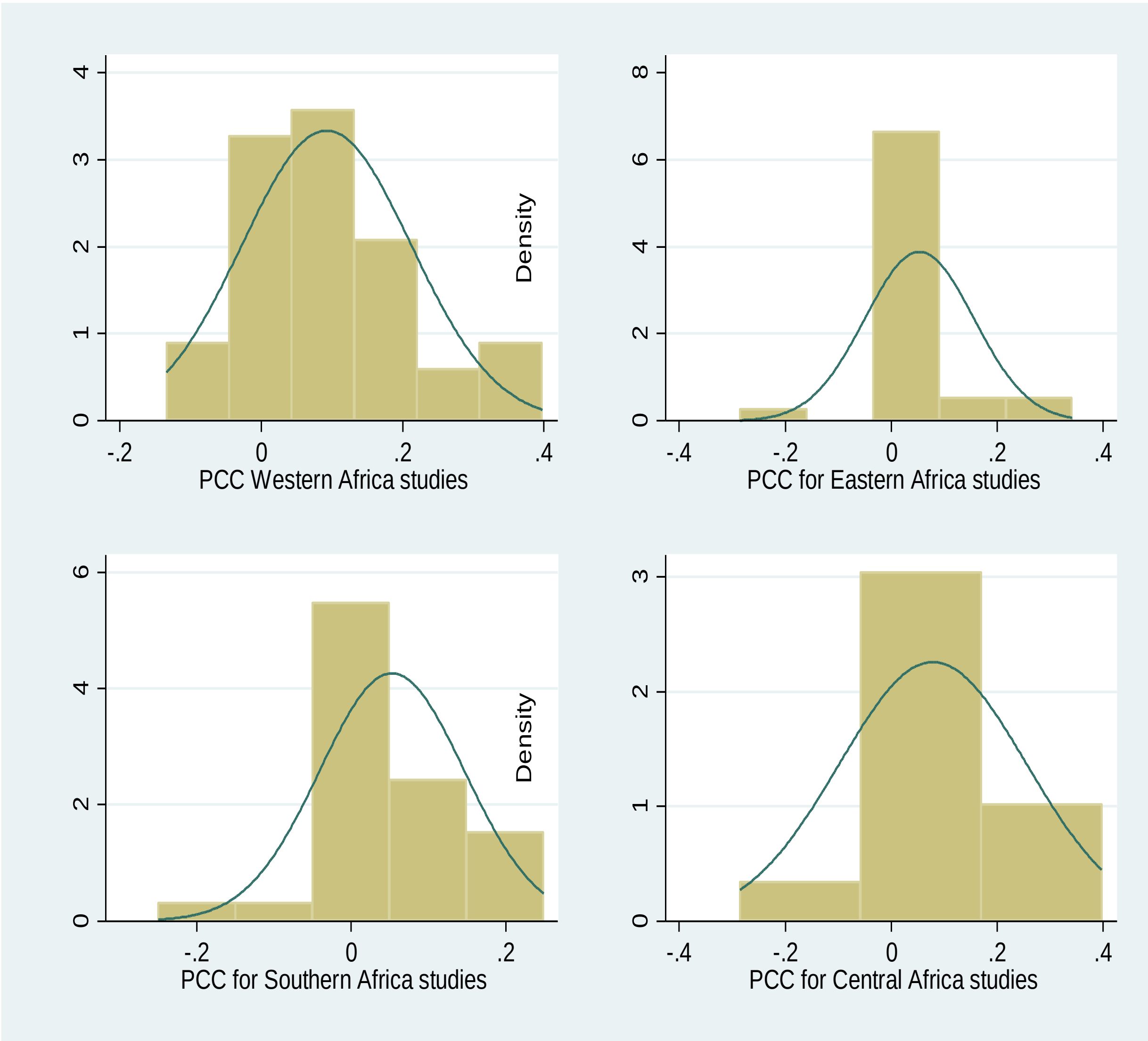

Fig. 2.14. Distribution of mean PCC of the impacts of CSA adopted on food and nutrition security across the whole sample data in the regions of SSA

Table 2.7. PCC for association between CSA practices and food and nutrition security

PCC	Values	95% confidence interval
Average Fixed Effect	0.295	0.0771 – 0.1131
Average Random Effect	0.265	0.1480 – 0.2152

2.4.3.4 Publication bias and genuine empirical effect

The scatter plot (Figures 2.8 and 2.9) revealed the univariate relationship between the PCC (impacts of CSA adopted on households' food and nutrition security in SSA) and the year of survey (year of data) of the sampled primary study. Following (Abegaz et al., 2023; Ogundari & Bolarinwa, 2019), this was done to provide answers to the first and second research questions as well as investigate the publication bias that may have resulted from the sampled primary studies on the impacts of CSA adopted by farmers on their food and nutrition security in SSA over the years. As revealed in Figure 2.15, when interpreted using the fitted line as a reference, demonstrates that there is a positive correlation association between the reported PCC and the year of survey for the whole sample primary studies that are being considered. In addition, we find evidence of linear positive connection in the research conducted in the Western Africa, Eastern Africa, Southern Africa, and Central Africa areas of SSA when the relationship is permitted to vary between the regions as shown in Figure 2.16.

Furthermore, we investigated the likelihood of publication bias in the research using a Funnel plot, Funnel Asymmetry Test-Precision Effect Test (FAT-PET) and Precision Effect Test - Precision Effect Estimate with Standard Errors (PET-PEESE) methods. Following (Awaworyi Churchill & Yew, 2018; Chaikumbung, 2023; Yuan et al., 2020) both FAT-PET and PET-PEESE use a meta-regression technique to measure publication bias mathematically, while the funnel plot evaluates publication bias graphically. According to (Chaikumbung, 2023; Ugur, 2014) publication bias skews the impact of the reported association in the sampled studies, thus causing a serious challenge in determining the genuine effect size of the reported associations.

Following (Ahmed et al., 2019; Egger & Smith, 1998; Ogundari & Bolarinwa, 2018), we first looked for any indications of publication bias in the Funnel plot (Figure 2.17). The PCC value is denoted by the vertical line (Figure 2.17) that extends from both figures and represents its average. The two dashed lines show the 5% threshold of conventional statistical significance level. Following (Chaikumbung, 2023; Ugur, 2014), this signifies that estimates outside these boundaries are statistically significantly different from the effect being measured in the studies. This shows the possibility of publication bias when estimates that are outside the boundary make up more than five percent of the total data in the primary studies examined.

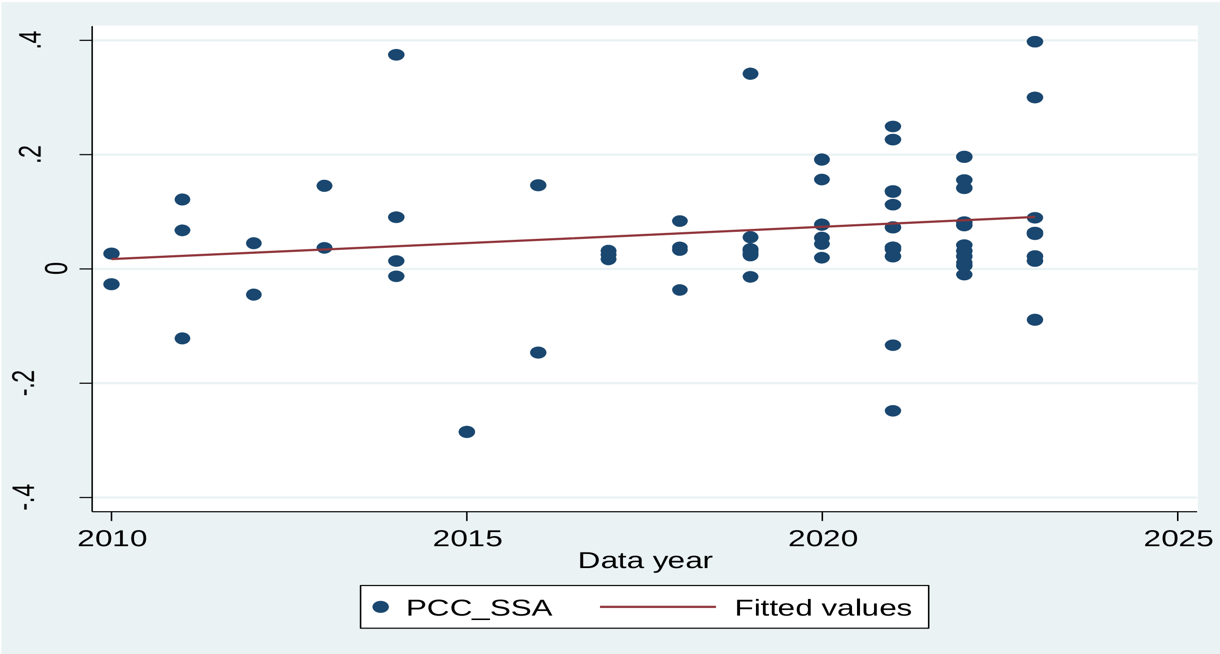

Fig. 2.15. Scatter plot of the univariate relationship between the mean PCC and year of survey for the whole sample primary studies in SSA

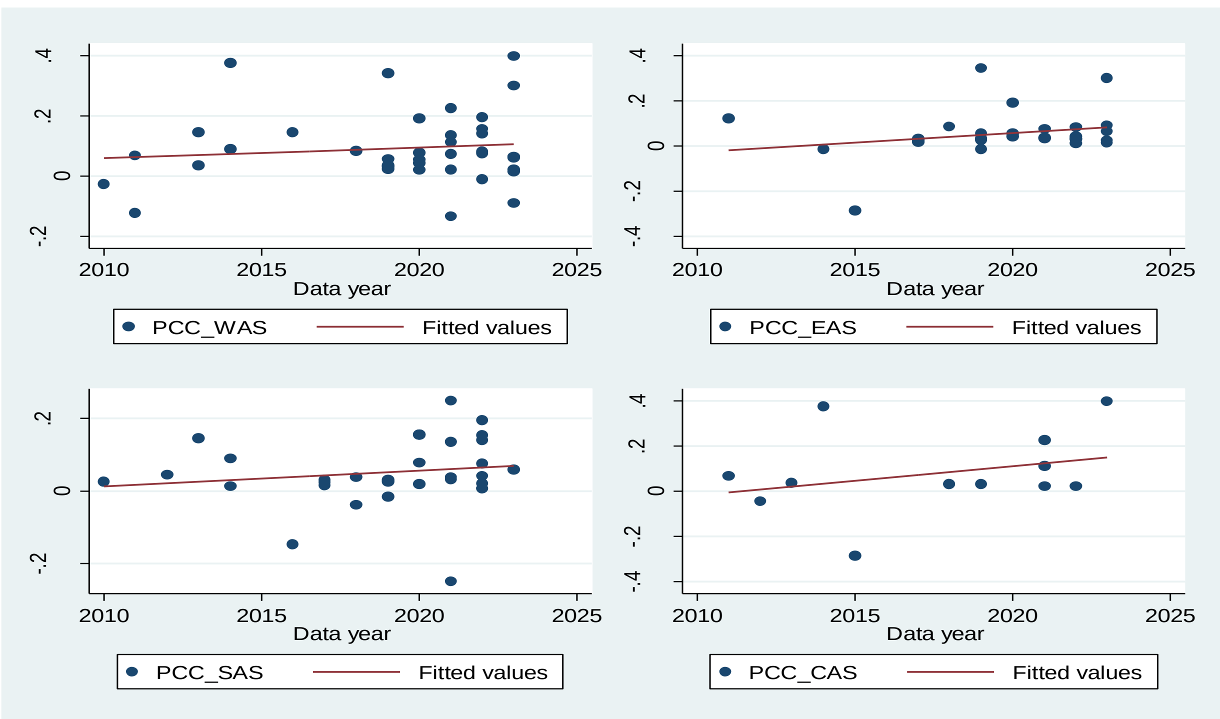

Fig. 2.16. Scatter plot of the univariate relationship between the mean PCC and year of survey for the sample primary studies across the regions in sub-Sahara Africa

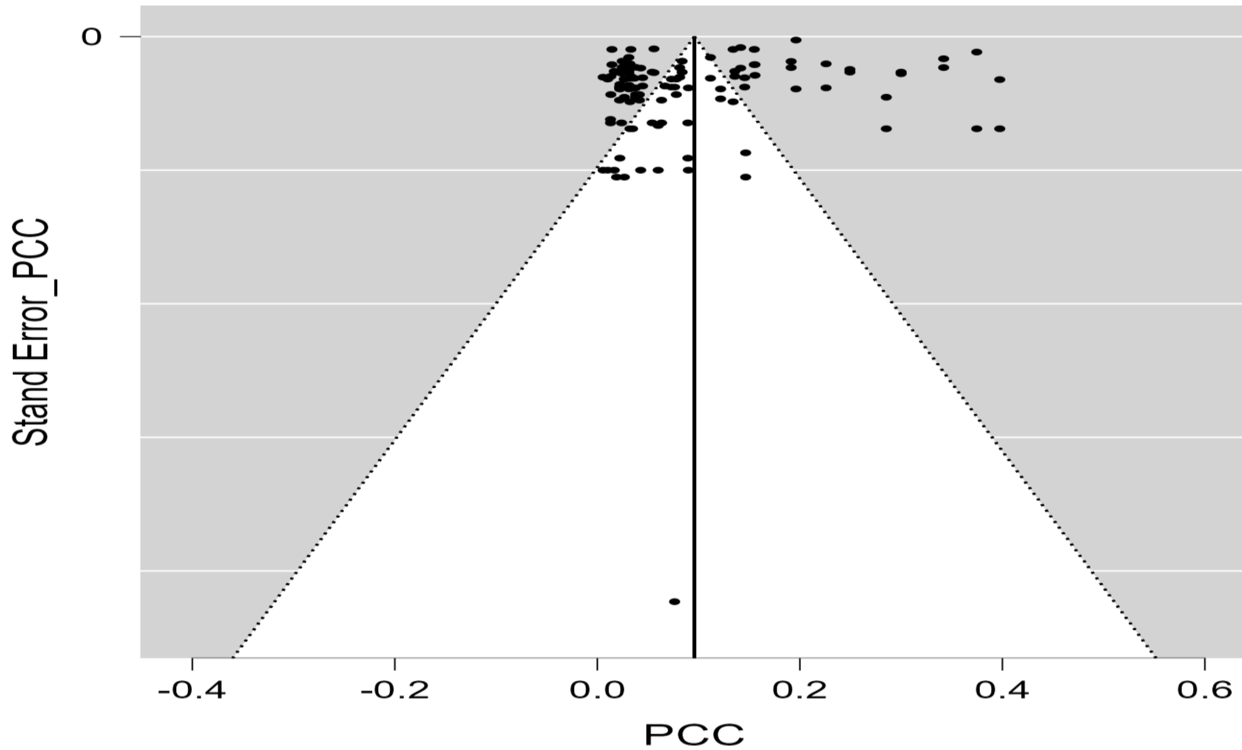

Fig. 2.17. Funnel plot of impacts of CSA adopted on food and nutrition security in SSA evidence from the sampled primary studies in SSA

In line with (Chaikumbung, 2023; Ugur, 2014), the visual assessment of Funnel plot is prone to subjectivity, thus, we evaluated FAT-PET and PET-PEESE MRA as an empirical test to more precisely determine the presence of publication bias. The outcomes are detailed in Table 2.8 which demonstrates that the coefficient of standard error (SE) over all of the possible outcomes has a positive value and is statistically significantly different from zero. This substantiates the findings of the Funnel plot, which therefore demonstrates the existence of publication bias (Yuan et al., 2020). Additionally, the positive coefficient of SE is a hint that the estimated PCC is positively skewed. This suggests that the negative estimations of the effect of CSA practice on food and nutrition security seem to be under-reported in the studies that were sampled. The constant component of the FAT–PET regression model shown in Table 2.8 provides evidence for the presence of a genuine empirical effect and the strength of associations after the publication bias has been accounted for in the sampled studies.

Table 2.8. Estimate Funnel Asymmetry Test and Precision Effect Test (N=114)

	FAT-PET using Weighted Least Square model	
	Estimates	95% confidence
Constant	0.458*** (0.091)	0.0063 – 0.1763
Standard Error (SE)	0.239*** (0.046)	0.0014 – 0.2890

Note: Dependent variable is PCC, where *** denotes a significant estimate at 1% level

Following (Ugur, 2014; Yuan et al., 2020), the findings of the estimated PET-PEESE shown in Table 2.8 offer superior results to substantiate the result of the findings. The first research question of this study (does adoption of CSA practices have any significant impact on food and nutrition security of farmers in SSA) is addressed by the statistical significance of the constant term. Furthermore, the findings (Table 2.9), demonstrated that the coefficients are positive and statistically different from zero. These results provide conclusive proof of the enormous impact of widespread implementation of agricultural innovation (CSA) would have on future outcomes in terms of food and nutrition security. This demonstrates unequivocally that the adoption of CSA practices has a considerable influence on the food and nutrition security of farmers in SSA. Per the parameters established (Egger & Smith, 1998; Ugur, 2014; Yuan et al., 2020) for the interpretation of PCC, the findings (Table 2.9) indicate that the influence of CSA on food and nutrition security seems to be high in SSA.

Table 2.9. Estimate PET-PEESE (N=114)

	Weighted Least Square model	
Constant	0.293*** (0.081)	0.0021 – 0.0105
Standard Error (SE)	0.819*** (0.058)	0.0020 – 0.0641

Note: Dependent variable is PCC, where *** denotes significant estimate at 1% level

2.4.3.5 Impact of study-specific attributes on the variations in the reported estimates of PCC from sampled primary studies

Tables 2.10 and 2.11 revealed the influence of the study attributes on the variations in the reported PCC evidenced from the sampled primary studies' in SSA and across the regions of SSA respectively. From Table 2.10, the data-year coefficient is positive and considerably distinct from zero. This demonstrates that, across the evaluated primary studies, the effect of adopting CSA grows considerably with time. The findings also show that PCC is significantly negatively impacted by using cross-sectional data in comparison to panel data. This suggests that PCC is considerably lower in cross-sectional studies than in panel studies when compared to the kind of data used in the studies. This demonstrates the significance of utilizing panel data to identify unobservable variability when assessing how the implementation of CSAs affects food and nutrition security (Yadav et al., 2019).

The findings demonstrate that the PCC of impacts of CSA adopted on food and nutrition security in SSA from sampled primary studies is much improved when experimental research techniques are used as opposed to nonexperimental approaches. It implies that estimates with the greatest statistically significant effect of CSA adoption on food and nutrition security in SSA are likely to be provided by experimental research approaches that compensate for observable and unobservable selection bias. Regarding the econometric techniques used in the original research, PCC is significantly improved when endogenous switching regression (ESR) and instrumental regression are used instead of ordinary least squares (OLS) and difference-in-difference analysis. As opposed to research that utilizes OLS and DD, this demonstrates that PPC is substantially greater in studies that employ ESR and instrumental regression (Yuan et al., 2020).

Furthermore, the result indicates that research published in journals has a greater impact (PCC) when compared with articles published in conference papers or proceedings while relatively, studies using an experimental design report greater influence on food and nutrition security. The findings of the attributes of the sample primary studies conformed with (Ugur, 2014; Yuan et al., 2020), reported that years of studies, articles published in journals and econometric attributes significantly impacted the PCC of sampled studies. As opined by (Anuga et al., 2022; Tilahun et al., 2023; Tione et al., 2022; Zhou et al., 2020), study locations, agricultural enterprises of the farmers and as well as agricultural innovation (CSA) adopted significantly boost the PCC of sampled primary studies in SSA.

Table 2.10. Meta-regression analysis based of mixed effect model across the sampled studies

Category	Variables	Coefficient	Standard Error
	Constant	0.1425***	0.0531
Years of study	Data years	0.3812***	0.1042
Publication outlets	Journals	0.0923***	0.0239
Types of Data	Cross-sectional data	-0.0725***	0.0225
	Panel data	0.1161	0.2813
Types of CSA	Management of natural resources	0.0371***	0.0121
	Zero tillage	0.5921***	0.1833
	High-yielding varieties	0.7012**	0.1013
	Integrated farming system	0.0147***	0.0061
	Integrated pest management	0.2215*	0.1091
Research design	Experimental method	0.1142**	0.0601
	Non-experimental method	0.0498	0.1237
Methodology	Parametric	-0.8673	0.6792
Econometric methods	Instrumental Regression	0.1678*	0.0880
	Endogenous Switching regression	0.2875***	0.0577
	Difference-in-difference technique	0.0072	0.0221
Agricultural Product	Crop	0.1853***	0.0190
	Livestock	0.0751	0.1782
Region	Western Africa studies	0.2714***	0.1024
	Eastern Africa studies	0.0814	0.0919
	Central Africa studies	0.0543***	0.0202
	Southern Africa studies	0.3076***	0.0101
	N	114	
	Prob.> χ^2	0.000	

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

In addition, the regional segregation (Table 2.11) of the study attributes that contribute to variation in PCC of the impact of CSA adopted on food nutrition security revealed that Southern Africa studies have the highest number of study attributes contributing to variation in PCC of the sample primary data in SSA closely followed by Western Africa studies, then Eastern Africa studies and Central Africa studies. The result revealed that years of the sampled primary studies, the publication outlet of the study (journal), the use of cross-sectional data and the econometric method employed were significant study attributes affecting the variation in PCC of the samples primary studies across the regions. This implies that variations in the estimated PCC are influenced by specific characteristics or factors unique to each study region. The study also buttressed that the studies conducted in Southern Africa have the highest number of such attributes, implying that the research conducted in this region has more diverse characteristics that affect the impacts of CSA on households' food and nutrition security. This conform with (Adesete et al., 2022; Akano et al., 2023), the adoption of CSA practices in Southern Africa is seen as critical for enhancing resilience to climate variability and securing food-nutrition outcomes.

The findings suggest that researchers and policymakers in the Southern Africa region are more actively engaged in investigating the association between CSA and food-nutrition security. This could be due to specific regional priorities, funding availability, or the urgency of addressing climate-related challenges in agriculture (Tione et al., 2022). Notably, the variation in the number of study attributes contributed to differences in the reported correlations and provide insights into the specific factors or variables that influence the relationship between CSA adoption and food nutrition security across different regions in SSA (Tione et al., 2022). Understanding these factors can provide insights into the dynamics shaping research in the field of CSA and food-nutrition security in SSA.

Table 2.11. Meta-regression analysis based of Mixed effect model across sampled primary data in regions of SSA

		Western Africa studies		**Southern Africa studies**		**Eastern Africa studies**		**Central Africa studies**	
Category	Variables	Coefficient	Standard Error	Coefficient	Standard Error	Coefficient	Standard Error	Coefficient	Standard Error
	Constant	0.6721***	0.0421	0.7830***	0.1211	0.9524***	0.2901	0.3568***	0.1157
Years of study	Data years	0.7143***	0.2211	0.4769***	0.1101	-0.1130***	0.0322	0.0871***	0.0259
Publication outlets	Journals	0.1623***	0.0620	0.3372**	0.0996	0.1875*	0.1001	0.1699**	0.0851
Types of Data	Cross-sectional data	-0.1962***	0.0431	-0.0732**	0.0251	0.0432	0.3012	0.0043	0.0103
	Panel data	0.3812	0.2915	0.0360	0.1982	0.1152	0.0883	0.7201	0.8273
Types of CSA	Management of natural resources	0.1931**	0.0521	0.0081***	-0.0022	0.0547**	0.0282	-0.1935	0.2816
	Zero tillage	0.5921	0.4833	0.7125***	0.2193	-0.0662	0.1174	-0.0281	0.1928
	High-yielding varieties	0.2012***	0.0801	0.3045***	0.0924	-0.2339	0.1994	0.1491**	0.0749
	Integrated farming system	0.0964	0.1932	0.0115	0.0391	0.0975	0.1654	0.6934	0.5047
	Integrated pest management	0.2357	0.1845	0.0634***	0.0238	0.0045	0.0391	0.0328	0.1058

Research design	Experimental method	0.0042	0.0091	0.0462***	0.0134	-0.8702***	0.2241	0.0524	0.1120
	Non-experimental method	-0.0313	0.0527	-0.0094	0.0272	0.0734	0.1184	-0.0093	0.0265
Methodology	Parametric	0.0240	0.1904	0.0852	0.2603	-0.1997	0.3212	0.1509	0.2542
Econometric	Instrumental Regression	-0.1645	0.1590	0.0852***	0.0153	0.0640	0.0794	0.1184	0.1647
	Endogenous Switching regression	0.4088**	0.2130	0.0091***	0.0011	0.0982	0.1064	-0.0119	0.2051
	Difference-in-difference technique	0.3726	0.2981	-0.0860	0.1290	-0.0346	0.1645	0.7190	0.2011
Agricultural product	Crop	0.1853***	0.0090	0.5745***	0.1052	-0.1684	0.3244	0.1174	0.0762
	Livestock	0.1721	0.2815	0.0024	0.01052	0.1088	0.3712	0.8921	0.7996
	N	37		25		33		19	
	Prob.> χ^2	0.000		0.000		0.0000		0.0000	

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

2.4.4 Conclusion and policy recommendation

Various research on synergy between CSA practices and food and nutrition security in SSA have been inconsistent, fragmented, or limited in scope. These discrepancies will affect agricultural research funding, regulations, and technology adoption in climate-impacted nations. The research used meta-analysis to explain the variations in PCC estimates of CSA adoption's impact on farmers' food and nutrition security in SSA. We applied meta-regression analysis (MRA) on professionally filtered and peer-reviewed 114 studies from 2001 to 2023 that focused on the influence of CSA adoptions on households' food and nutrition security in SSA. Given the nature of the research, our investigation involved searching for indications of publication bias in the selected primary studies. Additionally, we sought compelling empirical evidence demonstrating the significant influence of study-specific attributes on the study's outcomes. The summary results reveal a bias towards CSA practices that favour high-yielding cultivars and crop diversification, while overlooking other viable alternatives such as zero tillage, mulching, integrated farming, and integrated pest management, which could potentially complement them. The univariate MRA shows that CSA has a significant influence on the food and nutrition security of the farmers' measures in the sampled primary studies. The extent or magnitude of the association is high and hence strong. The MRA and funnel plot show some indication of publication bias in the sample primary studies. The multivariate MRA results emphasize the importance of study attributes such as publication outlets, year of study, econometric approaches, CSA adopted, and regional differences in explaining variations in the estimated PCC. In addition, Southern Africa has the highest study-specific attributes and PCC estimates, which denotes that impacts of CSA on food and nutrition security is highest in the region than other regions of SSA. This may be attributed to high level of adoption of CSA in this region. As a consequence, the findings of our study will be highly valuable to researchers in identifying study-specific variables necessary for predicting the influence of CSA on farmers' food and nutrition security for future research in SSA. It might also be used as a reference in assessing the sensitivity of their findings in terms of model design and technique selection. The study will improve our knowledge of agricultural innovation and technology adoption, therefore enhancing the chance of meaningful policy analysis.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter is an overview of the general research design used in the study. It details the research design, study area and population, sample size and analytical techniques employed to achieve the stated objectives of the research.

Table 3.1. Study objectives and methods

Objectives		Methods
1	Profile climate change trends, impact on agriculture and contribution of agriculture to GHGs emission in SSA	Presented in manuscripts 1, 2 and 3 in Chapter 2
2	Determine the impacts of climate change adaptation strategies on the productivity of smallholder maize farmers in South Africa	a. Questionnaire survey: 316 farmers b. Analysis: ESRM, NBRM and MVP[5] c. Presented in manuscript 4
3	Examine the impacts of the adoptions of CSA practices on productivity and welfare outcomes of smallholder maize farmers in South Africa	a. Questionnaire survey: 316 farmers b. Analysis: MESR, OLS, ATT and PSM[6] c. Presented in manuscript 5
4	Analyze the effects of CSA adoptions on food and nutrition security of smallholder maize farmers in South Africa	a. Questionnaire survey: 316 farmers b. Analysis: HFIAS and HDDS[7] c. Presented in manuscript 6.

3.2 Research design

A research design is used to structure the study and to display significant components of the research, such as sample size, action protocols, and techniques for answering the central research questions (Sorgho et al., 2020). According to Kangogo et al. (2021), the use of an appropriate research design as a framework, enables the researcher to ask the right questions to the relevant participant, who provide appropriate responses to address the key issue. The formulation of a research strategy is crucial for the successful completion of any academic project. According to Sorgho et al. (2020), a research design is intended to effectively structure the research process in order to enhance the overall validity of the results obtained.

[5] MVP = multivariate probit regression; ESRM = endogenous switching regression model; NBRM = negative binomial regression model
[6] PSM = propensity score margin; MESR = multinomial endogenous switching regression model; OLS = Ordinary least square regression; ATT = average treatment effect on treatment
[7] HFIAS = household's food insecurity access score; HDDS = household's dietary diversity score

3.3 Study area

The study was carried out in the North-West Province, one of nine in South Africa, adjoining Botswana to its north, Namibia to the west, Gauteng Province to the each and the by Free State province to the South. North-West Province was established in 1994, has a land mass of 106,512 square km, which makes it the fourth smallest province in South Africa at 8.7% (Stats SA, 2017). North-West province (Figure 3.1) has been consistently ranked (third) among the top provinces in South Africa for maize cultivation due to its favorable agro climatic conditions, including fertile soils and human capital, which make it suitable for maize production (Ricart et al., 2023). Notably, maize production contributes significantly to the province's economy and livelihoods of the dwellers. Unfortunately, the consistence rises in temperature coupled with epileptic rainfall due to climate change have influence the ecological balance and biodiversity in the province, thus, impacting maize productivity in the area.

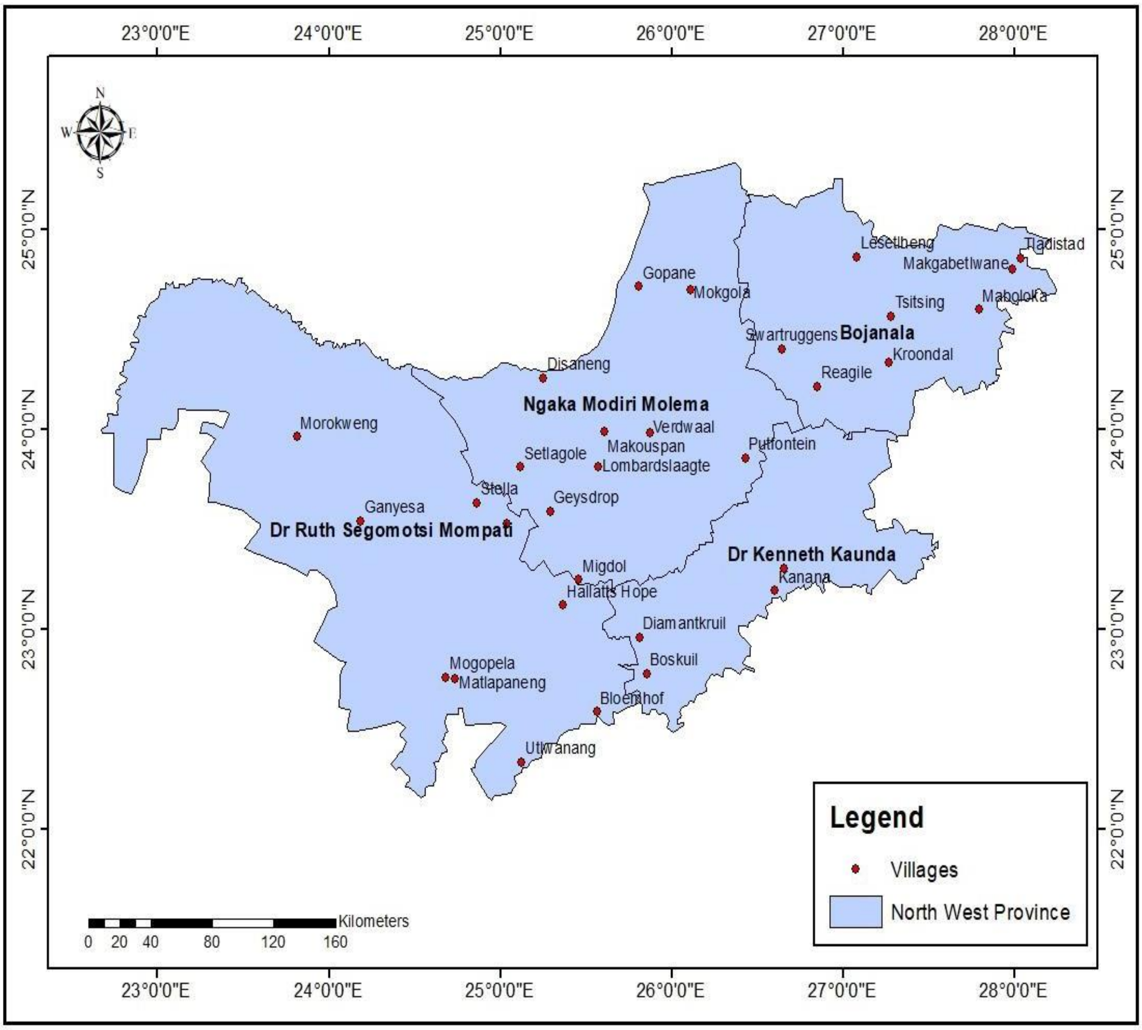

Fig. 3.1. District and municipal boundaries of North-West Province

Mahikeng is the capital city, with more than 80% economic activity in the province being concentrated in the southern region between Potchefstroom and Klerksdorp, as well as in the Rustenburg and the eastern region. Mining is the major contributor to the North-West Province economy, followed by farming activities, with maize being the main crop. North-West Province (Table 3.2) consists of four districts: Bojanala District Municipality, Ngaka Modiri Molema Municipality, Dr Kenneth Kaunda District Municipality and Dr Ruth Segomotsi Mompati District Municipality. The districts are further divided into 18 local municipalities, the study being undertaken in selected villages in these local municipalities.

Table 3.2. Description of North-West Province, South Africa

Description	Units
Area	28,206.08 Km^2
Population	842,699 (29.88 per Km^2)
Racial composition	Black Africa (94%)
	White (4%)
	Coloured (2%)
Languages	First language -Setswana (82%)
	Afrikaans (5%)
	English (3%)
	Other languages (10%)
Gender	Male (49%)
	Female (51%)

3.4 Study population

Study population is a total set of groups or individuals to whom the findings of the survey are extrapolated. South Africa has a diverse agricultural landscape with different regions, crops, and farming practices. The population of this study comprise of all the smallholder maize farmers in North-West Province, South Africa. Smallholder maize farmers are characterized by small volumes of output cultivated on less than 10 hectares of land (Sorgho et al. 2020). They represent a substantial portion of the agricultural community in South Africa, contributing significantly to food production, rural livelihoods, and the overall economy of the nation. Smallholder farmers often face various vulnerabilities, including limited access to resources, market challenges, and climate-related risks. Understanding these challenges and identify strategies to mitigate vulnerabilities will form integral part of rural development and the broader South African economy.

3.5 Sampling procedures and sample size

A multistage sampling technique was used to select maize farmers from the study area that consisted of five stages. Stage 1 entailed selecting North-West Province out of the nine provinces in South Africa as they contributed approximately 15% of total South Africa's maize and are the third highest maize production province in SA (Akanbi et al., 2021a). Stage 2 involved selecting all the municipalities in which smallholder farmers produced maize (Bojanala District Municipality, Ngaka Modiri Molema Municipality, Dr. Kenneth Kaunda District Municipality and Dr Ruth Segomotsi Mompati District Municipality) in the province to ensure data representativeness. Stage 3 entailed purposively selecting two villages known for maize farming from each of the 18 local municipality (total of 36 villages), while Stage 4 entailed the random selection of one-third of the identified villages within the local municipality (totaling 12 villages). Stage 5 involved proportionate sampling to size in order to select the respondents from the list of smallholder maize farmers based on the data from the Department of Rural Development, which resulted in 316 smallholder maize farmers being randomly selected for invitation to participate in this study.

3.6 Data collection methods

Data was collected via a field survey of the smallholder maize farmers in the North-West using individual interviews through a questionnaire survey of 316 farmers. A questionnaire was developed in English that consisted of questions that related to the following seven sections:

A. socio-economic characteristics of the households: ages, genders, education, household size, farming experience and race.
B. land characteristics: farm size for maize cultivation, total farm size for cultivating other food crops and land tenure system.
C. climate-smart agricultural practices: drought-tolerant maize varieties, organic manure, mulching, soil and water conservation, crop rotation and diversification.
D. households' vulnerability measure: amount spent of food consumption in households and source of drinking water.
E. climate change and livelihood: perceived rainfall, temperature and humidity.
F. production output of the smallholder maize farmers: quantity of maize produce and cost of production such as seeds, labour and fertilizer cost.
G. food consumption pattern and quantity consumed by the smallholder farmer: How many times do they eat in a day and class of food does the household spend the most on.

Each questionnaire was allocated a unique ID based on municipality and village to enable the data to be mapped, with neither the participants' names or those of their farms being recorded.

3.7 Data collection process

Once ethical approval had been obtained to conduct the study, permission was obtained from the North-West Provincial Department of Agriculture to conduct the study with their staff and at their offices. Furthermore, permission to collect data was obtained from each local municipal manager where the research was conducted. The data were collected by extension officers working in North-West province. Four extension officials who were fluent in the local dialect and had knowledge of the local traditions and customs were trained to undertake the surveys, as they visited the farms as part of the work and therefore know the farmers. The farmers were informed about the study Aim and required to sign an informed consent form before they were interviewed, after which they completed the survey in face-to-face interviews with the extension officers, if they were18 years of age or older, understood the content, and accepted their role of participating in the survey.

3.8 Validity and reliability

Before starting data collection, the questionnaires were pre-tested to ensure the validity of the data with the help of the four trained extension officers. A pilot study was carried out in 4 different municipalities before data collection to ensure the adequacy of the research instruments and to assess if the research protocol was realistic and workable. The questionnaire was tested, as were the pre-designed questions for the face-to-face interviews, with minor modifications being made to both instruments before the main study was undertaken. Questions that seem to overlap and were ambiguous during the questionnaire pre- testing were deleted or modified to ensure clarity. The reliability of the instrument was determined through half technique coefficient (0.75), which denotes the goodness of fit of the instrument.

3.9 Data Analysis methods

The methods used to analyze the data collected are as follows:

a. Questionnaire survey: the qualitative data were analyzed using descriptive statistics to provide the demographic context of the participants. While inferential statistic revealed the significant relationship between the adopted CSA practices, productivity and food security of the smallholder farmers.

b. Observational checklist: ensures that content-specific information is collected in a structured and consistent manner, making them particularly useful in this research contexts.

c. Content analysis consisted of the following:

    i. triangulation: explored the impacts of the perceptions of smallholder maize farmers about climate and access to climate information on the adoption intensity of CSA.

    ii. complementarity: reveals the complementary relationships among the adopted CSA and how they are being influenced by the institutional factors, socio-economic and farm variables of the sampled smallholder maize farmers.

To undertake the statistical analysis of data collected, the Statistical Package for the Social Science (SPSS version 30.0, 2022) and STATA 16 software were used to run the empirical data analysis, as presented in Table 3.3.

Ethical consideration

The Ethics Committee of the Faculty of Natural and Agricultural Sciences, North-West University, South Africa, provided ethical clearance (NWU-01267-23-A9) for the study. Prior to the distribution of questionnaires in the research areas, the Department of Rural, Environment and Agricultural Development, NW, South Africa, granted the researchers authorization to visit the study area. The researchers and participants in this study took great care to uphold the principles of privacy, autonomy, dignity, as well as respect through the following steps;

- Informed consents were obtained from the participant clearly explaining the purpose, procedure and benefit of the research.
- Clear communication on how research data will be used, stored and shared, including any potential publication of results. Provided clear and understandable information about the research process and its implications to help participants make informed decisions.
- Respect participants' autonomy by allowing them to make decisions regarding their involvement in the study.
- Giving the participants the opportunity to choose their level of involvement in the research, including whether they wish to be contacted for follow-up.

- Safeguard participants' personal and sensitive information by use coding or anonymization techniques to protect their identities.

3.10 Conclusion

A well-crafted research methodology is the backbone of a research study. It guides the entire research process, from data collection to analysis and interpretation. Consequently, the research methodology adopted in the study involved a critical step in addressing the complex and pressing challenges of our time in term of adaptation to climate change by smallholder farmers in South Africa. By employing a mixed-methods approach, ensuring ethical conduct, and considering the long-term implications, this research can contribute valuable insights to the fields of agriculture, environmental science, and food security. Moreover, it can inform policies and interventions that aim to enhance the resilience and well-being of smallholder farmers in the face of climate change. The methodology's strength adopted in the study lies in its ability to quantify relationships and identify significant variables (Table 3.3), executed with precision, adheres to best practices, and is transparency in its reporting. This contributes to the evidence base for informed decision-making and policy development, ultimately aiming to enhance the well-being of smallholder farmers in the context of climate change and food security.

Table 3.3. Summary of data analysis methods used to achieve the objectives of the study

S/N	Objectives	Data Analysis	Reason for choice of analysis
1	Profile climate change trends and impact on agriculture and contribution of agriculture to GHGs emission in SSA **Manuscript 1, 2 and 3**	Systematic literature review and Meta-regression analysis	The providing a comprehensive, evidence-based, and quantitative assessment of the existing research of climate change trends in SSA and the contributions of agriculture to GHGs emission, which can inform policies, strategies, and actions to address one of the most significant challenges of our time
2.	Determine the impacts of climate change adaptation strategies (CCAS) on productivity of smallholder maize farmers in South Africa **Manuscript 4**	Multivariate Probit regression model (MVP)	To capture the potential complementarities among the CCAS most frequently adopted by the smallholder farmers
		Endogenous switching regression model (ESRM)	To determine the farmer's decision to implement at least 1 adaptation technique in response to the change, and the impact of adoption on their productivity
		Negative Binomial Regression Model	To estimate the determinants of the intensity of adoption of CCAS, where the dependent variable is a count variable, measured as number of CCAS adopted
3.	Examine the impacts of simultaneous adoptions of CSA on productivity and welfare outcomes of smallholder maize farmers in South Africa **Manuscript 5**	Multinomial Endogenous Switching Regression (MESR)	Due to farmers' endogenous self-selection into adoption and non- adoption categories, it is possible for there to be bias owing to observable and unobserved factors. Used to measure the determinants of simultaneous adoption of CSA
		Ordinary Least Squares regression (OLS)	Combined with a selectivity correction term that was produced from the first stage of MESR, used to determine association between the outcome variables (productivity, per capita total household expenditure) and per capita household expenditure on food
		Average Treatment Effects (ATT)	To determine the impacts of combinatory adoptions of CSA on outcome variables

		Propensity-score matching estimation (PSM)	To solve the endogeneity problem, PSM was used to assessed the counterfactual and real impacts of adoption combination of CSA on outcome variables
4.	Analyze the effects of CSA adoptions on food and nutrition security (FNS) of smallholder maize farmers South Africa **Manuscript 6**	Household Food Insecurity Access Score (HFIAS)	HFIAS is a scale that quantifies and summarizes distinct behavioural and psychological dimensions of food insecurity (access). Household with no reported food insecurity receives a minimum score of 0 (better food access). Food-insecure household with a high frequency of ingesting less preferred foods or foregoing meals due to inadequate access to food receive a maximal score of 27
		household dietary diversity score (HDDS)	To measure the dietary-quality of the households such as food consumed by a household over the course of a week were classified into twelve distinct food categories
		Endogenous switching regression model (ESRM)	To estimate the relationship between CSA and FNS

3.11 Summary statistics of variables used in the models

Table 3.4 revealed the socioeconomic characteristics of smallholder maize farmers used in the models. Analyzing the socioeconomic characteristics of smallholder maize farmers in South Africa is vital for designing effective, targeted interventions, policies, and support systems that can improve the livelihoods of this group, promote sustainable agriculture, and address poverty and food security challenges. It is an essential step in ensuring that agricultural development efforts have a positive and lasting impact on the lives of these farmers and the broader society.

Table 3.4. Socio-economic characteristics of smallholder farmers

Variables	Descriptions	Mean	Std. Dev.
Gender	If HH is male= (1), if female= (0)	0.62	0.51
Age	Actual household head's age in years	44.69	15.82
Educational level	(1) formal education, (0) = non-formal	0.76	0.42
Farming experience	Years of maize farming experience	6.71	3.17
Marital status	If HH is married= (1), otherwise= (0)	0.73	0.48
Main occupation	(1) if HH's main occupation is farming, (0) if otherwise	0.84	0.35
Off-farm income	Income from livestock sale and other Activities	0.56	0.32
Household size	Number of people in household	4.15	2.17
Farm size	Total land cultivated (in hectares)	3.26	1.18
Extension contacts	(1) if HH has access, (0) if otherwise	0.72	0.47
Membership of Organization	(1) if HH is a member of any organization; (0) if otherwise	0.61	0.42
Credit source	(1) if HH has access, (0) if otherwise	0.68	0.56
Climate information			
Smartphone	(1) if HH receives climate info through smartphone, (0) if otherwise	0.72	0.39
Radio	(1) if HH receives climate info through Radio, (0) if otherwise	0.81	0.31
Community meeting	(1) if HH receives climate info through community meetings, (0) if otherwise	0.69	0.28
Flyers/Posters	(1) if HH receives climate info through flyers/posters (0) if otherwise	0.71	0.33
Local newspaper	(1) if HH receives climate info through newspaper, community bulletins, (0) if Otherwise	0.58	0.25
Extension training	If yes= (1), otherwise= (0) (Dummy)	0.71	0.34

Chapter 4: Manuscript 4

This chapter addressed Objective 2, that being to determine the impacts of climate change adaptation strategies on the productivity of smallholder maize farmers in North-West Province, South Africa. It is presented in manuscript format, having been prepared and submitted to the Journal of Ecological Economics, entitled: Unravelling the complimentary interactions between climate change adaption strategies and smallholder maize (Zea mays L.) farmer's productivity.

Unravelling the complimentary interactions between climate change adaption strategies and smallholder maize (Zea mays L.) farmers' productivity

Abstract

Climate change impacts are increasing over time, severely affecting some farming households and resulting in socio-economic problems such as hunger, low productivity and reduced incomes. This paper examines the complementary relationships between the adopted climate change adaptation strategies (CCAS) and the intensity of their adoption by smallholder maize *(Zea mays L.)* farmers in South Africa. A multistage sampling technique was adopted to select smallholder maize farmers across 30 villages in South Africa. Data were analyzed through descriptive and inferential statistics (Multivariate probit regression (MVP), Endogenous Switching Regression Model (ESRM), and Negative Binomial Regression Model (NBRM)). The results show that the majority (73%) of household heads were married, had a mean age of 44.69 years, a farm size of 3.26 hectares and household size of four individuals. The MVP modelled the complementarity among the adopted CCAS and the determinants of the strategies adopted, while the ESRM estimated the effect of CCAS on the productivity of the smallholder maize farmers. The ESRM showed that the CCAS have a significant impact on their net farm income. The complementary relationships between the multiple CCAS adopted by smallholder maize farmers were influenced by institutional factors, socio-economic attributes and other farm variables. Thus, it was recommended that policies and investment strategies tailored towards improving these identified factors are perused to ensure increased maize productivity in South Africa among smallholder farmers.

Keywords: Agriculture; Climate change; Food policy; Institutional factors; Socio-economics; Sustainability

4.1 Introduction

The global agricultural production system is facing serious constraints in meeting the increasing food demands and raw material supplies for industries owing to various factors (Paul et al., 2018). The relevant contributing factors are linked to social, political, economic as well as environmental problems, among which is climate change (Adesete et al., 2022; Thierfelder et al., 2017). Climate change is an important issue affecting the world, having been recognized as the most important environmental risk of the 21st century (Kangogo et al., 2021). It affects food production system directly in several ways, resulting in reduced staple food productivity and the death of livestock, and indirectly through fluctuation in food prices and market supply (Aggarwal et al., 2018; Branca et al., 2011; Omotoso et al., 2022).

The impacts of climate change on agricultural productivity depend on a combination of interacting factors, including the timing of extreme weather events, which are anticipated to become more prevalent in the immediate future (Akpan & Zikos, 2023; Barbon et al., 2022). Consequently, climate change is becoming an increasingly important threat, not only to the sustainable growth in agricultural activities globally, but also to human existence (Daud et al., 2018; Omotoso et al., 2022; Onyeneke, 2021). Considerable changes in rainfall and weather patterns, as well as rising temperatures, have led to adverse growth conditions in planting calendars and changing growing seasons, thereby severely impacting agricultural production (Mullins et al., 2018). These changes are affecting farm productivity, food security and agricultural food prices, land-use, and therefore uncertainties in farming households' livelihoods (Akpan & Zikos, 2023; Batisani et al., 2021).

In South Africa, maize is cultivated under diverse environmental conditions, this being the country's most important grain crop (Zizinga et al., 2022; Zografos et al., 2016). Its production is dependent on the appropriate use of inputs that will ensure a sustainable agricultural output (Clay & King, 2019; Galani et al., 2022). These inputs include appropriate soil tillage methods, proper plant populations, robust cultivars, the application of fertilizers, weeding, pest and disease management, harvesting, marketing and financial resources (Akano et al., 2023; Maindi et al., 2020). Approximately eight million tons of maize grain are produced annually in South Africa on an estimated three million hectares of land (Maindi et al., 2020; Mullins et al., 2018). Of this tonnage, 50% consists of white maize, which is grown for human consumption and requires around

450 - 600mm of water each growing season, primarily taken from the soil moisture content (Abegaz et al., 2023; Nantongo et al., 2023; Zizinga et al., 2022). Each millimetre of water used results in the production of approximately 16 kg of maize grains, which at maturity results in more pressure on the soil moisture contents (Abegunde et al., 2022; Galani et al., 2022).

The adverse impacts of climate change on maize output are influenced by agricultural adaptations, farmer investment decisions and appropriate policy recommendation (Abegaz et al., 2023; Fisher & Dodman, 2019; Galani et al., 2022). Being interrelated, these factors can have a detrimental impact on farming productivity if not well managed (Thothela et al., 2021; Traore et al., 2021). Various indicators of climate change, such as irregular rainfall, severe temperature stress, prolonged droughts, as well as flooding and temperature change, have been reported in the empirical literature, and shown to have varying impacts on South Africa's smallholder maize farming (Jennings et al., 2022). These farmers can directly perceive the effects of climate change on their enterprises, although the level of impact varies according to their respective outputs and adaptation strategies (Abegaz et al., 2023; Fisher & Dodman, 2019; Fusco et al., 2020).

To achieve sustainable output levels, smallholder maize farmers need to adopt various adaptation techniques to cope with the threats to their productivity posed by climate change (Gomes et al., 2020; Gram et al., 2020). There are several types of adaptation techniques, the individual farmer's own unique perception of climate change determining the type and extent of the methods that they choose to implement (Adego & Woldie, 2022). Farm-level adaptations to climate change can take many forms, including agroforestry, soil water conservation, crop management modifications and effective land-use management practices, such as crop diversification, mulching and irrigation (Abegaz et al., 2023; Batisani et al., 2021; Branca et al., 2013).

Identifying the complementary relationships among the adopted climate change adaptation strategies, as well as understanding the dynamics of the adaptation decisions of the smallholder maize farmers is therefore essential to sustain productivity in South Africa, especially in the North West province, which remains a key hub of maize production in the country. Most smallholder maize farmers in North-West Province have the potential to generate incomes from their maize production, but the deleterious effects of climate change currently posing severe influence on the productivity (Atta-Aidoo et al., 2022; Mullins et al., 2018).

There is a need for a deeper understanding of farmers' adoption behaviour of CCAS in order to advocate for policies that would encourage their uptake. This research will be the first attempt to identify the predictors of the adoption of multiple CCAS in South Africa in the context of the interactions between several socio-economic, institutional and farm factors in a national agricultural setting that is both complex and diverse. This is within the context of acknowledging the complementarity between the various CCAS considered, the determinant of the methods adopted by smallholder maize farming households and its impact on their productivity. This is essential for promoting effective policies to redefine the CCAS adoption strategies for agricultural innovations that will ensure sustainable agricultural practices in rural South Africa.

This requires investigating the likelihood of adoption of CCAS as well as the intensity of their uptake, with variations in agricultural and livelihood contexts of smallholder farmers in the study area resulting in their doing so differently. The findings emanating from this study will assist in identifying the restrictions associated with CCAS adoptions and maize production in order to design programmes and initiatives that would facilitate the successful implementation of policies that are necessary for addressing South Africa's maize and agricultural staple crops production challenges.

4.2 Context and related literature: climate change and maize farming in South Africa

Parts of the Southern African Development Communities (SADC) have been negatively affected by severe environmental and climatic conditions that have implication for their agri-food systems (Traore et al., 2021; Yu et al., 2019). The rising temperatures have negatively affected the agricultural activities of the region, while heavy rainfall in some areas has resulted in the flooding of both land surfaces and water bodies (Kombat et al., 2021; Leisner, 2020). South Africa, as a nation within this region, is among the most environmentally challenged countries (Mutengwa et al., 2023; Ngoma, 2018), due to a large proportion of the country being semi-arid and experiencing low annual rainfall (464mm) (Figure 4.1) relative to the world average of 990mm, with the predicted variations in precipitation having an adverse effect on the South Africa's food production system (Regmi et al., 2022).

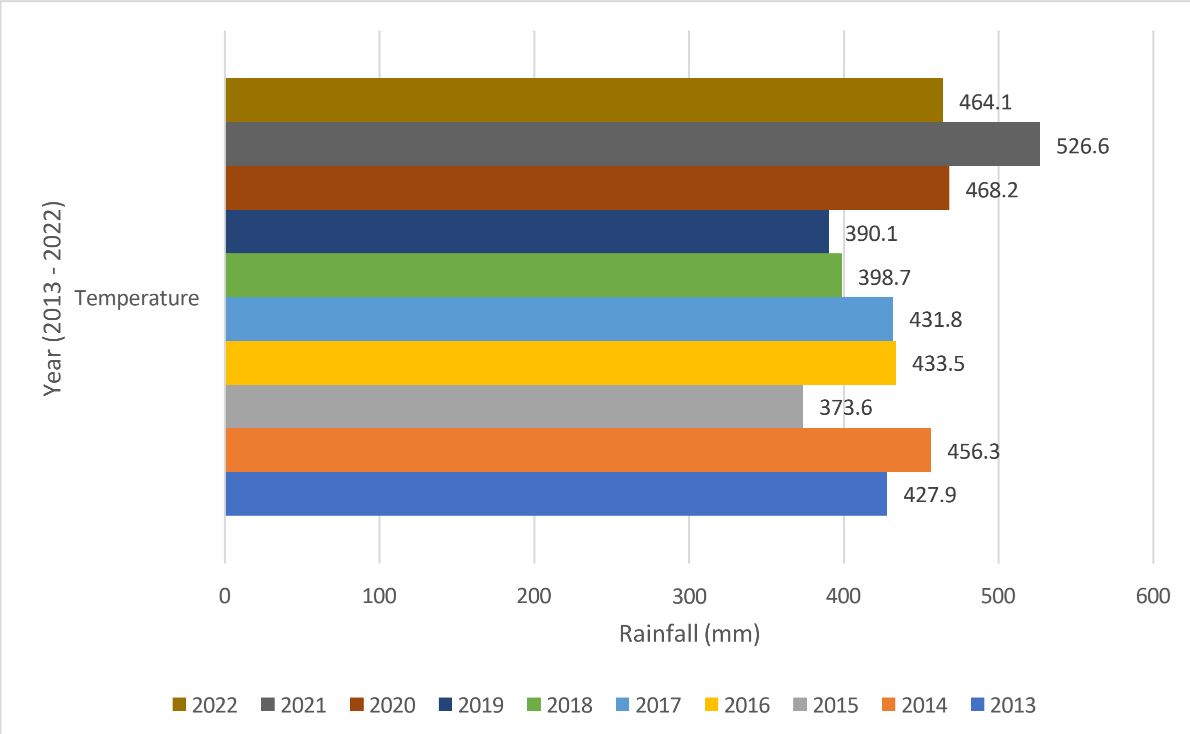

Fig. 4.1. Annual rainfall in South Africa from 2013-2022 [Adapted from (Galani et al., 2022)]

Despite the environmental challenges, maize farming (Figure 4.2) in South Africa remains the backbone for the majority of the rural smallholder households (Kumar et al., 2018). It contributes approximately 80% of the total grain produced nationwide, covers an estimated 65% of the cropping land area, and plays a central role in income generation and employment opportunities (Catherine *et al.* 2022). Although maize plants easily adapt to adverse conditions, the prolonged lower precipitation and drier climate will have negative impacts on productivity in the long-term (Oguge & Oremo, 2017; Onyeneke, 2021). Various authors (Abegaz et al., 2023; Rosenstock et al., 2019; Zografos et al., 2016) contend that due to a recent drought, South Africa had to import 934,000 metric tons of yellow maize from Argentina and Ukraine between 2015 and the end of March 2016 at $138 million.

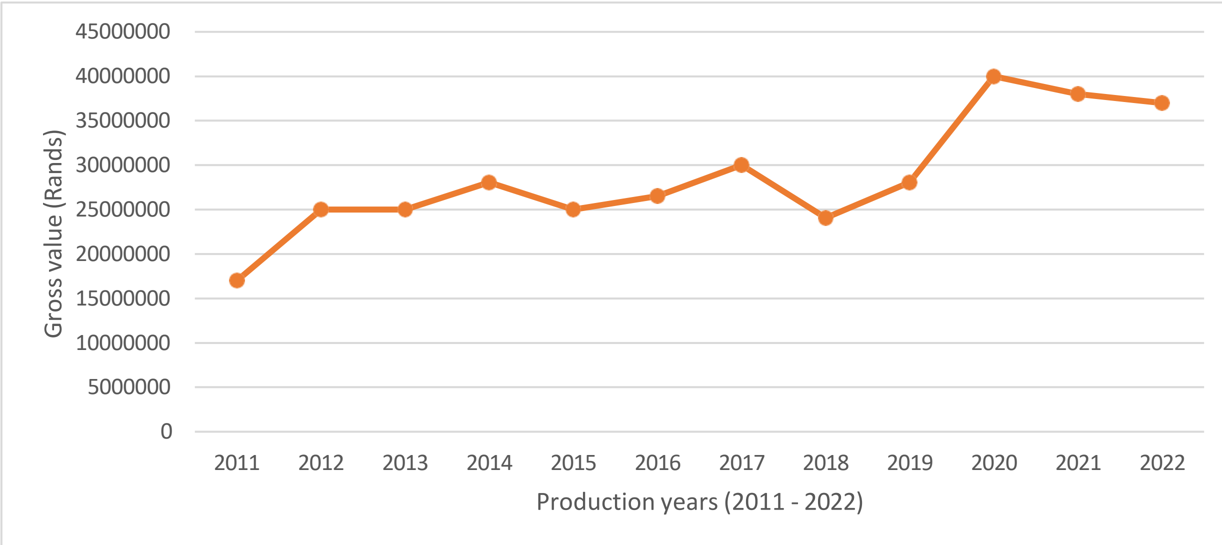

Fig. 4.2. Gross Value of Maize production in South Africa [adapted from Ramoroka & Muchopa, 2022]

The consequences of climate change have had an impact on Africa's rain-fed agricultural, particularly in economically and technologically underdeveloped countries (Abegaz et al., 2023; Clay & King, 2019), this being the main form of agriculture practiced by the smallholder maize farmers in developing nations, such as South Africa. This can be attributed to the inadequate rainfall and high temperature conditions (unsatisfactory climatic conditions), and the poor irrigation facilities of this vulnerable farmers (Abegaz et al., 2023; Rosenstock et al., 2019; Saj et al., 2017).

Rosenstock et al. (2019) noted that the vulnerability of smallholder farmers in South Africa, especially in the North West Province, is increasing due to their limited adaptive capacity and low level of economic development. As a result, smallholder maize farmers in this province are struggling to mitigate the impacts of climate change due to the limited services offered by weak institutions, their meagre sources of income, ineffective extension services and cooperative societies, as well as inadequate infrastructure and markets (Abegaz et al., 2023; Osinubi & Apanisile, 2021; Regmi et al., 2022). Thus, the farmer's reliance on rainfall increases their susceptibility to climate change impacts, highlighting the need for timely and conscious coping decisions (Akter et al., 2023). These farmers in North West Province are now faced with the choice of either falling casualty to adverse climate change impacts on their productivity levels or adapting to the impacts of climate change through the various adaptation measures available to them. In doing this, they can become agents in promoting economic improvement, reducing poverty and guaranteeing the food security of the nation (Akpan & Zikos, 2023; Akter et al., 2023; Dey & Mishra, 2022).

An analysis of the CCAS adaptation techniques for efficiently producing maize, a major grain in South Africa's North West Province, has become necessary, with a review of the literature (Adesete et al., 2022; Akano et al., 2023; Ricart et al., 2023) revealing that there is little scientific knowledge on the implications of climate change on the productivity levels of farmers in the North West province. Despite the province's contribution to the country's large maize production sector, more detailed and current investigations are needed to establish the complementary relationship among the selected strategies for adapting to climate change, in addition to those that would serve to address the negative impact of climate change on the maize farmers' productivity.

4.3 Methods

A questionnaire survey was undertaken of smallholder maize farmers in North-West Province that included their demographic details, farm output, CCAS adopted and perceptions on average temperature, rainfall, dry periods, flooding and other climatic variables experienced in the study area. Once ethical approval had been obtained to conduct the study from the North-West University and the provincial Department of Rural Development, four extension officers working at the district offices were trained to conduct the surveys during their routine visits to the smallholder farmers between November 2022 and February 2023. Of the 320 who were invited to participate, 316 signed informed consent and completed the questionnaire. The data collected included variables related to institutional (access to extension training and climate information), household socio-economic factors (age, household size and gender) and perceptions about climate change, with multivariate probit model was used to determine the factors affecting CCAS adopted by the farmers.

A smallholder farmer is likely to adopt climate change adaptation strategies (CCAS) if the likely benefits of adoption outweigh the risks of non-adoption. Let U_j and U_i denote the predicted benefit for farmers adopting and not adopting, respectively. A farmer decides to use adaptation procedures if the net benefit of adoption (latent variable, Uj - Ui >0) is greater than the non-adoption benefit. The latent variable is influenced by the observed socio-economic traits of the household, the institutional and farm variables, and the error terms. Firstly, this research examined the complementary relationships among the adopted multiple CCAS by means of a basic conceptual framework (Figure 4.3). In order to capture the potential complementarities among the adopted CCAS, a multivariate probit model was later used, following Regmi et al. (2022), which is expressed as follows;

$$Y^{*}_{ik} = E\ (Yi = 1/Xi)\ \beta_i X_i + \varepsilon i \quad (4.1)$$

Where Y^{*}_{ik} denotes the binary variables representing the five most frequently adopted CCASs by the farmers (1 = adopted, 0= nonadopted); Y_1 = mixed cropping; Y_2 = improved varieties; Y_3 = crop rotation; Y_4 = mulching; Y_5 = agroforestry. X_i is a vector of independent variables, which are institutional variables, the households' socio-economic characteristics, and farm variables; while β_i is the coefficient of the parameter estimates.

a. Institutional factors

Following Abegaz et al. (2023) and Akter et al. (2023), this study used three binary variables, namely, educational status, access to extension services and climate information, as institutional factors. Various literature sources (Abegaz et al., 2023; Ogundari & Bolarinwa, 2019; Regmi et al., 2022) discussed the positive significant roles of institutions, such as extension services, radio media, informal education and climate information centers, to disseminate information and build capacity in agrarian communities, these being our key determinants of the adoption of CCAS (Abegunde et al., 2019; Adego & Woldie, 2022).

Smallholder farmers often face challenges in accessing accurate and timely climate information due to factors such as limited technology infrastructure, low literacy rates and remote geographical locations (Kangogo et al., 2021). Farmers could gain knowledge concerning novel agricultural techniques and their benefits from extension personnel, making adoption decisions easier (Regmi et al., 2022). Having access to basic education also exposes farmers to in-depth knowledge about new agricultural practices and makes it easier for them to embrace modern farming equipment (Acharyya, 2020). Higher educational attainment of a farmer means better access to information on improved agricultural techniques, and as a result, a greater possibility of adopting CCAS (Aggarwal et al., 2018).

Additionally, access to climate information may assist farmers in adopting sustainable farming operations, which could assist them in adapting to the impacts of climate change (Antwi-Agyei et al., 2021). Many smallholder farmers in rural areas rely on local radio broadcasts for weather forecasts and agricultural advice from extension agents (Omotoso et al., 2022; Thinda et al., 2020). Extension agents often collaborate with meteorological agencies to deliver weather updates and climate information to farmers through local newspapers, posters, telephone calls, sms or community notice boards.

b. Households' socio-economic characteristics

Household's socio-economic variables include the gender of the household head, years of maize farming experience, annual revenue earned from maize farming, and membership of cooperatives or farmers' organizations. One of the major variables influencing household decisions, in terms of the choice of a particular adaptation technique, is the gender of the farmer (Regmi et al., 2022). Farmers with a large number of economically viable family members are more likely to employ a labour-intensive farming approach (Abegunde et al., 2019). Years of schooling and farming experience are frequently cited as key drivers for adapting behaviour to climate change, as covered in the literature (Anuga et al., 2022; Atta-Aidoo et al., 2022; Maindi et al., 2020). Annual household income, off-farm income and membership of cooperatives or organizations are included as they are likely to have a significant influence on the adoption of CCAS (Barbon et al., 2022; Obi & Maya, 2021).

c. Farm variables

Following various authors (Anuga et al., 2022; Atta-Aidoo et al., 2022; Maindi et al., 2020), farm variables posited to influence the adoption-decision of smallholder farmers on choice of CCAS include farm size, years of farming experience, access to credit, membership of cooperative society and farmers group.

d. Perceptions about climate change

In designing this research, perceptions of the smallholder farmers pertaining to the changes in the local weather patterns over time were modelled. Farmers are more likely to adopt CCAS if they perceived changes in the local weather patterns (Regmi et al., 2022). In accordance with the literature (Atta-Aidoo et al., 2022; Kangogo et al., 2021; Ngoma, 2018; Paul et al., 2018), it was hypothesized that if farmers did so, they would be more likely to adopt multiple adaptation strategies to deal with the effects of climate change.

4.3.1 Triangulation and complementarity among climate change adaptations strategies and institutional factors

Two methods were used to highlight the synergy between climate change adaptations strategies **(**CCAS) adopted by the smallholder farmers and institution factors, the first being the triangulation of data on farmers' perception on climate change and the second is complementarity data on linkage between the selected CCAS adopted.

a. Triangulation

The study was influenced by the complementarity framework proposed by Regmi et al. (2022), which indicates the relationship between the CCAS adopted by farmers and the influence of explanatory variables (institutional, socio-economics and farm factor) on the adoption of CCAS in the farming households. This study explored the influence of the perceptions of smallholder maize farmers about climate and access to climate information on the adoption intensity of CCAS, and the impacts of the adoption of CCAS on the overall productivity of smallholder maize farmers.

The associations among farmers' perceptions, local climate trend data and survey responses are illustrated in the conceptual model of triangulation (Figure 4.3), as they indicated that they had observed the climate trends in their region and perceived a notable change in them over the past few years. Through the survey, coupled with climatic parameters, the farmers expressed their perceptions on average temperature, rainfall, dry periods, flooding and other climatic variables. Based on the survey data, it was clear that climate change was negatively impacting their farming practices in terms of seed germination delays, crop losses resulting from flooding, reduced soil water availability, weed infestations, and grain loss during the harvesting period, thus resulting in a lower maize output and net income from farm production. Trends in climatic conditions due to temperature increases and fluctuating rainfall were having severe implications for farmers' productivity levels in the sub-Saharan Africa (Keshavarz & Sharafi, 2023; Regmi et al., 2022). This statement concurs with the small holder maize farmers' perceptions of the changes in temperature trends and the variability in rainfall patterns in South Africa.

b. Complementarity

They way in which the complementary relationships among the adopted CCAS were influenced by the institutional factors, socio-economic and farm variables of the sampled households were examined (Figure 4.3). Of the several adaptation strategies adopted, mixed cropping was explored, as was planting improved varieties, crop rotation, mulching and agroforestry practices. The institutional factors affecting the adoption of CCAS, such as educational status, access to extension services (information on smart agricultural practices and training), and climate information, were included (Atta-Aidoo et al., 2022; Regmi et al., 2022). The socio-economic factors that influence the adoption of CCAS included gender, income, farming experience and membership of organizations (e.g. farmer's association and cooperative societies), while the farm characteristics included farm size and net income from the sale of maize.

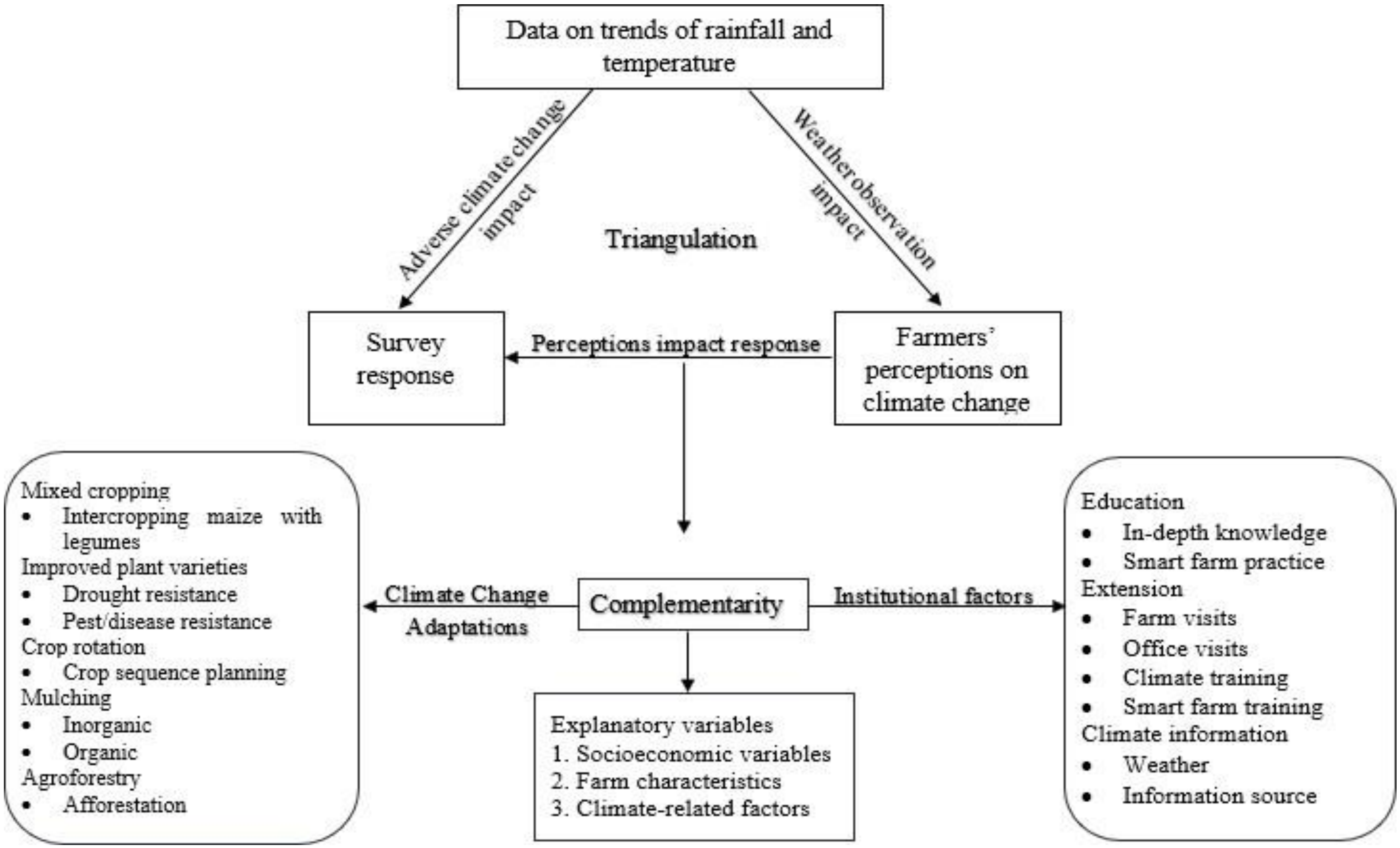

Fig. 4.3. Conceptual model of complementarity and triangulation between CCAS and the relevant institutional factors

4.3.2 Study area

This study was conducted in the North-West province, South Africa (Figure 4.4), where mining and farming, especially maize farming, contributed significantly to its economy. Smallholder farms are those below 10 hectares in size, often family businesses, with multiple members working in the business. The area has summer rainfall that often includes storms, the dry winter months extending from May to September, when the land is left fallow. The crops receive are rain-fed, the rainy season starting in October and ending in April, with the maize being planted in September and harvested in November.

4.3.3 Survey design

Primary data were acquired via a field survey of the smallholder maize farmers in the North West over the 2022 farming season (from November 2022 to February 2023). A multistage sampling procedure was adopted to select 316 smallholder maize farmers across the four municipalities (Bojanala District, Ngaka Modiri Molema, Dr Kenneth Kaunda, and Dr Ruth Segomotsi Mompati District Municipality) that comprise the province. All four municipalities in North West province were included to ensure data representativeness, the first stage of sampling involving randomly selecting 15 local municipalities that are well known for maize production, with the assistance of the district extension officers. Stage 2 involved the random selection of two villages within each of the 15 municipalities that were known for subsistence maize farming, with the help of local extension officers (totaling 30 villages) (Figure 4.4). Finally, the last stage involved selecting 316 actives[8] smallholder maize farmers in the villages from the list of all smallholder maize farmers available with the district extension officers.

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[8] Active: Smallholder maize farmers that constantly attend extension meetings and training on improved agricultural production practices (Galani et al., 2022; Omotayo et al., 2022)

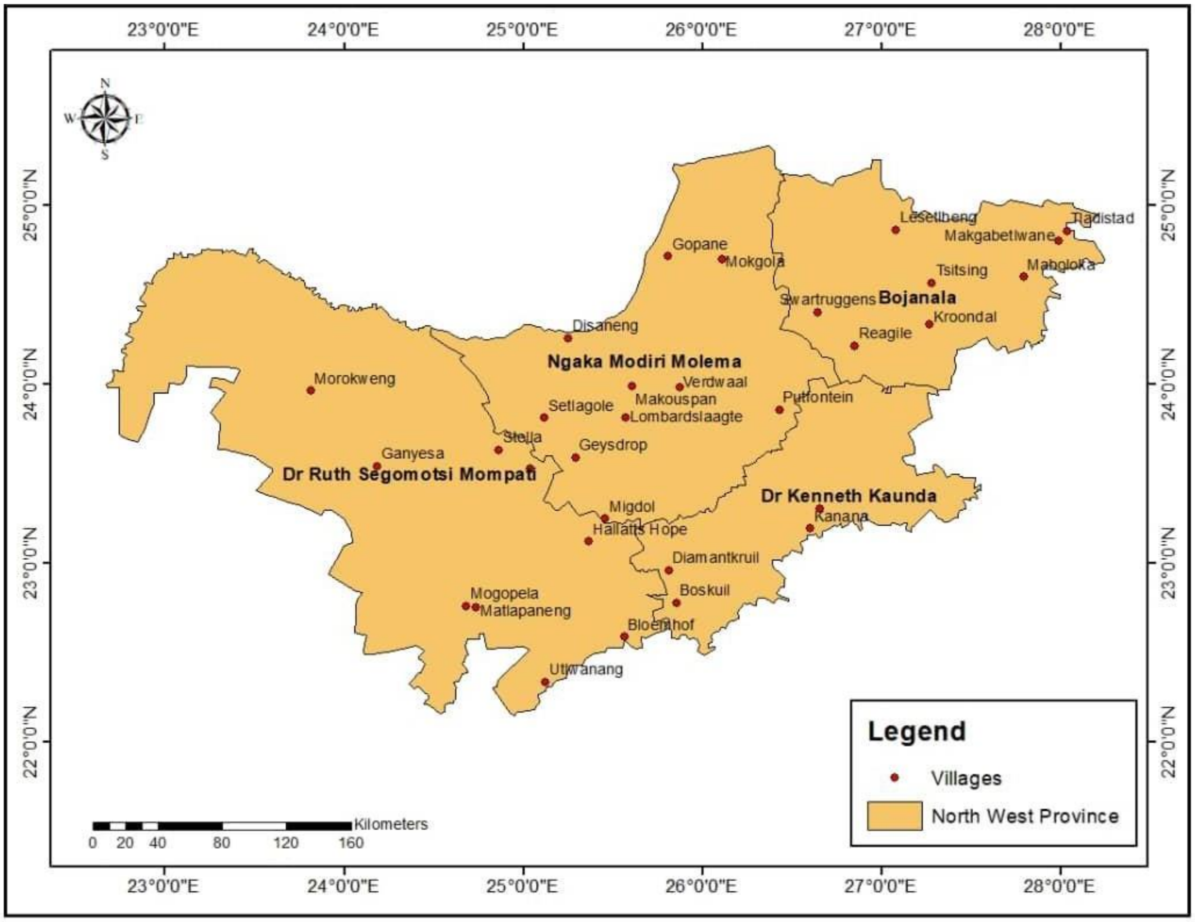

Fig. 4.4. Selected maize production villages in North West Province, South Africa

4.3.4 Survey data

Four extension officials who were fluent in the local dialect and had knowledgeable of the traditions and customs of the people of North West Province were trained to undertake the surveys. Potential participants were informed about the study and required to sign an informed consent form before they were interviewed. Farmers completed the survey in face-to-face interviews with the enumerators if they were18 years of age or older, understood the content, and accepted their role of participating in the survey. The survey consisted of four sections: households socioeconomic, farm variable, institutional variables and perception about climate change, with respondents being required to select answers from Yes/No options to various CCAS adopted in farming activities and stipulate the intensity of adoption.

4.3.5 Data analysis

The data was descriptively analyzed to obtain summary numbers, percentages, means and standard deviations (SD). The endogenous switching regression model (ESRM) was employed to evaluate the influence of the adaptation strategies on the farmers' net farm income[9] (for both the adopters and non-adopters). Multivariate probit (MVP) regression was employed to investigate the complementarity among the adopted CCAS and the drivers of the adopted CCAS, while negative binomial regression (NBR) was used to analyze the adoption intensity in respect of the CCAS.

4.3.6 Model Specifications

4.3.6.1 Adaptation impact on the net income of farmers (adopters and non-adopters): the endogenous switching regression model

An endogenous switching regression model (ESRM) was adopted as an impact model as it is capable of controlling for any bias that might obfuscate the output (Kumar et al., 2018). This model is divided into two sections, the first part, endogeneity, emanating from self-selection, was modelled by a Probit regression, which determines the farmers' adoption decisions in respect of CCAS. A farmer's decision to implement at least one adaptation technique in response to the effects of climate change was considered to be a dummy variable (assuming the value of 1 as an adopter and 0 as a non-adopter). The second part models the determinants of net farm income of adopters and non-adopters CCAS. Farmers would be more likely to adopt CCAS if the expected benefit of adopting it outweighs their non-adoption. Let U_j, and U_i denote that the expected benefits of adoption (latent variables $U_j - U_i > 0$) are greater than non-adoption (Dey & Mishra, 2022; Kumar et al., 2018). The explicit form of ESRM is expressed, considering that the farmer might decide to adopt an adaptation strategy (or not), the expected benefits would then assume the following values:

$Y_j = 0$ (non-adopters): $Y_jK = X'\beta_jK + U_jK$ if $D_j = 0$...(4.2)

$Y_j = 1$ (adopters): $Y_jA = X'\beta A + U_iA$ if $D_j = 1$ ....(4.3)

Where Y_jA and Y_jK are the dependent variables for an adopter and a non-adopter of CCAS, respectively, while X' is the collective symbol for the vectors of the explanatory variables. A selection instrument was used to acquire a more robust identification (Atta-Aidoo et al., 2022;

[9] Net farm income: Following (Aidoo et al., 2021), was used as a proxy for smallholder farmers' productivity.

Kangogo et al., 2021). Access to extension training on enhanced agricultural production practices was used as our selection instrument (Dummy; 1=Access to extension training on enhanced agricultural production practices, 0=Otherwise), and often includes hands-on training sessions and demonstrations, enabling farmers to learn the essential skills to successfully apply and use agricultural innovations (Atta-Aidoo et al., 2022; Kangogo et al., 2021). Improved skills boost farmers' confidence in embracing new technologies and improves their capacity to use them effectively (Akano et al., 2023; Atta-Aidoo et al., 2022). The acceptability of the suggested instrument (access to extension training on enhanced agricultural production practices) was proven using a falsification test. The findings (Appendix A1) indicated that the chosen instrument is important for influencing the adopter choice behaviour of smallholder maize farmers, but not significant for non-adopters of CCAS in South Africa.

The Estimates of Average Treatment Effects on the Treated (ATT) was used to investigate the impacts of adoption of CCAS on smallholder maize farmer’s productivity, and was calculated using the above-mentioned ESRM estimate (Equations 4.2 and 4.3) by comparing the predicted results of adopters with and without adoption.

4.3.6.2 Adoption intensity of CCAS: Negative Binomial Regression Model approach

The Poisson regression approach was initially employed to estimate the determinants of the intensity of adoption of the CCAS, where the dependent variable is numeric denoting number of CCAS adopted (Adeagbo et al., 2021). It should be noted that ordinary least squares (OLS) regression does not work well with numerical data as the data in this case are non-normal. The Poisson regression is typically the first step in analyzing numerical data (Adeagbo et al., 2021), with the model assuming a Poisson distribution for the dependent variable and the vector of the predictor variables (Atta-Aidoo et al., 2022; Kangogo et al., 2021).

Following (Green et al., 2023), the Poisson regression model is expressed as follows:

$$\Pr(Y = y) = \frac{e^{-\beta(h)}\beta i\,(h)^{H}}{\varphi\,(1+H)} \quad \text{where } \beta > 0 \text{ ......(4.4)}$$

where, $\beta i = Exp\,(\mu + L^{i}\alpha)$ and $Y_i = 0, 1, \ldots, i$ ......(4.5)

Y_i is the adoption intensity of CCAS and L^{i} denotes the collective symbol for the vectors of the explanatory variables, while μ and α are the parameters to be estimated (see Table 4.1).

Following Atta-Aidoo et al. (2022), the Poisson regression (PR) was rejected for this study, while the negative binomial (NB) regression model was adopted as the model of choice due to over-dispersion of the distribution of the data set as it involves adoption decision that is count data with excess zero. Its superiority over the PR model was deduced from the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC), as well as from the likelihood ratio statistics of alpha equal to zero. Thus, Table 4.1 revealed the variable description used in the model.

The Negative Binomial regression model variance is λ^2

Where $\nu = \lambda + \frac{\lambda 2}{\theta}$ and where λ is an over-dispersion parameter......................................(4.6)

$$Ln\ Y = \sum_{0} ln \lfloor 1 - {}'\Upsilon(\acute{\alpha}\delta)\, {}'\Upsilon\left(\frac{Xi\beta}{\delta}\right) \rfloor + \sum_{1} ln\, [{}'\Upsilon(\acute{\alpha}\delta)\frac{1}{\delta}\, {}'\Upsilon\,(qi - Xi\delta)]$$ ....(4.7)

Table 4.1. Variables description used in the negative binomial regression model

Variable	Description	Measurement
Dependent variables		
Productivity	Net farm income from maize production in 2022 agricultural production season (Rands)	Rands/hectare (Continuous)
Intensity of adoption	Number of CCAS adopted by the HH	Number of CCAS (Continuous)
Independent variables		
Gender	Household head's gender	If male= (1), female=(0)
Age	Age of the household head	Number of years (Continuous)
Educational level	Household head's educational level	Years of academic education (Continuous)
HH size	Number of people within the Household	Number of household members (Continuous)
Farm size	Total land area cultivated for farming	Number of hectares (Continuous)
Farming Experience	Years of experience in farming	Number of years (Continuous)
Marital Status	Marital status of household head	(1) if married, (0) if otherwise
Extension contacts	Contact with extension agents	(1) if contacted and (0) if otherwise (Dummy)
Main Occupation	Main occupation	If farming= (1), otherwise= (0) (Dummy)
Credit	Access to the credit source	If yes= (1), otherwise=(0) (Dummy)
Climate Information		
Smartphone	Access climate information through Smartphone (sms, calls)	If yes= (1), otherwise=(0) (Dummy)
Radio	Access climate information through Radio	If yes= (1), otherwise=(0) (Dummy)
Community meeting	Access information through community meeting	If yes= (1), otherwise=(0) (Dummy)
Flyers/Posters	Access information through flyers/posters	If yes= (1), otherwise=(0) (Dummy)
Local newspaper	Access to climate information through newspapers, community bulletins	If yes= (1), otherwise=(0) (Dummy)
Extension training	Access to extension training on enhanced agricultural production Practices	If yes= (1), otherwise=(0) (Dummy)
Member of an Organization	Member of a farming organization	If yes= (1), otherwise=(0) (Dummy).

4.3.6.3 Determinants of the Adoption of selected climate change adaptation strategies: the Multivariate Probit regression

To capture the potential complementarities among the five CCAS most frequently adopted[10] by smallholder maize farmers, the multivariate probit (MVP) model was used (Aggarwal et al., 2018; Lin et al., 2023). The MVP is generally employed to analyze the determinants of the CCAS that are adopted, as this approach simulates the influence of a set of regressors on each of the adopted adaptation strategies of the farmer. The MVP model was with five dummy dependent variables that represented the adaptation strategies most commonly adopted by the respondents (Table 4.2) (Adeagbo et al., 2021). These variables included mixed cropping, planting improved varieties, crop rotation, mulching, and agroforestry. The MVP model is specified as follows.

$$C = Y + \acute{\alpha}\sum_{i=k}^{h} Xh + Vk \quad \text{...}(4.8)$$

$$Y^{*}_{ik} = E\ (Yi = 1/Xi)\ \beta_i X_i + \varepsilon i \quad \text{..}(4.9)$$

Where Y^{*}_{ik} denotes the binary variables representing the five adaptation strategies mostly adopted: Y_1 = Mixed cropping; Y_2 = Improved maize varieties; Y_3 = Crop rotation; Y_4 = Mulching; Y_5 = Agroforestry. X_i is the collective symbol for the vectors of the regressors, β_i represents the coefficients of the parameter estimate, while ε_i is the error term.

The variables below denote the mostly adopted CCAS by smallholder farmers:

i. **Mixed cropping:** this involves planting different crops in the same field during the same growing season, and can provide several benefits, including better land use, reduced risk from crop failure due to climate change, and increased overall productivity (Mullins et al., 2018; Renwick et al., 2020). Pumpkins/quash, cowpea, beans, sorghum, herbs and spices are some crops that farmers mix along with maize cropping in South Africa (Akanbi et al., 2021a; Akano et al., 2023; Ricart et al., 2023). This approach has been found to mitigate the impacts of climate and improve maize productivity of smallholder maize farmers in South Africa (De Pinto et al., 2020; Mutengwa et al., 2023).

ii. **Crop rotation:** farmers in South Africa rotate maize with other crops such as soybeans, sunflowers, sorghum or vegetables, as this helps to improve soil health, reduce pests and diseases, and maintain soil fertility by alternating nutrient due to their differing nutrient demands (Renwick et al., 2020; Rosenstock et al., 2019).

iii. **Agroforestry:** this involves the intentional integration of trees and shrubs with agricultural crops or livestock pastures (Maindi et al., 2020). This practice offers multiple benefits, including soil conservation, increased biodiversity, improved microclimates, wind break and additional sources of income (Akanbi et al., 2021b; Smith et al., 2014). In South Africa, some of the tree species incorporated in maize farming include: *Acacia karroo* (sweet thorn), *Eucalyptus Smithii,* Ana Tree, Winter Thorn and Lead-tree (Leucaena)**.** Farmers often choose tree species that align with their needs for improved sustainability, diversified income and enhanced ecosystem services (Smith et al., 2014).

iv. **Improved varieties:** Several improved maize varieties have been developed and cultivated in South Africa to enhance crop yields, disease resistance and overall agricultural sustainability (Omotayo et al., 2020; Rosenstock et al., 2019). PANNAR is a leading seed company that has developed a range of maize hybrids adapted to local conditions. Varieties such as PANNAR 7V12, PANNAR 9M10, CAP 9001 and CAP 9021 have been favoured by smallholder farmers for their performance and drought-tolerance ability.

v. **Mulching:** this offers several advantages that can contribute to maize output through soil moisture conservation, soil health and temperature regulation, and soil organic matter (Akanbi et al., 2021a; Tilahun et al., 2023). Materials such as straw, hay, leaves, compost, and crop residues are used as organic cover placed on top of the soil. As these materials break down, they release nutrients into the soil, enriching it over time. Farmers in South Africa apply mulch to a thickness of 5 to 10 centimeters (2 to 4 inches) (Akanbi et al., 2021a; Tilahun et al., 2023; Tione et al., 2022), as this provides adequate coverage to suppress weeds, conserve moisture and protect the soil surface.

4.3.7 Ethical Approval

The Ethics Committee of the Faculty of Natural and Agricultural Sciences, North-West University, South Africa, provided ethical clearance (NWU-01267-23-A9) for the study. Prior to the distribution of questionnaires in the research areas, the North West Provincial Department of Rural, Environment and Agricultural Development, gave permission for the district offices to be used in the research and extensions officers to undertake the survey interviews. The principles of privacy, autonomy and confidentially were upheld by allocating unique identifiers rather than using the farmers names.

Table 4.2. Variable descriptions used in the MVP model

Variable	Description	Measurement
Dependent variables		
CCAS 1	Adoption of mixed cropping	If yes= (1), otherwise= (0) (Dummy)
CCAS 2	Adoption of planting improved varieties	If yes= (1), otherwise= (0) (Dummy)
CCAS 3	Adoption of crop rotation	If yes= (1), otherwise= (0) (Dummy)
CCAS 4	Adoption of mulching	If yes= (1), otherwise= (0) (Dummy)
CCAS 5	Adoption agroforestry	If yes= (1), otherwise= (0) (Dummy)
Independent variables		
Gender	Gender of the household head	If male= (1), female= (0)
Age	Age of the household head	Number of years (Continuous)
Educational level	Household head's educational level	Years of academic education (Continuous)
Household size	Number of people within the household	Number of household members (Continuous)
Farm size	Total land area cultivated for farming	Number of hectares (Continuous)
Farming Experience	Years of experience in farming	Number of years (Continuous)
Marital Status	Household head's marital status	(1) if married, (0) if otherwise
Extension contacts	Contacts with extension agents	(1) if contacted, (0) if otherwise
Main Occupation	Main occupation	(1) if farming, (0) if otherwise
Credit	Access to credit	If yes= (1), otherwise= (0)
Climate Information	Access to climate information (through smart phones, radio, community meeting, newspaper, flyers/posters)	If yes= (1), otherwise= (0)
Extension training	Access to extension training on enhanced agricultural production practices	If yes= (1), otherwise= (0) (Dummy)
Member of Organization	Member of a farming organization	If yes= (1), otherwise= (0)

4.4 Results and discussions

4.4.1 Socio-economic characteristics of smallholder maize farmers in South Africa

As indicated in Table 4.3, the respondents' average age was 45 years, indicating that a large percentage were young and had the potential to contribute positively to agricultural productivity in the study area. The results also revealed that the majority (73.0%), which is in line with Omotoso et al. (2022), who noted that married farmers are more dedicated to their agricultural endeavours as its success is essential to their family's survival. The average household size of four people will affect the amount of money spent on food and clothes, as well as in implementing farming decisions. The majority of agrarian communities see the size of the household as an important factor as it points to the availability of labour to work on the farm (Omotoso et al., 2022; Tilahun et al., 2023).

The majority (79.00%) of respondents indicated that they had access to climate information, while about two-thirds (72.0%) had contact with extension agents, such advisory services being very important to disseminate information and encourage the adoption of new technologies by farmers for efficient production and improved farm outputs (Atta-Aidoo et al., 2022). The productivity distribution of the respondents (Appendix A3) indicated that the monthly mean net farm income of the smallholder farmers was approximately R5 593.72. The result reveals the subsistence farming nature of the respondents, and are in line with Kangogo et al. (2021) and Tilahun et al. (2023), who reported that smallholder farming is a nuanced concept that encompasses various dimensions, such as low-income, small-scale production, poor resource access, family labour patterns and inadequate market engagement.

Table 4.3. Socio-economic characteristics used in the models

Variables	Descriptions	Mean	Std. Dev.
Dependent variables			
CCAS adoption	(1) if the household head (HH) adopted any CCAS, (0) if Otherwise	0.77	0.58
Adoption intensity of CCAS	Number of CCAS adopted by the HH	6.02	3.17
Productivity			
a. Quantity harvested (ton/ha)	Quantity of maize harvested (both adopters and non-adopters)	8.34	4.31
Adopter's Qty maize	CCAS adopters' Qty of maize harvested	13.85	7.09
Non-adopter's Qty maize	CCAS non-adopters' Qty of maize harvested	7.26	3.77
b. Net farm income (Rands/ha)	Revenue from maize sale (both adopters and non-adopters)	5593.72	1495.34
Adopter's Net farm income	CCAS adopters' revenue from maize sale (Rands/ha)	7834.91	5118.16
Non-adopter's Net farm income	CCAS non-adopters' revenue from maize sale (Rands/ha)	4904.35	2821.27
Independent variables			
Gender	If HH is male= (1), if female= (0)	0.62	0.51
Age	Actual household head's age in years	44.69	15.82
Educational level	(1) formal education, (0) = non-formal	0.76	0.42
Farming experience	Years of maize farming experience	6.71	3.17
Marital status	If HH is married= (1), otherwise= (0)	0.73	0.48
Main occupation	(1) if HH's main occupation is farming, (0) if otherwise	0.84	0.35
Off-farm income	Income from livestock sale and other activities	0.56	0.32
Household size	Number of people in household	4.15	2.17
Farm size	Total land cultivated (in hectares)	3.26	1.18
Extension contacts	(1) if HH has access, (0) if otherwise	0.72	0.47
Membership of organization	(1) if HH is a member of any organization; (0) if otherwise	0.61	0.42
Credit source	(1) if HH has access, (0) if otherwise	0.68	0.56
Climate information			
Smartphone	(1) if HH receives climate info through smartphone, (0) if Otherwise	0.72	0.39

Radio	(1) if HH receives climate info through Radio, (0) if otherwise	0.81	0.31
Community meeting	(1) if HH receives climate info through community meetings, (0) if otherwise	0.69	0.28
Flyers/Posters	(1) if HH receives climate info through flyers/posters (0) if Otherwise	0.71	0.33
Local newspaper	(1) if HH receives climate info through newspaper, community bulletins, (0) if otherwise	0.58	0.25
Extension training	If yes=(1), otherwise=(0) (Dummy)	0.71	0.34

4.4.2 Climate change adaptation strategies adopted by smallholder maize farmers

Figure 4.5 shows the distribution of CCAS adopted by smallholder maize farmers, their understanding of climate change having a significant impact on the level of adaptation and the steps they take to combat the impacts of climate change on their outputs (Baiyegunhi et al., 2022). This suggests that the majority of smallholder maize farmers are cognizant of local climatic variations and thus able to make informed decisions on adaptations to deal with its impact on their farms. The smallholder maize farmers in North West Province have developed a wide variety of adaptation techniques to deal with the changing climatic conditions, including mulching, varying planting and harvesting dates, mixed cropping, the use of improved plant varieties, agroforestry and crop rotation (Figure 4.5). Other strategies include the use of organic and inorganic fertilizers and minimal tillage. While 19.70% of the respondents were limited users of CCAS, 70.10% and 10.12% proved to be medium and high users, respectively (Figure 4.6), this finding agreeing with Daud et al. (2018) and Omotayo et al. (2022). They who noted that little mention is made of CCAS methods in rural areas, their relevance not being well understood, which could be the reason, as indicated by the study, for their moderate adoption.

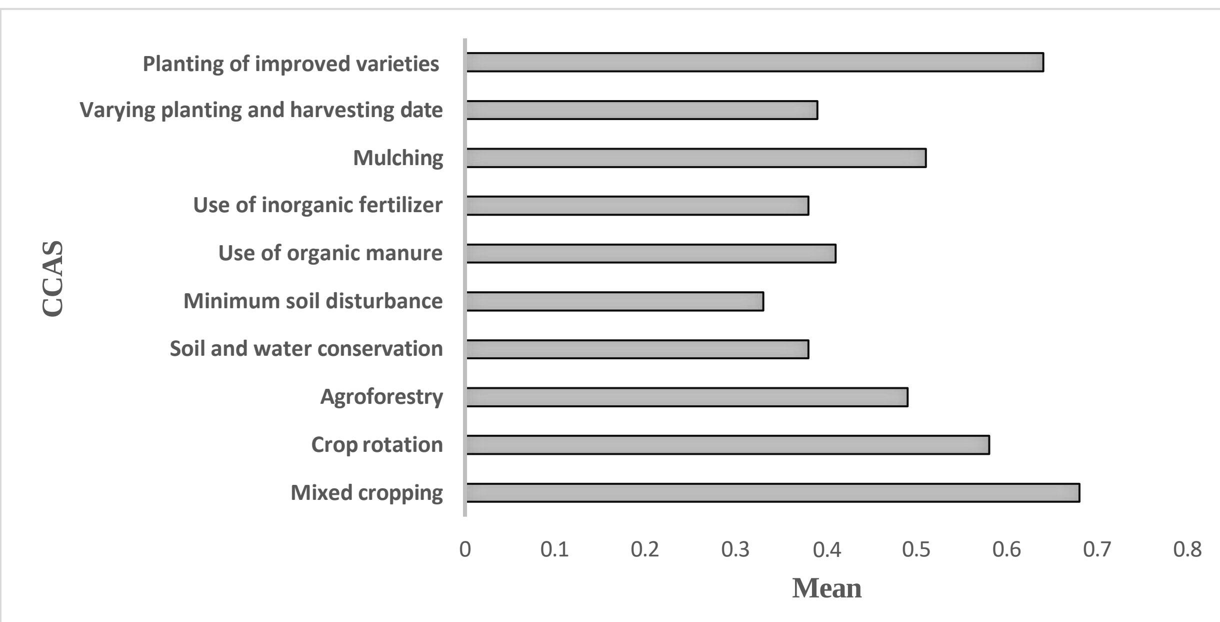

Fig. 4.5. Distribution of CCAS adopted by the smallholder maize farmers in North West Province

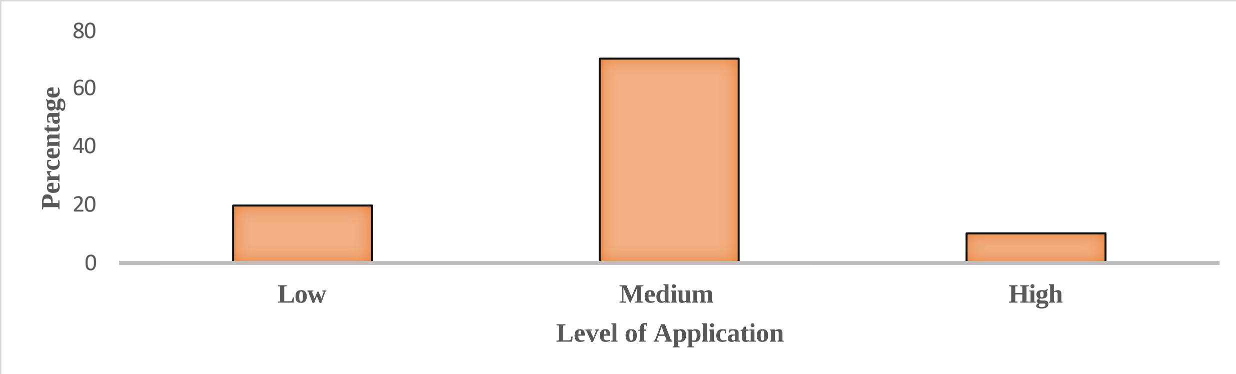

Fig. 4.6. Level of CCAS usage by smallholder maize famers

4.4.3 Adaptation impact of climate change adaptation strategies on farmers' (adopter and non-adopter) net farm incomes

The ESRM estimates to determine CCAS adoption and their impacts on the net farm income of the sampled farmers are presented in Tables 4.4 and 4.7. The correlation coefficient rho_1 in ESRM is positive and significant for the correlation between CCAS adoption and net farm income. The statistical significance of the likelihood ratio test at 1% for the combined independence of the three equations indicates that they should not be assessed individually.

4.4.3.1 Determinant of adoption of climate change adaptation strategies: First stage

The second column of Table 4.4 denotes the Probit regression, which determines the CCAS adoptions by the smallholder maize farmers. It reveals that the coefficients of the household size, educational status, access to extension training on enhanced agricultural production practices and access to climate information (through smartphones and radio) had a statistically significant influence on the adoption of CCAS. The coefficient of household size (β=-0.227; $p > 0.05$) had a negative significant influence on the adoption of CCAS, which implies that the probability that a large household would adopt adaptation strategies decreases. As posited by Thinda et al. (2020), education plays an important role in human capital development and enhances adaptation capabilities.

From the result, it is clear that the coefficient of educational status (β = 0.819; $p>0.01$) exerts a positive significant influence on the adoption of CCAS, as indicated by Adeagbo et al. (2021) and Thinda et al. (2020). The findings indicate that education provides people with information and knowledge, both important for human capacity building, and thus enable them to enhance them productivity. Furthermore, respondents' access to climate change information was found to be positively significant with the adoption of CCAS, which indicates that with adequate knowledge of climate change, the respondents would have a higher likelihood of adopting adaptation strategies. As reported by Tilahun et al. (2023), adequate knowledge of climate change enables the development of adaptive strategies that enhance resilience, reduces the susceptibility of rural farmers to climate change impacts and improves their farm productivity (Paul et al., 2018).

4.4.3.2 Determinants of net farm income of adopter and non-adopter of climate change adaptation strategies

The third and fourth columns of Table 4.4 present estimates from the second stage of ESRM on the determinants of net farm incomes of the adopters and non-adopters of CCAS. The coefficients of marital status, farm size and educational status were significant in explaining variations in net farm income among the adopters of CCAS, while the coefficients of off-farm income, farm size and farming experience are significant in explaining variations in net farm income among the non-adopters of CCAS. The coefficient of the smallholder farmers' marital status ($\beta = 0.117$; $p>0.01$) was positively significant in explaining the variation in net farm income of CCAS adopters. Married farmers have the ability to pool their resources, both financial and non-financial, to invest in the farm (Mullins et al., 2018; Paul et al., 2018), which could enable larger-scale farming activities, the adoption of new technologies or the purchase of better inputs, ultimately impacting net farm income (Maindi et al., 2020).

The parameter estimates of the respondent's educational status ($\beta=0.890$; $p>0.01$) was positively significant in explaining the variation in net farm income of adopters of CCAS, but not significant in non-adopters. This denotes that the number of years spent in school would increase the probability of adopting CCAS, thereby improving productivity and enhancing the net farm incomes of the adoptees. According to Akano et al. (2023) and Thinda et al. (2020), educated household heads are more likely to embrace CCAS, to therefore probably achieve greater efficiency in their maize production levels and ensure increased productivity. Smallholder's maize farm size ($\beta=0.101$; $p>0.01$) was positively significant in explaining the variations in net farm income from maize cultivation of both adopters and non-adopters of CCAS.

This implies that farmers with larger farm sizes are likely to have a greater propensity to invest in CCAS than their smaller size counterparts, and is in line with the empirical findings of Atta-Aidoo et al. (2022) and Kangogo et al. (2021), who reported a positive relationship between farm size and the adoption of CCAS. This finding is also corroborated by Akano et al. (2023) and Thinda et al. (2020), who reported that farm size and an increase in a farmer's net income emanating from efficient farm production methods were directly related.

Table 4.4. Maximum likelihood estimates of ESRM for the adoption of CCAS in South Africa

	Adaptation		**Net farm income**			
			Adopters		**Non-adopters**	
Variables	Coef.	Std. Error	Coef.	Std. Error	Coef.	Std. Error
Gender	-0.216	0.164	-0.505	0.416	-0.604	0.713
Age of household head	0.668	0.756	0.389	0.615	0.364	0.669
Educational status	0.819**	0.402	0.890***	0.167	-0.188	0.371
Household size	-0.227*	0.101	-0.731	0.878	0.136	0.442
Marital status	-0.078	0.109	0.147**	0.065	-0.012	0.069
Main occupation	0.835	0.981	-0.150	0.261	0.170	0.233
Farm size	-0.831	0.798	0.057***	0.011	0.101***	0.023
Years of farming Experience	0.538	0.904	0.062	0.120	-0.362**	0.197
Off-farm income	-0.041	0.170	-0.057	0.088	0.126*	0.071
Membership of Organization	-0.409	0.391	0.312	0.289	0.377	0.483
Credit	0.667	0.545	-0.011	0.045	-0.126	0.241
Extension contacts	-0.515	0.976	0.041	0.059	0.070	0.092
Smartphone	0.516***	0187	-0.962	1.091	0.147	0.822
Radio	0.038***	0.012	0.012	0.101	0.084	0.077
Community meeting	0.0261	0.110	0.016***	0.006	0.116	0.099
Flyers/Posters	0.184	0.099	0.116	0.103	0.093	0.105
Local newspaper	0.004	0.025	0.028	0.077	0.271	0.185
Access to extension training	0.097***	0.027				
Constant	0.124***	0.017	0.578***	0.190	0.132***	0.038
rho_1	0.851***	0.105				
Likelihood ratio test of Independence	27.67***					
Number of observations	316		243		73	

Note: *, **, and *** denotes 10%, 5%, and 1% significance level, respectively

4.4.4 Determinants of the adoption intensity of climate change adaptation strategies: Negative Binomial Regression Model

The results of the parameter estimate of the Poisson regression (PR) model and NBRM to determine the adoption intensity of CCAS by smallholder maize farmers are presented in Table 4.5 and Appendix A2, respectively. As shown in the Tables, the estimations of the AIC and BIC are important in indicating a better model for analyzing numerical data in respect of the adoption intensity of CCAS. The values of AIC for PR and NBRM are shown as 1402.06 and 1283.023, respectively, while the BIC values for Poisson and NBRM are shown as 1370.31 and 1126.395, respectively. Using AIC and BIC values, the NBRM fits better than the Poisson regression model for analyzing numerical data pertaining to the adoption intensity of CCAS by smallholder maize farmers in North West Province as the lower these values (AIC and BIC), the more efficient the model (Green et al., 2023; Regmi et al., 2022).

For this reason, the NBRM result (Table 4.5) shows that the coefficient of age (β = -0.075; p>0.01) of the smallholder maize farmers negatively and significantly influenced the adoption intensity of CCAS. This implies that younger farmers are less likely than older farmers to adopt CCAS. This proves that age is a proxy for agricultural experience, thus implying that the more experienced farmers are the older ones who recognize the necessity of adapting to climate change. Clay and King (2019) and Oduniyi (2018) reported that age significantly affects the perception of climate in a negative way, younger farmers usually being associated with limited farming experience and therefore less likely to adopt adaptation strategies to mitigate the effects of climate change.

Similarly, the coefficient of household size (β=0.160; p >0.05) positive and significantly influenced the adoption intensity of CCAS, suggesting that a large household contributes to increments in agricultural productivity, thus significantly influencing the options of farmers and their intensity of adoption. In addition, off-farm income (β = 0.155; p>0.10) was found to positively and significantly influence the adoption intensity of CCASs, such an increase in income would provide additional financial power and enable farmers to invest in adaptation strategies in order to enhance their productivity. This result is in line with that of Adeagbo et al. (2021), Obi and Maya (2021) and Onyeneke (2021), who noted that income from off-farm activities provide farmers with additional financial leverage and motivation to adopt various CCAS, such as mixed cropping, crop rotation, mulching and agroforestry in arable crop production.

Furthermore, access to credit facilities (β= 0.137; p >0.05) and climate information (β= 0.148; p >0.01) are important variables that influence farmers positively in their adoption of CCAS. Farmers' investments in adaptation measures have been shown to increase with their access to climatic information from other Southern African Development Communities, such as Botswana, Rwanda and Congo (Ricart et al., 2023). Studies elsewhere (Atta-Aidoo et al., 2022; Kangogo et al., 2021) have revealed that accessibility to weather-related information is essential for enhancing farmers' perceptions of climate change, thereby increasing the possibility that they would adopt adaptation strategies and enhance their farm productivity. This result corroborates existing literature findings (Maindi et al., 2020; Outhwaite et al., 2022), where it was reported that access to credit is an essential variable that has a positive influence on farmers productivity in that it promotes their adaptation behaviour and decision-making around agricultural enterprises.

Table 4.5. Factors influencing smallholder maize farmers' adoption intensity of CCAS - NBRM

Variables	Coefficient	Robust Std. Err.	Marginal effect
Gender	0.060	0.121	0.034
Age of household head	-0.075***	0.018	-0.096
Educational status	-1.070	0.891	-0.048
Household size	0.160**	0.072	0.047
Marital status	-0.318	0.441	-0.004
Main occupation	0.051**	0.021	0.057
Farm size	0.191**	0.093	0.053
Years of farming experience	0.573***	0.113	0.034
Off-farm income	0.155*	0.081	0.073
Membership of organization	-0.079	0.084	-0.108
Credit	0.137**	0.051	0.031
Extension contacts	0.373	0.527	0.006
Smartphone	0.148***	0.036	0.025
Radio	0.027	0.011	0.004
Community meeting	0.049	0.103	0.116
Flyers/Posters	0.077	0.119	0.072
Local newspaper	0.034*	0.018	0.004
Access to extension training	0.061**	0.031	0.052
Constant	1.531***	0.591	
Pseudo R^2	0.657		
Chi-square	129.21		

Number of observations	316	
Inalpha	-31.71	107.362
AIC	1283.023	
BIC	1126.395	
Prob > chi^2	0.000	

Note: *, **, and *** denote 10%, 5%, and 1% significance level, respectively

4.4.5 Determinants of the adaptation strategies to climate change in South Africa

Table 4.6 indicates the MVP model parameter estimates for the factors influencing the adoption of the selected CCAS, with the coefficient of age of household head having a negative but significant influence on the decision to adopt agroforestry and crop rotation, but not on the other adaptation alternatives. The inverse relationship between the two variables suggests that, in comparison to older farmers, younger farmers are more likely to choose these adaptation options. The household size coefficient had a substantially positive impact on the decision to use a mixed cropping adaptation strategy to mitigate the effects of climate change.

The choices of adopting adaptation options in respect of mixed cropping, mulching and agroforestry were found to be positively and significantly influenced by the off-farm income coefficient. This positive and significant correlation between the two variables implies that as long as the amount generated from their off-farm income increases, smallholder maize farmers have a 14.1%, 13.9% and 23.1% likelihood of adopting mixed cropping, mulching and agroforestry adaptation strategies, respectively. Smallholder maize farmers who engage in off-farm activities would confidently invest in various adaptation strategies, any shortcoming in the investment associated with these strategies being mitigated by involved in off-farm activities (Adeagbo et al., 2021; Aggarwal et al., 2018).

The adoption of agroforestry CCAS is positively influenced by the farm size coefficient (β= 0.295, p >0.10), this being consistent with the studies (Ado et al., 2020; Akanbi et al., 2021a; Baiyegunhi et al., 2022) that reported a positive relationship between farm size and agroforestry practices. Farmers' access to extension services and climate information (through smartphones), significantly influences their choice in adopting crop rotation, mulching and agroforestry CCAS. It was also found that if they have access to extension services and climate information, 16.5% and 15.0%, respectively, of smallholder maize farmers are more likely to adopt a crop rotation strategy. This finding aligns with past studies (Abegaz et al., 2023; Aidoo et al., 2021; Akanbi et al., 2021a, 2021b; Gebre et al., 2023), which concluded that institutional factors, such as access to extension services, training and information, would increase the probability of adopting CCAS and the complementarity among the adopted CCAS.

Various empirical findings show that access to credit, training on improved agricultural production practices and climate information are major determinants of CCAS by smallholder farmers. Gomes et al. (2020) and Kangogo et al. (2021) contend that the optimization of existing knowledge could be hampered by limited resources, as the cost of adaptation techniques could be prohibitively expensive for farmers with limited financial capability. Consequently, access to credit tends to influence the decision to adopt improved plant varieties, crop rotation, mulching and agroforestry as adaptation strategies. Adopting an adaptation strategy could be costly in terms of capital, thus necessitating investments in improved planting materials, technology and other essential inputs.

Table 4.6. MVP model for determining the selected adaptation strategies to climate change by smallholder maize farmers

Variables	**Mixed cropping**		**Planting improved varieties**		**Crop rotation**		**Mulching**		**Agroforestry**	
	Coef.	**M.E**	**Coef.**	**M.E.**	**Coef.**	**M.E**	**Coef.**	**M.E**	**Coef.**	**M.E**
Gender	-0.023	-0.011	0.030	0.070	-0.103	-0.094	-0.192	-0.107	0.071	0.020
	(0.119)		(0.024)		(0.169)		(0.101)		(0.092)	
Age of household head	0.017	0.036	-0.046	-0.103	-0.152**	-0.083	0.097	0.008	-0.139**	-0.016
	(0.033)		(-0.066)		(0.032)		(0.055)		(0.510)	
Educational status	0.018	0.014	0.038	0.004	-0.225	-0.072	0.319	0.063	-0.048	-0.005
	(0.027)		(0.104)		(0.194)		(0.096)		(0.137)	
Household size	0.221***	0.245	0.178	0.053	0.405	0.030	-0.167	-0.058	-0.307	-0.034
	(0.021)		(0.199)		(0.477)		(0.231)		(0.189)	
Main occupation	-0.027	-0.100	0.108	0.022	-0.071	-0.057	-0.124	-0.061	0.095	0.046
	(0.019)		(0.116)		(0.114)		(0.141)		(0.052)	
Farm size	-0.039	-0.078	0.031	0.108	-0.292	0.028	-0.187	-0.072	0.295*	0.065
	(0.055)		(0.155)		(0.257)		(0.162)		(0.103)	
Farming experience	0.096	0.031	0.130***	0.092	0.063	0.009	0.150	0.085	-0.805	-0.024
	(0.134)		(0.011)		(0.031)		(0.172)		(0.773)	
Off-farm income	0.141**	0.082	0.318	0.033	0.117	0.006	0.139**	0.016	0.231***	0.077
	(0.102)		(0.113)		(0.290)		(0.072)		(0.044)	
Membership of organization	-0.091	0.006	0.173	0.004	-0.192	-0.004	0.811	0.028	0.014	0.001
	(0.215)		(0.152)		(1.012)		(0.977)		(0.109)	
Credit	0.050	0.047	0.023*	0.007	0.180***	0.091	0.614*	0.037	1.071*	0.135
	(0.049)	1	(0.011)		(0.113)		(0.325)		(0.929)	
Contant with extension	0.930	0.251	-0.256	0.008	0.150*	0.105	0.965**	0.095	0.647*	0.107
	(0.721)		(0.613)		(0.086)		(0.422)		(0.294)	
Smartphone	0.076***	1.342	0.052	0.026	0.165**	0.057	0.279**	0.007	-0.137	-0.008
	(0.021)		(0.088)		(0.081)		(0.138)		(0.134)	

Radio	0.061***	0.051	0.045	0.002	0.110	0.005	0.072**	0.032	-0.095	-0.004
	0.020		0.101		0.152		0.033		0.115	
Community	0.007	0.011	0.167	0.073	-0.005	-0.011	0.281	0.002	0.652	0.061
meeting	0.023		0.099		0.043		0.199		0.559	
Flyers/Posters	-0.094	-0.129	0.071*	1.003	0.022	0.105	0.008	0.001	0.038***	0.118
	0.114		0.038		0.116		0.015		0.011	
Local newspaper	0.033**	0.033	0.088	0.009	0.076*	0.082	0.054	0.175	-0.009	-0.004
	0.017		0.104		0.041		0.121		0.042	
Access to	0.173***	1.083	0.089*	0.039	0.115**	0.041	0.096***	0.112	0.167**	0.071
extension training	(0.028)		(0.053)		(0.061)		(0.031)		(0.085)	
Constant	0.145**	0.381	0.595***		0.075***		0.403***		0.060***	
	(0.081)		(0.044)		(0.018)		(0.195)		(0.029)	
Log-likelihood =	-262.891									
χ^2 (26) =	319.010; Prob > 0.000									

Note: *, **, and *** denote 10%, 5%, and 1% significance level, respectively; numbers in parenthesis indicate the robust standard error while M.E denotes marginal effects.

4.4.6 Average Treatment Effect: Impacts of adoption of climate change adaptation strategies on net farm income

The results in Table 4.7 revealed the average treatment effect (ATT) of the impacts of CCAS on net farm income of adopters and non-adopter in South Africa. The findings demonstrated that adoption of CCAS improved the net farm income of smallholder maize farmers by R3689.19/ha in the study area. Other authors (Ahmed, 2022; Ngoma et al., 2021) have also reported that adopting multiple CCAS is crucial for enhancing the productivity of rural farming households in developing nations with a changing climate, limited access to water for irrigation and land for agricultural expansion.

Table 4.7. Impact of adoption of CCAS on net farm income of smallholder maize farmers

Categories	Expected net farm income	ATT	t-value
Adopters	7891.94	3689.19***	5.29
Non-adopters	4202.75		

Note: *** denotes significant at 1%

4.5 Conclusion and policy implications

As the impacts of climate change intensifies over time, smallholder maize farming households have been adversely affected, resulting in low productivity, decreased incomes, structural unemployment and poverty especially among the rural settings. As a result, an understanding of their adaptation techniques to offset the negative effects is required, as is an understanding of the complementarity among the adopted CSAP and their impact on the productivity of smallholder maize farmers. The study examined the complementary relationships among numerous CCAS (planting of improved varieties, mixed cropping, mulching, crop rotation and agroforestry) adopted by smallholder maize farmers in North West Province and noted that they were influenced by the institutional factors, the socio-economic characteristics of the households, as well as the farm variables. The results reveal that all of the adopted CCAS are mutually complementary.

Likewise, the institutional factors, such as access to extension service and climate information (through smartphones and radio broadcast) were found to enhance the probability of adopting mixed cropping, while access to climate information through newspapers and community meeting was found to increase the probability of the adoption of crop rotation, mulching and agroforestry.

Additionally, the socio-economic variables (e.g. age and household size) of some of the selected households, as well as certain farm variables (e.g. access to credit and farming experience), enhanced the complementarity between the adopted CCAS. The findings indicate that to achieve FAO's sustainable agricultural goals and creating a world free hunger by 2030, South Africa's farmers must improve their resilience to climate change by adopting CCAS to augment their food productivity. The following recommendations are made to enhance the complementarity among the adopted CCAS and the intensity of adoption of CCAS by smallholder maize farmers in South Africa.

Government policies and investment plans should be oriented towards improving extension services, on-farm demonstration training, and the dissemination of CCAS knowledge for smallholder maize farmers across the country. The implementation of various climate mitigation strategies should be undertaken by the government, non-government organizations and private institutions, including the distribution of drought-tolerant maize seeds and seeds of other food crops that exhibit resilience to drought conditions. Additionally, promoting climate-related information through mediums such as radio, smartphones and local newspapers should be prioritized. Furthermore, the construction of dams to facilitate irrigation and training in minimum tillage techniques are also essential measures to be undertaken. It is essential for the government and all stakeholders involved to enhance the public agricultural finance system in order to facilitate the adoption of climate-smart farming techniques by maize farmers, thus aiding in the mitigation of climate change impacts. The creation of enable environment by government for establishment of alternative livelihood namely off-farm earnings, is important for supporting smallholder farmers, especially those with large families, in effectively managing the impacts of climate change and enhancing productivity.

Chapter 5: Manuscript 5

This chapter addressed objective 3, that being to examine the impacts of the simultaneous adoption of CSA on productivity and welfare outcomes of smallholder maize farmers in South Africa. It is presented in manuscript format, titled "Impact of Concurrent Adoption of Drought-Resistant Maize Varieties and Organic Manures on Productivity and Welfare Outcomes" having been prepared as per the guidelines, submitted and already in print at Australian Journal of Agricultural and Resource Economics

Impact of Concurrent Adoption of Drought-Resistant Maize Varieties and Organic Manures on Productivity and Welfare Outcomes

Abstract

Climate change threatens rural farming households in sub-Saharan African nations and particularly in South Africa. Addressing these challenges could be achieved through climate-smart agriculture (CSA) practices, recognized as a sustainable solution. This study employed a multistage sampling technique to select rural maize farmers across some selected villages in South Africa. Data were analyzed using propensity-score matching (PSM) and multinomial endogenous switching regression model. The results showed that DTMVs and organic manure adoptions had significant impacts on productivity and welfare outcomes, with joint adopters experiencing a 28% increase in the DTMVs productivity. More so, the per capita household expenditure for the joint adopters of DTMVs and organic manure was 4% higher than DTMVs adopters alone and 8% higher than organic manure adopters only. We concluded that the adoptions of DTMVs and organic manure alone or the combination significantly increase rural farmers' household maize productivity and welfare. Government and major stakeholders should encourage the use of CSA, such as the joint adoption of DTMVs and organic manure, to help farmers resist climate-change-related threats, improve productivity and welfare in the rural South Africa.

Keywords: Climate-smart technology; Food policy; Food sovereignty; Rural development; Sustainability

5.1 Introduction

The occurrence of climate change has posed a serious threat to human society, particularly in the sub-Saharan Africa (SSA), where its impact is most pronounced on rural smallholder farmers, who are becoming increasingly vulnerable to the impacts (Adesete et al., 2022; Baiyegunhi et al., 2022). The consequences of climate change which is usually visible via changes to the land and water regime are expected to affect the agricultural sector in SSA for the foreseeable future (Omotoso et al., 2023; Traore et al., 2021). In accordance with (Abegaz et al., 2023; Tilahun et al., 2023; Tione et al., 2022), most rural smallholder farmers in the SSA are susceptible to climate change due to their inability to predict weather, poor climate forecast services, climatic conditions as well as high levels of poverty, making it difficult for them to utilize adaptation measures to lessen the impacts. This posed a serious danger to local food production as well as the rural smallholder farmers' livelihood and well-being in many SSA countries, resulting in malnutrition, hunger, and chronic poverty (Batisani et al., 2021; Galani et al., 2022; Hammed et al., 2019).

Regrettably, like other nations of the SSA, a considerable amount of South Africa's rural smallholder farmers heavily relies on rain-fed agriculture for livelihood (Amadu et al., 2020; Batisani et al., 2021). Increased temperatures coupled with unpredicted rainfall had led to lower grain yields in the nation, especially maize yields whereas, maize remains a key staple crop in South Africa; therefore, food insecurity, welfare and poor nutritional status are projected to deteriorate due to rising food costs brought on by the change in climate (Bai et al., 2019; De Pinto et al., 2020). Meanwhile, agricultural production depends on the appropriate use of inputs that will ensure a sustainable agricultural output as well as environmental sustainability (Akamani, 2021; Anderson et al., 2020). These inputs are inter alia, appropriate soil tillage, proper plant population, improved cultivars, fertilizer application, weeding, pest and disease management, harvesting, marketing, and finance are among these inputs (Batisani et al., 2021; Descheemaeker et al., 2016; Omotayo et al., 2022).

Notably, drastic changes in rainfall patterns as well as rising temperatures led to adverse growth conditions in planting calendars, changing growing seasons and impacting South Africa's crop production (Aggarwal *et al.* 2019; Bhandari *et al.*, 2022). Consequently, these changes affect food prices, land-use and cause uncertainty in farming households' welfare status (Omotayo et al., 2022; Owuso Essegbey et al., 2015). The capacity to manage the effects of unstable weather events and natural disasters on maize production brought on by climate change primarily dependents on the farmers' resilience, or their capacity to endure and recover from the impacts (Ng'ang'a et al., 2021; Odularu, 2020). In order to enable them to ensure sustainable livelihoods and welfare, it is crucial to increase their adaptability and resilience to climate change's detrimental effects on their productivity (Li et al., 2022; Maindi et al., 2020).

Climate-smart agricultural (CSA) practices are a major strategy for combating climate change impacts as well as ensuring agricultural sustainability through building resilience to climate change (Mbuli et al., 2021; Neufeldt et al., 2013; Oguge & Oremo, 2017). CSA aims to boost agricultural production and incomes in a sustainable way by promoting climate change adaptation through decreasing or eliminating greenhouse gas (GHG) emissions in comparison to traditional agricultural practices (Bai et al., 2019; Batisani et al., 2021). Specifically, improved seeds, such as drought-tolerant maize varieties (DTMVs) and organic manure, are the essential component of CSA practices mostly adopted by rural farmers in South Africa.

Noteworthy, without taking into account other related CSA practices, the adoption of one practice is unlikely to have a substantial impacts on the productivity and welfare of the rural smallholder farmers (Adego & Woldie, 2022; Aggarwal et al., 2018). The simultaneous adoption of DTMVs and organic manure represents a holistic approach to climate resilience in agriculture (Omotoso & Omotayo, 2024; Oyetunde-Usman et al., 2023). Existing studies (Amadu et al., 2020; Bahri et al., 2021; Kangogo et al., 2021), mainly focused on individual components of CSA (such as crop rotation, soil and water conservation and agroforestry), but this research addresses the combined impact of two crucial elements—crop resistance to drought and improved soil fertility through organic manure. Through examining the combined impact of DTMVs and organic manure, the research uncovers synergistic effects that goes beyond the sum of individual interventions. Understanding how these practices interact and complement each other is essential for designing effective and integrated CSA strategies.

Consequently, (Akanbi et al., 2021a; Rosenstock et al., 2019) posited that the vulnerability of rural smallholder farmers in South Africa, especially in the North West province is increasing due to their limited adaptive capacity and their low level of economic development (Akanbi et al., 2021a). As a result, smallholder farmers in this province are struggling to mitigate the impacts of climate change due to the poor services offered by the weak institutions, meager sources of income, ineffective extension services and inadequate infrastructure (Abegaz et al., 2023; Osinubi & Apanisile, 2021; Regmi et al., 2022). Notably, North West province is one of the country's leading producers of maize (Akanbi et al., 2021a). As a result, there is little doubt that an analysis of the simultaneous adoption of organic manure and DTMVs for efficient maize production, the major economy catalyst in South Africa's North West Province, has become a critical factor. Despite the continuous and constant upsurge of the severe consequences of climate change, particularly among the province's smallholder maize farmers, a review of the existing literature (Adesete et al., 2022; Akano et al., 2023; Ricart et al., 2023) has revealed that there is little scientific knowledge on the implications of climate change on the productivity and welfare status of farmers in the North West province.

While many studies (Akanbi et al., 2021a; Tione et al., 2022), focused on the agronomic impacts of CSA, such as yield improvements, this research delved into the economic and social dimensions of the concurrent adoption of CSA practices. Our study investigates the impacts on farmers' livelihoods (productivity), and welfare outcomes in term of consumption-expenditure and food security, providing a comprehensive understanding of the broader implications. Additionally, the paper's contribution extends to the practical implications it offers for policymakers and other development agencies. Furthermore, by generating empirical evidence on the concurrent adoption of DTMVs and organic manure, the research provides policymakers with actionable insights to design and implement more effective and integrated climate-smart agricultural policies for small holder farm production systems in South Africa.

5.2 Response to climate change through adoption of DTMVs and organic manure: Implications on rural welfare in South Africa

The connection between climate change, productivity and/or welfare of rural smallholder farmers has become an intriguing research focus (Kangogo et al., 2021). Numerous studies (Omotoso et al., 2023; Ricart et al., 2023; Tione et al., 2022), reported that climate change would exacerbate multidimensional poverty and severely impacts the productivity of rural farmers in most developing nations, particularly in the rural Southern Africa. Inarguably, agriculture is the principal effect route for climate change in these areas since the majority of rural communities rely on rain-fed agriculture for a living (Anuga et al., 2022; Omotoso et al., 2022; Tilahun et al., 2023). It is anticipated that South Africa would experience less precipitation, which will have severe impacts on the country's agricultural output over the long future (Adego & Woldie, 2022; Akanbi et al., 2021a; Mullins et al., 2018).

In accordance with (Akano et al., 2023; Mullins et al., 2018; Omotayo, Ijatuyi, et al., 2020), the country's annual rainfall would decrease by 3% and 6% by the years 2050 and 2100, respectively, while the mean temperature of the country will rise approximately by 1.9 °C and 2.3 °C, over the same period. These shifts in temperature and rainfall will certainly lower the amount of water that is available throughout the nation by 13% in the year 2100, which will have detrimental effects on productivity and welfare status of rural smallholder farmers (Anuga et al., 2022; Gram et al., 2020; Mullins et al., 2018). Regrettably , drought is the major component of climate change primarily contributing to both decreased agricultural productivity and welfare of rural households of the country (Bahri et al., 2021; Kangogo et al., 2021). It is estimated that agricultural yields are reduced by 39.3% when drought conditions occur in the middle of the growing season, especially during the vegetative and productive periods (Aggarwal et al., 2018; Gram et al., 2020).

Accordingly, the anticipated rise in temperature is quite likely to have enormous repercussions for the production of maize and, as a consequence, for the well-being and means of subsistence of rural farmers (Ricart et al., 2023). Thus, it is very necessary to acclimatize to these climate variations so as to maintain the economic and the food system of the country (Njuguna et al., 2022). The DTMVs and organic manure are two major CSA strategies integrated into agricultural practices that have been implemented to mitigate climate change impacts in the country (Asravor, 2022; Mullins et al., 2018). Therefore, DTMV and organic manure integration have been seen as a part of the answer to maintaining maize output, particularly under smallholder farming settings, and ensuring sustainable households' welfare (Brempong et al., 2023; Keshavarz & Sharafi, 2023; Tran et al., 2019).

In addition, experimental evidence by (Akamani, 2021; Onyeneke, 2021), has shown that using organic manure does not only increases yield by 15% but also increased soil bulk density, improve soil's physical makeup and biological activity which is essential for proper functioning of crop planted. Likewise, (Cheng et al., 2022; Gram et al., 2020), reported that DTMVS increases the productivity of maize farmers by 25% through withstanding environmental harsh conditions compared to the conventional maize breed. According to (Maindi et al., 2020; Tran et al., 2019), improved farm yield denotes high productivity, which will improve the income and consumption-expenditure of the farming households and at long run improve their welfare status. Despite their significance, the simultaneous adoption of DTMV and organic manure have not yet received the same level of recognition as chemical fertilizers or conventional maize seeds, which are still commonly used by smallholder farmers (Leisner, 2020; Ricart et al., 2023). According to (Akanbi et al., 2021b; Amadu et al., 2020), perception for delayed nutrient release, labor-intensive, extension failures, inadequate knowledge, and lack of understanding of the benefits are impediments to their adoption.

Correspondingly, there have been few research on sole adoption impact of organic manure and DTMVs on rural farmers' productivity, but studies on simultaneous adoption impact of DTMV and organic manure are inconsistent, fragmented, or limited in scope. Currently, South Africa face two key environmental related challenges among others: (i) increases in agricultural output to meet the needs of an expanding population, which is expected to reach 100 million by 2050, without compromising the wellbeing of the farmers and (ii) increase the resilience of the region's agri-food systems to the effects of present and predicted future climate change (Baiyegunhi et al., 2022; Green et al., 2023; Merga et al., 2023). The research aims to develop and promote practices that empower farmers to adapt and thrive in changing conditions. Therefore, study on simultaneous adoption of DTMV and organic manure is germane because it will aid government and other stakeholders in policy discussions on DTMVs and organic manure, implementation techniques, as well as decision-making that will enhance agricultural sustainability and welfare of rural smallholder farmers in South Africa.

5.2.1 Conceptual and theoretical framework

Following (Atta-Aidoo et al., 2022; Tilahun et al., 2023), theory of planned behaviour (TPB) was adopted for this study to understand the various ways in which CSA practices adoption have impacted on the productivity of smallholder farmers, and how such impacts mitigate their vulnerability and welfare outcomes. The TPB is based on the assumption that rational thinking about adopting certain technology influences people's decisions, choices and actions (Atta-Aidoo et al., 2022; Gwara et al., 2022). Consequently, the three goals of CSA practices are to promote a sustainable increase in agricultural productivity, adapt to the challenges of climate change, and reduce or remove greenhouse gas (GHG) emissions that emanates from agricultural practices (Ewunetu et al., 2023; Gebrehiwot, 2015; Omotoso & Omotayo, 2024). The CSA in this framework (Figure 5.1) was intended to integrate these three goals to enhance agricultural productivity and welfare outcomes among smallholder maize farmers under a changing climate. As indicated in Figure 1, the conceptual framework (TPB) is intended to provide an understanding of how the impact of climate change on the productivity and welfare outcomes of smallholder maize farmers could be mitigated through the adoption of climate-smart agricultural (CSA) practices. The framework consists of the following eight sections:

1. CSA framework: to promote a sustainable increase in agricultural productivity, adapt to the challenges of climate change, and reduce or remove greenhouse gas emissions through positive attitude towards CSA practices.
2. Previous agricultural practices: farmers' perceptions of their ability to control and implement specific practices can be crucial. They can discontinue previous practices due to perceived barriers, lack of resources, or inadequate knowledge and skills. Identifying these control factors can help in addressing barriers to adopt new agricultural technology.
3. Welfare outcomes: TPB can be applied to assess farmers' intentions to adopt sustainable agricultural practices to enhance their welfare outcomes. It can help understand why farmers choose particular farming methods, crop varieties, or conservation techniques.
4. New CSA practices: in the face of farmers' positive attitudes and strong intentions to adopt these technologies, interventions can focus on providing training, access to resources, and support to facilitate their adoption.
5. Farmers' socioeconomic characteristics: play a significant role in influencing adoption behaviour, including the adoption of new practices, technologies, or innovations.
6. Adoption of CSA (extension services): the uptake of new technology, this being a reflection of the farmers having a positive attitude towards new technology through having had contact with and support from participation in extension training.
7. Adoption level: subjective norms consider the influence of social factors on adoption behaviour. If individuals perceive that important other (e.g., peers, leaders, experts) support

the adoption of a specific behavior, it can positively impact adoption level. The endorsement of an innovation by trusted individuals or groups can encourage its adoption.

8. Maize farmers' productivity: the adoption of CSA practices offers substantial potential for improving maize productivity in the context of climate change and variability.

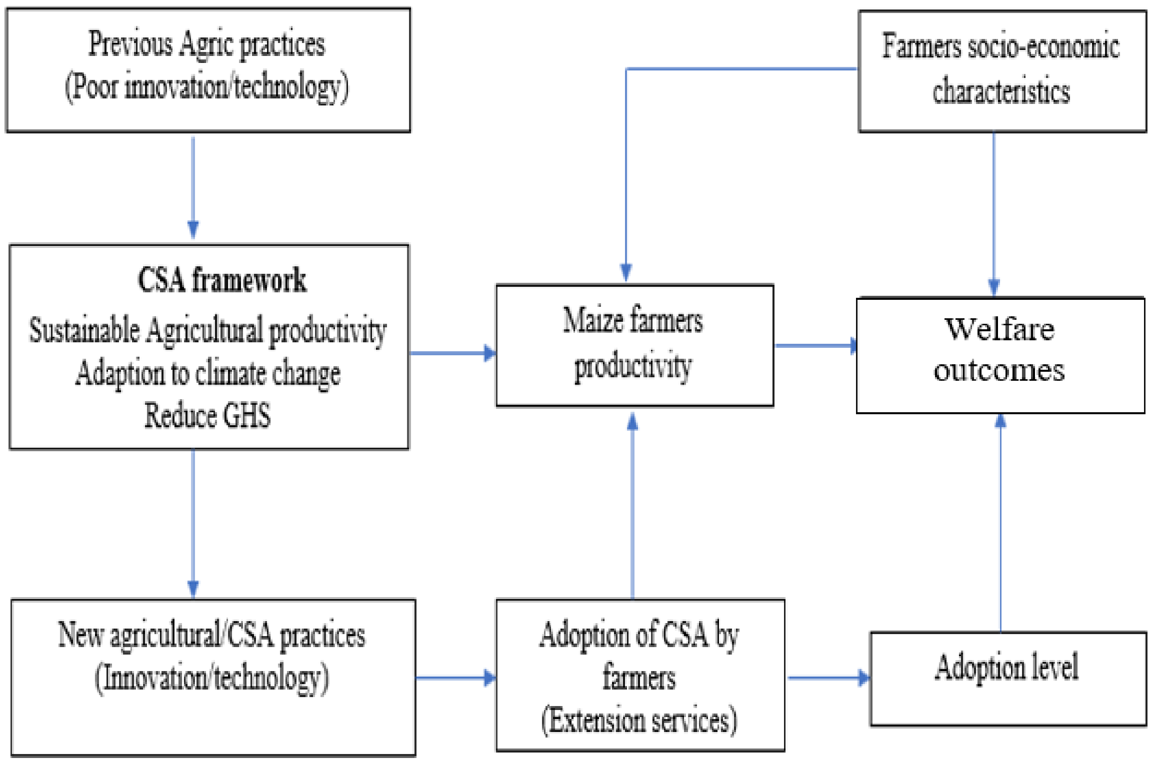

Fig. 5.1. Conceptual framework of the adoption impacts of Climate-Smart Agricultural Practices on smallholder's maize productivity and welfare outcomes

5.2.2 Measurement of welfare

i. Consumption-expenditure: Per capita household expenditure

The rural households' welfare status can be measured using food security status, income or per capita household expenditure (Odularu, 2020; Olawuyi et al., 2022; Tran et al., 2019). Following (Baiyegunhi et al., 2022; Merga et al., 2023), money-based indicators of household welfare were used to mimic the economic behavior of households under limited utility maximization. It is considered that the social and economic conditions in which production choices are made are described by the amount of money households spend on consumption (Merga et al., 2023; Tran et al., 2019). The consumption-expenditure welfare expression notion seems to be a suitable indication of farmers' actual wellbeing (realized welfare) as opposed to their predicted future welfare increases (income) (Dey & Mishra, 2022; Kangogo et al., 2021).

Following (Baiyegunhi et al., 2022; Olawuyi et al., 2022), the households per capita estimations of consumption-expenditure on food and non-food items were used to generate the welfare indicator and expression for this study (Table 1). Comparing this method to other related ones for creating welfare indicators (such as poverty and food security status), it outlined variable outcomes that are more suited for investigating impact research (Omotayo et al., 2022; Ritzema et al., 2017). Following (Baiyegunhi et al., 2022; Bjornlund et al., 2022), the households' welfare of the respondents was expressed as;

$$W_i = \frac{per\ capital\ total\ consumption - expenditure\ of\ ith\ households}{\frac{2}{3}\ mean\ per\ capital\ total\ expenditure\ of\ all\ households} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

Where W_i = Index of households' welfare status

ii. Food security indices: Households Dietary Diversity Scores (HDDS)

Considering the multidimensional nature of welfare status, we also captured it using household dietary diversity score (HDDS). Following (Issahaku & Abdulai, 2020; Neufeldt et al., 2013; Tran et al., 2019), HDDS which denote the food security status of the rural smallholder households was used as proxy to measure the welfare status in term of dietary-quality of the households. This welfare indicator (HDDS) assesses food diversity arising from dietary quality and adequacy as a result of output from farm and CSA practices adopted to improve farming operations (Tilahun et al., 2023). Following (Akter et al., 2023; Omotayo et al., 2022; Omotoso et al., 2022), food consumes by a family over a week was divided into twelve categories: cereals, tubers and roots, vegetables, fruits, meat and poultry, eggs, fish, pulses and nuts, legumes, milk and milk products, oils and fats, sugar and honey, and miscellaneous. This was utilized to calculate the HDDS, which was shown to be an excellent predictor of families' nutritional condition in South Africa.

5.3 Methodology

5.3.1 Study area

South Africa is Africa's southernmost nation, having a land area of 1,221,037 square kilometers. The nation is bounded to the south by the South Atlantic, with 2,798 km of coastline, and to the north by Botswana, Namibia, and Zimbabwe. This research was carried out in South Africa's North-West province (Figure 5.2). The province is located on the Botswana border, to the north of South Africa, and is flanked to the west, east, and south by the Kalahari Desert, Gauteng province, and Free State province, respectively. It is located at an elevation of 1389.85m above sea level with a sub-tropical steppe climate (Akanbi et al., 2021a). It has a yearly temperature of 22.36^{0}C and typically experience approximately 36.6mm of precipitation with about 61.9 rainy days annually (Abler, 2023; Ren et al., 2018). North-West province (Figure 5.2) accounts for about 9.0% of South Africa's land area, with a land mass of 106,512 square kilometers, making it the fourth smallest province in South Africa (Akano et al., 2023). Mahikeng is the province's capital city, where more than 80% of the province's economic activity is now concentrated. Mining and farming, particularly maize production, contribute considerably to the province's economy.

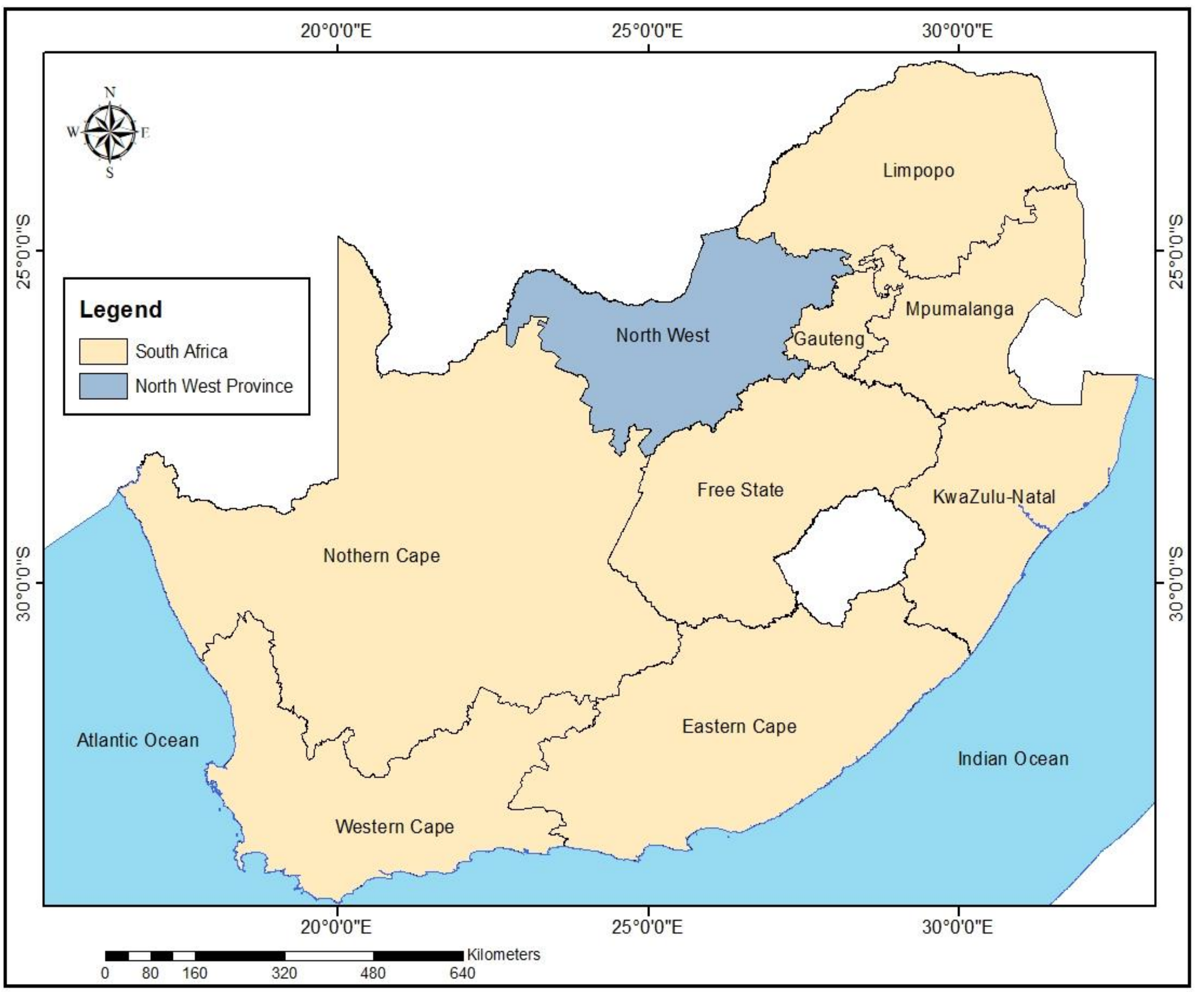

Fig. 5.2. Map of South Africa showing geographical location of North West province

Maize farming is the backbone of the majority of South African rural farm families and grown in various regions throughout the country due to its adaptability to different climatic conditions (Akano et al., 2023). It a staple food crop which accounts for over 70% of total grain production in the country, covers approximately 65% of cropping land area, and its cultivation essential for ensuring food-nutrition security and supporting the livelihoods of many rural farm households through revenue generating and job creation (Ricart et al., 2023). Interestingly, North-West province has been consistently ranked (third) among the top provinces in South Africa for maize cultivation due to its favorable agro climatic conditions, including fertile soils and human capital, which make it suitable for maize production (Ricart et al., 2023).

Unfortunately, the consistence rises in temperature coupled with epileptic rainfall due to climate change have influence the ecological balance and biodiversity in the province (Akano et al., 2023). Notably, maize production contributes significantly to the province's economy and livelihoods of the dwellers (Omotayo, Omotoso, et al., 2020; Rosenstock et al., 2019). Research on the impact of adoption of CSA (DTMVs and organic manure) on rural maize farmers’ productivity and welfare would highlight potential economic implications of climate change, such as changes in yield, farm incomes, and households’ per capita expenditure. This information can guide economic planning and decision-making at both local and national levels.

5.3.2 Sampling procedures and data analysis

The dataset utilized in this study relied on primary information gathered via a field survey of smallholder maize farmers in South Africa's North-West province (Figure 5.3) at the end of 2022 agricultural season. The province's four municipalities (Bojanala District, Ngaka Modiri Molema District, Dr Kenneth Kaunda District, and Dr Ruth Segomotsi Mompati District Municipality) were sampled using a multistage sampling approach. To ensure that the data obtained is precise, dependable and unbiased, the initial stage included choosing all four municipalities in the province. In the second stage, fifteen local villages in the North West province that are widely known for their maize production were chosen at random.

The third stage required selecting two communities at random from each local municipality that were mostly recognized for subsistence maize farming (a total of 30 villages). Finally, the last stage involved the selection of all the 316 smallholder maize farmers that participated in extension training on improved agricultural technology from the attendant available with the district extension officers. Descriptive statistic was used to analyze the data, resulting in the establishment of frequencies, means, and standard deviations (SD). The Multinomial Endogenous Switching Regression model (ESRM) was used to analyze the impacts of simultaneous adoption of DTMVs and organic manure on the rural farmers' productivity and welfare outcomes in South Africa.

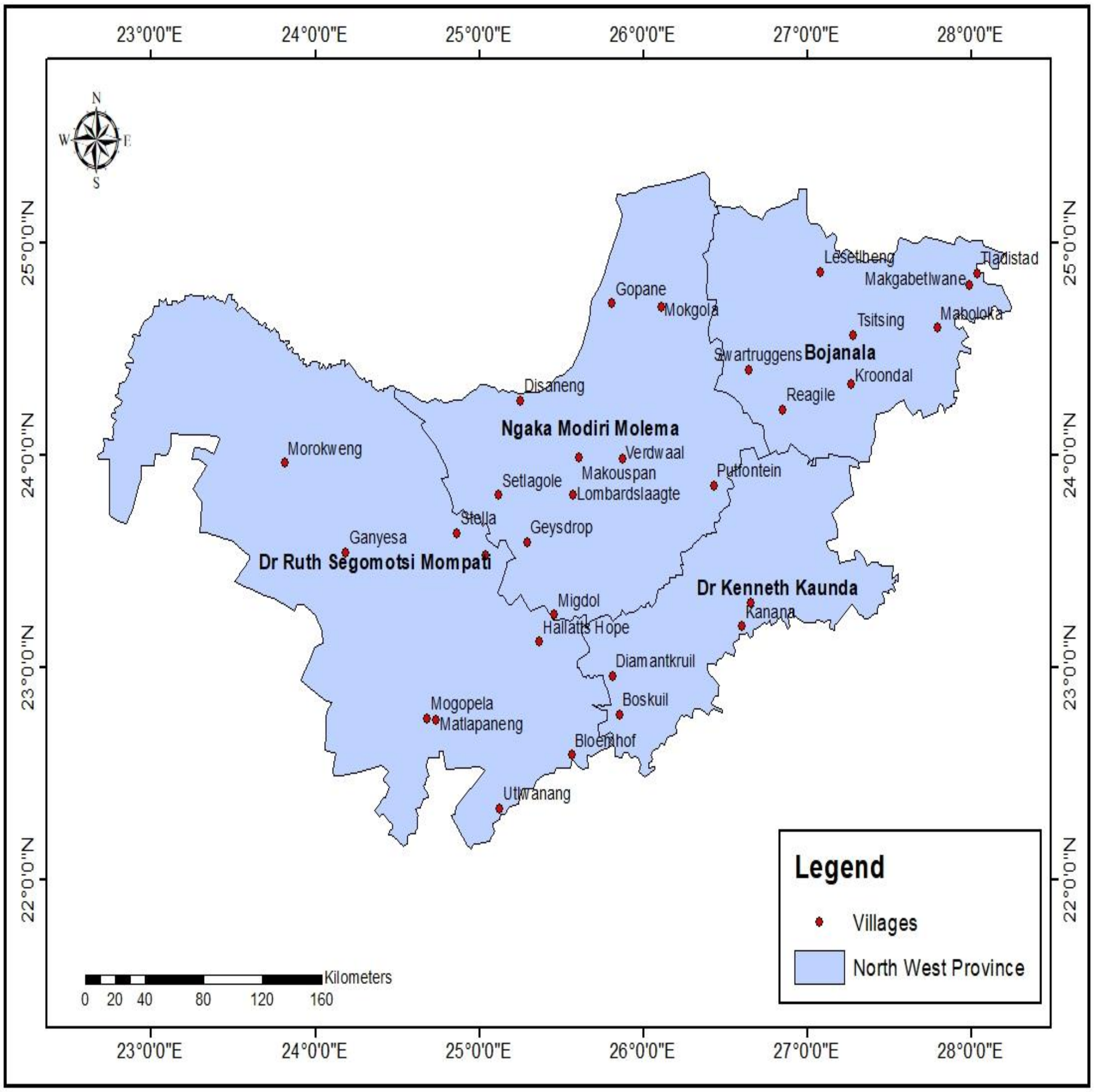

Fig. 5.3. Geographical representation of the 30 selected maize production villages in North West province, South Africa

5.3.3 Model specification and estimation strategies

5.3.3.1 Technology adoption decision and impact evaluation

Using a random utility framework, we modelled a household's choice to adopt DTMVs and organic manure. Let M_i indicate the difference in utility between adopting DTMVs and organic manure (U_{i1}) and using traditional practices (U_{i0}). Rural farmers choose to simultaneously adopt DTMVs and organic manure if the value of adoption outweighs utility of conventional practices or adopting only one; $U_{i1} - U_{i0} > 0$. However, the two utilities are non-observable, such that the net benefit (M_i,) obtains by the farmer by adoption is a latent variable determined by the observed and unobservable attributes provided in equation (1).

$$M_i = X_i\beta + \mu_i \quad \text{given that } M_i = \begin{cases} 1 \text{ } if \text{ Mi} > 0 \\ 0 \text{ } otherwise \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.2)}$$

Where M_i is a binary variable denoting the adoptions of DTMVs and organic manure; β is a vector of parameters to be estimated; X is a vector of rural smallholder farmers' socioeconomic and institutional characteristics influencing farmers' adoption decisions (Table 5.1); and μ is the random error term. However, this research evaluates the relationship between DTMVs and organic manure in the context of rural smallholder farmers' household, with the goal of boosting their productivity and welfare status. Consequently, due to the many climatic threats that rural smallholder farmers in South Africa must contend with, simultaneous adoptions of CSA practices have been shown in several research to improve their productivity and welfare (Anuga et al., 2022; Galani et al., 2022; Rosenstock et al., 2019; Siegwart et al., 2023).

Following (Ado et al., 2020; Jellason et al., 2021), the possible adoption options for DTMVs and organic manure are as follows (Table 1); 1) adopting neither DTMVs nor organic manure (D_0M_0). 2) adopting DTMVs alone (D_1M_0); 3) adopting organic manure solely (D_0M_1); and 4) adopting both DTMVs and organic manure (D_1M_1). Given the limitations of current rural smallholder farmers, thus they base their adoption decisions on the anticipated productivity and welfare improvements. As a result, we model the results of productivity and welfare outcomes (Y_{ji}) as a linear forecast of adoption choices (T_{ji}) and rural smallholder farmers' socioeconomic characteristics (X_{ji}).

$$Y_{ji} = \alpha X_{ji} + \beta T_{ji} + \mu_{ji} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.3)}$$

Where α and β are parameters to be estimated and μ_{ji} represent the error term. However, farmers choose to adopt certain technology depending on the knowledge available to them, adopters and non-adopters of DTMVs and organic manure may not be randomly allocated to the two groups because they are systematically different. As a result, selectivity bias must be resolved. To do this, following (Ankrah et al., 2023; Ogundari & Bolarinwa, 2019), we combined the Multinomial Endogenous Switching Regression (MESR) with Propensity-Score Matching (PSM) to determine the estimation impacts. The combination of the two models improved the estimates since each model has constraints that cannot be rectified separately (Ankrah et al., 2023; Ogundari & Bolarinwa, 2019).

i. Multinomial Endogenous Switching Regression (MESR)

Due to rural farmers' endogenous self-selection into adoption and non-adoption categories, it is possible for there to be bias owing to observable and unobserved factors (Ankrah et al., 2023; Ngoma et al., 2021). Following (Merga et al., 2023; Olagunju et al., 2020), we employed MESR, for selectivity bias correction based on a multinomial logit model. Furthermore, a number of empirical studies (Ngoma, 2018; Obi & Maya, 2021; Oyetunde-Usman et al., 2023), that assessed the influence of agricultural technology revealed the importance of unobservable elements in impact assessment. As a result, we used MESR to account for unobservable factors influencing both the adoptions and outcome variables.

The MESR framework is divided into two stages. The first stage involves estimating the selection equation i.e., rural farmers' decision to adopts various combination package (DTMVs and organic manure) or not. A multinomial logit model was used in the first stage of the MESR model, which models the determinant of individual and combinatory selections of DTMVs and organic manure which accounted for the unobserved heterogeneity. Following (Ahmed, 2022), the selection equation for the adoption decision is specified as;

$$M_i = X_i\beta + \mu_i \qquad \text{given that } M_i = \begin{cases} 1 \; if \; \text{Mi} > 0 \\ 0 \; otherwise \end{cases} \qquad (5.4)$$

Where M_i is a binary variable denoting the adoption combinations of DTMVs and organic manure; β is a vector of parameters to be estimated; X is a vector of rural farmers' socioeconomic, and institutional characteristics (access to extension training on improved agricultural production practices, credit and climate information) influencing farmers' adoption decisions; while μ is the random error term. The MESR model, in addition to accounting for selectivity bias, it estimates the influence of CSA (individual and simultaneous adoptions of DTMVs and organic manure) practices on outcome variables through interaction between the choices of various CSA practices and the explanatory variables (Antwi-Agyei et al., 2021; Njuguna et al., 2022).

In the second stage, an Ordinary Least Squares regression is combined with a selectivity correction term that was produced from the first stage to determine the association between the outcome variables (productivity, per capita total household expenditure, per capita household expenditure on food and HDDS) with collection of explanatory factors conditional on the adoption decision of DTMVs and organic manure (D_1M_0, D_0M_1, and D_1M_1). The model result is presented in Appendix B2 to B5. The explicit form of ESRM is expressed as follows:

Considering that the rural farmer might decide to adopt an adaptation strategy (or not), the expected benefits would then assume the following values:

$M_j = 0$ (non-adopters): $M_jK = X'\beta_jK + U_jK$ if $D_j = 0$ ……………… (5.6)

$M_j = 1$ (adopters): $M_jA = X'\beta A + U_iA$ if $D_j = 1$ ……………… (5.7)

Where M_jA and M_jK are the dependent variables for an adopter and non-adopter of DTMVs and organic manure, respectively, while X' is the vectors of the explanatory variables. Following (Gebre et al., 2023; Siegwart et al., 2023), we applied selection instrument to get a more robust identification. Following (Kangogo et al., 2021; Paul et al., 2018), participation in extension training on improved agricultural production practices (Dummy; 1=Participate in extension training, 0= otherwise) was used as our selection instrument. Notably, “access/contact with extension” is a broader term that encompasses all interactions between farmers and extension services, while "participation in extension training" specifically refers to formalized educational opportunities aimed at enhancing farmers' skills and knowledge in adopting certain technology (Dercon et al., 2009; Gebrehiwot, 2015).

Additionally, participation in extension training on improved agricultural technology not only facilitates the adoption of advanced agricultural technologies but also contributes to positive outcomes in terms of increased productivity and improved welfare for farmers (Danso-Abbeam et al., 2018). Participation in extension training often involves hands-on training sessions and demonstrations, allowing farmers to develop the necessary skills to effectively implement and utilize agricultural technologies (Ado et al., 2020; Akanbi et al., 2021a; Omotayo, Ijatuyi, et al., 2020). Improved skills increase the confidence of farmers in adopting new technologies and enhance their ability to utilize them optimally (Ado et al., 2020; Akanbi et al., 2021a; Omotayo, Ijatuyi, et al., 2020). The knowledge, skills, and support gained through extension training create a foundation for sustainable and resilient agricultural practices (Danso-Abbeam et al., 2018; Gebre et al., 2023). Likewise, improved productivity from technology adoption can directly translate into increased income for farmers, positively impacting their economic well-being (Gebre et al., 2023). Following (Antwi-Agyei et al., 2021; Njuguna et al., 2022), through a falsification test, the acceptability of the indicated instrument (participation in extension training on improved agricultural production practices) was established. The result (Appendix B1), demonstrated that the selected instrument is considerably essential in describing the adopter's decision behaviour but not in explaining the non-adopter's outcome variables in South Africa.

Average Treatment Effects on the Treated (ATT) estimations

Following (Ahmed, 2022; Merga et al., 2023), the ATT was employed to determine the impacts of combinatory adoptions of DTMVs and organic manure on outcome variables. It was estimated using the paradigm described above (equation 5.8 & 5.9) by comparing the expected outcomes of adopters with and without adoption as follows:

Adopters with adoption

$$M(K_{ij}/j = 0) = K_i^u \alpha_j^u + \alpha_j\lambda_j$$

$$M(K_{ij}/j = J) = K_i^u \alpha_j^u + \alpha_j\lambda_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5.8)$$

Adopters, had they decided not to adopt

$$M(K_{ij}/j = 0) = K_i^u \alpha_0^u + \alpha_j\lambda_j$$

$$M(K_{ij}/j = J) = K_i^U \alpha_0^U + \alpha_j\lambda_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5.9)$$

ATT was computed as the difference (7a) and (8a) which given as following;

$$ATT = M(K_{ij}/j = 0) - M(K_{ij}/j = 0) = K_i^u (\alpha_j^u - \alpha_0) + (\lambda_j - \lambda_0) \quad \ldots\ldots\ldots\ldots\ldots..(5.10)$$

ii. Propensity-score matching estimation

The most difficult task facing empirical research on adoption impact is establishing a causal relationship between the use of the adopted technology and the outcome variables (Siegwart et al., 2023; Thakur & Uphoff, 2017). The motivations for a household's adoption of technology may be linked to household personal characteristics, which will have significant effect on productivity and welfare results (Ahmed, 2022; Galani et al., 2022). Following (Oyetunde-Usman et al., 2023; Tilahun et al., 2023), we employed propensity-score matching (PSM) to solve the endogeneity problem. Following (Baiyegunhi et al., 2022; Merga et al., 2023), we assessed the counterfactual and real impact of adoption combination of DTMVs and organic manure on outcome variables through PSM methodology, which solely takes into account the impact based on observables. This approach is predicated on the idea that there are no unobservable differences between adopters and non-adopters of each combinatory option category (Hasan et al., 2018; Jennings et al., 2022). This was used as follows in estimating the ATT in each adoption decision categories:

$$ATT = E\,[Y\,(1)/T = 1, p\,(x)] - E\,[Y\,(0)/T = 1, p\,(x)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.11)$$

However, there are drawbacks to the PSM technique, such as the fact that typical approaches like regression analysis are more likely to reduce model reliance after the matching process is complete due to preprocessing difficulties like reweighting and discarding of data (Abegaz et al., 2023; Traore et al., 2021; Zografos et al., 2016). Following (Akter et al., 2023), we employed the nearest neighbor matching (NNM) technique (Appendix B3), to check the robustness of ATT through employing a method that accounts for the covariate balance through employing weigh functions to correct for the control units. Following (Atta-Aidoo et al., 2022; Issahaku & Abdulai, 2020), estimates is expressed as;

$$E\,[Y\,(0)\,l\,D = 1] = \quad \sum_1 \alpha \left[{}'\Upsilon\,(\acute{\alpha}\delta)\,\frac{1}{\delta}{}'\Upsilon(qi\; - \;Xi\delta)\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.12)$$

5.3.3.2. Productivity estimation

Agricultural productivity can be measure by the termed Total Factor Productivity (TFP) which denotes the index of measurement of agricultural value of output in relation to the input (Kangogo et al., 2021; Tran et al., 2019). TFP is adequacy as a result of output from farm and CSA practices adopted to improve farming operations. Following (Anuga et al., 2022; Mutengwa et al., 2023), TFP was used to measure the productivity of rural farmers in South Africa by computing an index of agricultural input to output in 2022/2023 agricultural season (Appendix B1). According to (Regmi et al., 2022; Siegwart et al., 2023), the productivity of the farm households was expressed as;

$$TFP = \frac{Y}{\sum_1^n xi, x2, \ldots, xn} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.13)$$

Where Y = quantity of maize harvested (ton/ha)

X = values of input used in production

5.4 Results and discussions

5.4.1 Descriptive statistics

The CSA practices evaluated in this study include Drought Tolerant Maize Varieties (DTMVs) and Organic Manure, resulting in four possible combinations (D_0M_0, D_1M_0, D_0M_1, and D_1M_1) as shown in Table 5.1. Approximately 90.0% of farm households adopt various combinatory package of DTMVs and organic manure (D_1M_0, and D_0M_1 D_1M_1) on their farm while about 1% of farm households did not adopt any of them (D_0M_0). It also depicts (Table 5.1) the distribution of each adoption classification according to the outcome factors (productivity (ton/ha), per capita households' expenditure, per capita household expenditure on food and HDDS). As revealed, returns on outcome variables are marginally greater for simultaneous adopters of DTMVs and Organic Manure (D_1M_1) compared to solely adopters of DTMVs and Organic Manure (D_1M_0, and D_0M_1).

Additionally, the data comprehensively addressed numerous household characteristics relating to adoption decision of the farm households. For the study, following (Mutengwa et al., 2023; Tilahun et al., 2023; Tran et al., 2019), we considered factors derived from comparable empirical studies on adoption and impact, conducted previously on climate-smart practices. We adapted the characteristics of rural farmers, which include socioeconomic factors (such as gender, age, family size, farm experience, land ownership, and farm size), and institutional factors (climatic information, access to social grant and participation in extension training). Table 5.2 provides a description of variables and statistical summaries based on adoption of combinatory package of DTMVs and Organic Manure collected via the field survey of smallholder farmers. Following (Gebre et al., 2023; Oyetunde-Usman et al., 2023; Zheng et al., 2023), previous impact studies on enhanced maize varieties, the outcome variables considered are productivity (ton/ha), per capita households' expenditure, per capita household expenditure on food and household dietary diversity score as a measure of welfare outcomes.

The average age of these household heads in South Africa's rural areas was 45 years. This imply that the household heads may have significant experience in traditional agricultural practices. This experience would influence their openness and willingness to adopt new technologies (Amadu et al., 2020). With regard to education status (Table 5.1), the majority of the household heads are educated. Higher education scores are indicator of strong human capital which equips farmers with knowledge and skills to make informed decisions about improved agricultural production practices (Ricart et al., 2022). With improved agricultural practices, rural farming households would experience higher crop yields and better income generation, contributing to poverty reduction and economic growth in the community (Ricart et al., 2022).

Additionally, the majority of the rural farmers participated in extension training on improved agricultural technology. Participation in improved agricultural technology incorporated with climate-smart training have significant implications on the adoption of agricultural technology and climate change adaptation strategies among rural farm families (Amadu et al., 2020; Wossen et al., 2017). More so, extension training plays a significant role in knowledge dissemination, providing technical assistance, and supporting farmers in making informed decisions on agricultural production (Wossen et al., 2017). As depicted in Table 5.2, rural farmers with a wider range of income sources have the potential to adopt various combination of DTMVs and organic manure, because they have a wider range of resilient livelihood alternatives which influences the adoption decision of the households on improved CSA technology in South Africa.

According to (Mutengwa et al., 2023; Tilahun et al., 2023; Tran et al., 2019), at the initial stage of the adoption of new technology, investments and savings are essential because they may be utilized to increase capital and lessen susceptibility to climate change impacts on rural farmers' productivity and welfare outcome. Likewise, remittances in the form of access to social grants will boost and diversify the sources of income for rural households, which might lessen their vulnerability to climate change and enhance their combinatory adoptions of DTMVs and organic manure in the study area. Ceteris paribus, a household's vulnerability to climate change decreases with the amount of money it gets in gifts and the number of individuals (networks) it can depend on when faced with climate shocks (Anuga et al., 2022; Mutengwa et al., 2023).

The model also included agricultural enterprise diversification to explore whether it might enhance the DTMVs and organic manure adoption decision of the rural households. This comprised agricultural operation for animals, poultry, and other micro-livestock. Opined by (Mutengwa et al., 2023; Tilahun et al., 2023; Tran et al., 2019), agriculture across different enterprises lowers risk and increases the likelihood that families will have steady revenues, allowing them to adopt capital-intensive technology and less erratic agricultural operations (Omotayo et al., 2022; Ritzema et al., 2017). This encourages stable food intake in the home and reduces vulnerability to climate change impacts (Daud et al., 2018; Kangogo et al., 2021; Omotoso et al., 2022). Because of this, a satisfying connection is anticipated.

In terms of being a member of social organizations (such as cooperative societies or farmers' associations), strengthens social networks and relationships. These connections serve as platforms for knowledge sharing and dissemination of information on new agricultural technologies (Omotayo et al., 2022; Ritzema et al., 2017; Wossen et al., 2017). By being a member of such organizations, rural farmers gain access to information about innovative technologies, their benefits, and successful case studies, which can lead to increased awareness and interest in adopting these technologies which will transform into improved productivity and welfare of the rural farmers (Odularu, 2020; Olawuyi et al., 2022; Tran et al., 2019).

Table 5.1. Descriptions and summary statistics of the variables used in the analysis

Variables	Descriptions	Mean	Std. Dev.	Min	Max
Outcome variables					
Productivity	Maize per hectare produced in 2022/2023 agricultural season (ton/ha)	3.84	2.13	1.04	4.98
Per-capita total household expenditure	Estimate value of all household expenditure divided by the total household's size. The total household expenditure comprises of total expenditure on food and non-food item (Rands)	5300.33	5630.82	1000	25000
Per-capita food expenditure	Total expenditure on food divided by the total household's size (Rands)	3816.72	6156.19	200	15000
Households Dietary Diversity score (HDDS)	Measured by intake of 12 food groups consumes by the HH within a week	7.82	4.05	2	11
Treatment variables					
D_0M_0	Adopt neither DTMVs nor organic manure	0.110	0.084	0	1
D_0M_1	Adopt organic manure alone	0.262	0.291	0	1
D_1M_0	Adopt DTMVs alone	0.471	0.196	0	1
D_1M_1	Adopt both DTMVS and organic manure	0.167	0.107	0	1
Socioeconomic characteristics					
Age	Actual age of household head (HH)	45.10	11.51	19	74
Gender	Dummy; 1=male, 0=female	0.686	0.55	0	1
Household size	Total member of household	4.73	2.25	1	12
Marital status of the head	Dummy; 1 if married, 0 if otherwise	0.759	0.47	0	1

Educational status of the household head	Dummy; 1 if educated, otherwise	0.852	0.63	0	1
Years of experience	Actual year (continuous)	25.21	14.51	5	36
Off-farm income	Dummy; 1 if yes (HH engaged in off-farm income generating activities), 0 if otherwise	0.672	0.38	0	1
Land ownership	Dummy; 1 if yes (HH the ownership of the farmland), 0 if otherwise	0.575	0.304	0	1
Total land area used for other crops cultivation	Actual farm size used for other crop (such as sunflower, potatoes and vegetables) cultivation (Continuous)	4.30	2.04	2	6
Total land used for maize cultivation	Actual land area used for maize cultivation (Continuous)	5.54	3.08	1	7
Enterprise diversification	Dummy; 1 if yes (HH engaged in livestock farming), 0 if otherwise	0.389	0.172	0	1
Source of finance	Dummy; 1 if personally financed by HH in 2022/2023 agricultural production season), 0 if otherwise	0.705	0.480	0	1
Membership of cooperative society	Dummy; 1 if yes (HH member of coop society), 0 if otherwise	0.721	0.448	0	1
Access to credit	Dummy; 1 if yes (HH have access to credit in 2022/2023 agricultural production season), 0 if otherwise	0.584	0.278	0	1
Institutional variables					
Participation in extension training	Dummy; 1=Yes to HH participate in extension training on improved agricultural production practices, 0= otherwise	0.675	0.327	0	1
Information on climate change	Dummy; 1 if yes, 0 if otherwise	0.651	0.374	0	1
Social grant	Dummy; 1 if HH receive social grant, 0 if otherwise	0.575	0.287	0	1

Table 5.2. Summary statistics used in MESR

Variables	**D_0M_1**		**D_1M_0**		**D_1M_1**	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Outcome variables						
Productivity	1.75	0.56	2.39	1.58	4.07	2.17
Per-capita total household expenditure	3742.37	4321.74	5942.38	3219.44	6812.56	2196.91
Per-capita food expenditure	5816.66	3295.16	3396.70	2906.39	4965.18	2287.07
Households Dietary Diversity score (HDDS)	5.17	3.06	7.83	4.52	9.77	5.02
Socioeconomic characteristics						
Age	51.31	25.97	48.71	19.30	47.67	17.92
Gender	0.619	0.582	0.786	0.531	0.518	0.331
Household size	5.82	3.91	4.73	2.96	6.11	3.95
Marital status of the household head	0.651	0.562	0.759	0.562	0.893	0.351
Educational status of the household head	0.601	0.341	0.596	0.349	0.860	0.651
Years of experience	19.89	11.85	22.98	15.87	27.33	16.95
Off-farm income	0.674	0.561	0.582	0.314	0.763	0.540
Land ownership	0.566	0.391	0.431	0.227	0.885	0.562
Total farm size for other crops cultivation	13.90	6.90	17.89	12.53	9.52	4.80
Total land used for maize cultivation	7.56	4.32	6.72	3.91	5.01	34.5
Enterprise diversification	0.416	0195	0.274	0.103	0.508	0.281
Source of financing farm operation	0.567	0.345	0.683	0.369	0.459	0.221
Membership of cooperative society	0.482	0.220	0.521	0.251	0.719	0.228

Obtained loan from cooperatives	0.391	0.186	0.542	0.273	0.674	0.351
Institutional variables						
Information on climate change	0.508	0.328	0.617	0.562	0.783	0.450
Participate in extension training	0.509	0.261	0.418	0.205	0.774	0.373
Social grant	0.575	0.276	0.401	0.227	0.618	0.318

5.4.2 Multinomial logit estimation of the determinants of adoption package of DTMVs and organic manure

Table 5.3 displays parameter estimations of the factors affecting the adoption package of DTMVs and inorganic manure (solely or simultaneously). The non-adopters of DTMVs and organic manure (D_0M_0) serves as based category in which the result is compared with. Using the Wald test, the model fits the data reasonably well [χ^2 (75) = 198.67, p = 0.001)], and the null hypothesis stating that 'regression coefficients are equal to zero' was rejected. Moreover, the result demonstrates that estimated coefficients vary considerably across the various adoption packages. The results indicate that the adoption of the combination package of the two technologies (DTMVs and organic manure), have a direct correlation with cultivated farmland. This indicates that farmers with large cultivated farmland are more likely to adopt both enhanced maize varieties and organic manure than those with smaller farm size. This is justifiable because South Africa is majorly semi-arid area, proxy for affluence and a reflection of the capacity to spend on commercial inputs. The result is consistence with (Akanbi et al., 2021a; Tione et al., 2022), demonstrate that the probability of adopting DMTVs and organic manure in South Africa increases as the amount of cultivated land increases.

The literacy of the household head was found to have a direct correlation with simultaneous adoption of DTMVs and organic manure (D_1M_1), indicating that having an educated household head increases the likelihood of simultaneously adopting DTMVs and organic manure. Researchers (Bahri et al., 2021; Daud et al., 2018; Dey & Mishra, 2022; Maindi et al., 2020), have argued that education aids farm households in understanding the advantages of new agricultural technologies by increasing their awareness and enhancing their adoption decision. The simultaneous adoption of DTMVs and organic manure (D_1M_1) and sole adoption of DTMVs (D_1M_0) were also found to be positively associated with membership in agricultural cooperatives. This was in line with (Abegaz et al., 2023; Ahmed, 2022; Omotayo, Ijatuyi, et al., 2020), reported that being a member of agricultural cooperative societies have a positive and significant effect on the adoption of agricultural technology and the productivity of farm households.

Cooperatives facilitate member access to inputs, credit, and market (Baiyegunhi et al., 2022; Rosenstock et al., 2019). The findings also revealed that households with limited access to credit are less likely to adopt D_1M_1 and D_0M_1 in South Africa. This implies that adoption of new agricultural technology requires a financial investment. Prior research (Akano et al., 2023; Olagunju et al., 2020; Ozsahin & Ozdes, 2022), has demonstrated that access to credit increases the probability that enhanced agricultural innovations will be adopted by rural households. Conversely, (Tilahun et al., 2023; Tione et al., 2022), revealed that rural households' access to climate information has a substantial influence on their propensity to employ agricultural technologies. Consistently, this study discovered a positive effect of access to climate information on the adoption of the all the combination adoption package of DTMVs and organic manure (D_1M_1, D_0M_1 and D_1M_0). This might be attributed to the endogeneity of access to climate information through media and extension agents which enhanced the adoption and promotion of CSA practices. These packages are often knowledge-intensive which need reassurance on usage and management procedures (Gebrehiwot, 2015). This verifies the validity of participation in extension training on improved agricultural practices used as an instrumental variable in the MESR model.

Furthermore, off-farm income is an additional significant variable influencing the joint adoption of DTMVs and organic manure (D_1M_1), indicating that on-farm and off-farm activities are complementary. This implies that engaging in off-farm income-generating activities free farmers from financial constraints that could prevent them from adopting new agricultural technology (Akpan & Zikos, 2023; Omotayo et al., 2022; Regmi et al., 2022). Additionally, simultaneous adoption of DTMVs and organic manure (D_1M_1) as well all other adoption package of DTMVs and organic manure (D_1M_0, and D_0M_1) are frequent among elderly farmers. This may be linked to variables such as the building of experience through time, which can account for older rural farmers' ability in handling the demands of integrating both practices, thereby enhanced their adoption decision (Ahmed, 2022; Bazzana et al., 2022). However, choices to simultaneously adopt DTMVs and organic manure (D_1M_1) are favorably significant for farmers with many years of experience in maize farming. The probability of adopting all the combination package of DTMVs and organic manure (D_1M_0, D_0M_1, and D_1M_1) increased markedly among rural farmers in South Africa large household sizes. This could be attributed to the availability of labor supply from large family households for agricultural production activities, especially in conservation practices, such as organic manure which is labor-intensive (Pawlak & Kołodziejczak, 2020; Scridel et al., 2018; Siegwart et al., 2022).

Table 5.3. Multinomial logit model- Parameter estimates of the adoption packages

Variables	D_0M_1		D_1M_0		D_1M_1	
	Coefficient	**Robust SE**	**Coefficient**	**Robust SE**	**Coefficient**	**Robust SE**
Explanatory variables						
Age	0.5021**	0.2842	0.0792*	0.0459	0.0056**	0.0031
Gender	-0.0463	0.1850	0.1758	0.2477	0.0452**	0.0232
Household size	0.0852**	0.0421	0.0053**	0.0026	0.0081***	0.0033
Marital status	0.1085	0.0998	0.0385	0.1084	-0.1196	0.2083
Educational status	0.0067	0.0641	0.0071	0.0106	0.0372***	0.0052
Years of experience	0.0952	0.1852	0.0540*	0.0321	0.1063**	0.0662
Off-farm income	0.1060	0.0976	00895	0.1085	0.0852*	0.0565
Participation in extension training	0.1006**	0.0520	0.6902***	0.1647	0.0991***	0.0290
Land ownership	0.0114***	0.0032	-0.0071	0.0185	0.0011	0.0271
Total farm size in hectares	0.7917**	0.3759	0.0332***	0.0185	0.0077**	0.0036
Total land used for maize cultivation	0.1758	0.2477	0.0729	0.1865	0.0942**	0.0507
Enterprise diversification	-0.0621	0.0819	-0.0384	0.1022	-0.7431	07072
Source of financing farm operation	-0.2710	0.2518	0.1085	0.0996	0.0863	0.1087
Membership of cooperative society	-0.1453	0.2134	0.1153**	0.0447	0.0341**	0.0176
Access to credit	0.3095*	0.1724	0.2710	0.2518	0.1165**	0.0562
Information on climate change	0.0086***	0.0016	0.0059*	0.0030	0.0962	0.1123
Social safety	0.0621	0.0819	0.4028	0.5096	0.1008	0.0975
Contact	0.0862***	0.0174	0.1167**	0.0598	0.0341**	0.0026

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

5.4.3 PSM- Impact of adoption combinations of DTMVs and organic manure on outcome variables

In addition to MESR results, we employed Propensity-Score Matching (PSM) estimate of the impacts of adoption choice categories of DTMVs and organic manure on outcome variables which serve as a robustness check for the MESR results presented in Appendix B2 to B4. The result presented in Table 5.4 are consistent with the outcome variables results from the MESR model. The PSM estimates indicate a significant positive impact on productivity of all the adopter categories of DTMVs and organic manure (D_1M_0, D_0M_1, and D_1M_1), however, simultaneous adopters of DTMVs and organic manure (D_1M_1) gained significantly more than the solely adopters of DTMVs or organic manure in South Africa. Likewise, the PSM demonstrate a positive influence of all the adoption categories of DTMVs and organic manure (D_1M_0, D_0M_1, and D_1M_1) on HDDS of rural households in the study area. On the other hands, the estimates of per capita household expenditure demonstrate that solely adopters of DTMVs (D_1M_0) gained significantly more than simultaneous adopters of DTMVs and organic manure (D_1M_1) but not significant with sole adoption of organic manure (D_0M_1) in the study area.

The estimates of per capita household expenditure on food are positively significant with adopters of organic manure only but not significant with other adopter categories of DTMVs and organic manure. As a consequence, the potential of agricultural sector to increase food security and the welfare of rural farmers in South Africa is inextricably linked to the adoption of contemporary productivity-boosting technology (Pawlak & Kołodziejczak, 2020; Scridel et al., 2018; Siegwart et al., 2022). In accordance with (Ahmed, 2022; Gebre et al., 2023; Oyetunde-Usman et al., 2023), the result of this finding demonstrated the significance of the simultaneous adoption of organic manure and DTMVS in increasing agricultural production and welfare of rural farm households in South Africa. However, using organic manure alone might not be enough to remedy farmers' difficulties. Rather than depending on a single technology, it is advised that a variety of farm technologies be used to increase agricultural productivity and welfare outcomes in South Africa. For instance, (Tilahun et al., 2023; Zizinga et al., 2022), suggested that by combining Drought-tolerant maize variety with other enhanced production practices such as organic manure, South Africa maize farmers might raise their productivity by almost ten million tonnes per year just on one-quarter of the farm for cultivation.

Table 5.4. PSM estimates for all adoption choice categories

	Productivity		**Per capita household expenditure**		**Per capita expenditure on food**		**Household Diversity Dietary Score (HDDS)**	
	Coefficients	Std. Er	Coefficients	Std. Er	Coefficients	Std. Er	Coefficients	Std. Er.
D_0M_1	481.01***	85.78	61.71	272.94	305.38*	168.05	1.07***	0.05
D_1M_0	680.37***	153.43	808.54***	249.01	-162.65	174.59	2.49***	0.86
D_1M_1	591.34***	103.27	509.17*	279.88	-312.82	290.67	1.68***	0.58

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

5.4.4 MESR - Impacts of adoption combinations of DTMVs and organic manure (Average Treatment Effect)

Consequently, after identifying the determinants of adoption categories of the two technologies (DTMVs and organic manure) and the determinants of outcome variables by the adoption category of rural farmers (Appendix B2 – B4); following (Ahmed, 2022; Ngoma et al., 2021), the MESR model's predicted estimates (ATT) on outcome variables was used to calculate the impacts of adopting DTMVs and organic manure (Table 5.5) on the outcome variables (productivity, per capita household expenditure and HDDS).

The results in Table 5.5 revealed the average treatment effect (ATT) of the impact of DTMVs and organic manure on household's outcome variables in South Africa. In terms of productivity, the results show that farmers who used both DTMVs and organic manure (D_1M_1) made an average of 2044.23kg/ha more output, which is equal to a 28% return on adoption. Compared to other adoption groups, users of organic manure only (D_0M_1) and DTMVs only (D_1M_0) earned 764.57kg/ha and 1384.66kg/ha more from their production, which is about 11% and 14% increase, respectively.

The returns on welfare outcomes also indicate that gains from joint adoption of DTMVs and organic manure (D_1M_1) are significant and proportionally greater than in sole adoptions of DTMVs and organic manure. As shown in Table 5, the average welfare gains (per capita total households' expenditure) for the joint adopters of DTMVs and organic manure (D_1M_1) are nearly one-third (23%) those of adopting organic manure alone (D_0M_1) (15%) and are also 4% higher than adopting DTMVs alone (D_1M_0). Consistently, the result indicates that per capita household's expenditure on food increased by 15% for joint adopters of DTMVs and organic manure (D_1M_1) and sole adopters of DTMVs (D_1M_0), but only significant ($p<0.01$) for sole adopter of organic manure (D_0M_1) which increases by 13%. In term of HDDS which denote the welfare of the rural households in form of food security status, the results show that farmers who used both DTMVs and organic manure (D_1M_1) experienced about 20% return on adoption. Compared to other adoption groups, users of organic manure only (D_0M_1) and DTMVs only (D_1M_0) earned about 15% and 11% increment in return on adoption, respectively. This result was in accordance with (Akanbi et al., 2021a; Kangogo et al., 2021; Zizinga et al., 2022), combination of various forms of CSA practices produces superior outcomes in terms of both yield/ha and welfare when compared to their adoptions in isolation. Additionally, (Bazzana et al., 2022; Fusco et al., 2020), reported that adopting CSA is a crucial step towards enhancing the well-being of rural farm households in developing nations with a changing climate and limited land for agricultural expansion.

Following (Bjornlund et al., 2022; Merga et al., 2023; Olawuyi et al., 2022), adopting nearest neighbor matching (NNM) techniques, the impacts are estimated to determine the robustness and the reliability of the findings. NNM, in contrast to the ESR model, only accounts for observable differences between adopters and non-adopters and does not adjust for differences based on unobservable factors. Therefore, it is not anticipated that the results will be quantitatively identical. The outcome of the robustness test is shown in Appendix B5. The results of the robustness test indicate that the simultaneous adoption of DTMVS and organic manure results in substantial improvements in welfare and productivity of the small holder rural farm households in South Africa.

Table 5.5. Impact of adoption on the outcome variables (ATT estimate)

	Adopting categories	Output by adoption status		ATT	% impact
Outcome		Expected output with adoption	Expected output without adoption		
	D_0M_1	7553.83 (333.65)	6168 (278.43)	1384.66	11.13
Productivity	D_1M_0	6704.69 (509.41)	5940.12 (390.11)	764.57	14.41
	D_1M_1	7938.35 (557.27)	5894.12 (167.12)	2044.23	28.02
	D_0M_1	414.67 (47.57)	276.50 (32.96)	138.16	15.18
Per capita expenditure	D_1M_0	4826.71 (593.51)	2929.41 (383.51)	1877.30	19.26
	D_1M_1	4287.58 (554.22)	3396.77 (346.31)	890.8	23.20
	D_0M_1	1260.15 (187.25)	1170.03 (720.87)	90.12	13.28
Per capita food expenditure	D_1M_0	2250.43 (531.24)	870.47 (0.89)	1470.96	6.14
	D_1M_1	1220.32 (123.13)	1000.28 (1.09)	220.04	9.20
	D_0M_1	8.87 (3.07)	5.02 (1.98)	3.85	15.01
HDDS	D_1M_0	7.18 (4.11)	4.55 (2.03)	2.63	11.38
	D_1M_1	10.25 (2.84)	6.17 (1.99)	4.08	20.63

Note: ATT = Average Treatment Effect

5.5 Conclusion and policy implications

Agriculture in South Africa supports over two-thirds of rural families. Presently, the country's agricultural sector is failing, with production falling short of global norms and poor farm households' welfare. One key cause of this is poor productivity by rural farming households which leads to inadequate food consumption. This study evaluates the impacts of the simultaneous adoption of DMTVs and organic manure on the productivity and welfare status of rural farmers employing a multinomial endogenous switching regression technique. We focused on maize production because it is the country's most essential commodity in terms of production volumes, land allocation and farmer's participation The results herewith indicate that the adoption of DTMVs and organic manure alone or the combination significantly increases farm household's productivity and welfare. Joint adopters saw a 28% increase in productivity, which is quite higher than individual adoptions of DTMVs and organic manure. Additionally, the Per capita total household expenditure increased by 4% and 8% when adopting DTMVs and organic manure simultaneously. Furthermore, farm size, access to climate information, and credit facilities significantly impact both individual and combinatory adoption of DTMVs and organic manure by the rural farmers. The research results emphasized the significant impact of the joint adoption of DTMVs and organic manure on DTMVs productivity and welfare in South Africa. Consequently, adopting technology in isolation may not provide the desired results hence, farmers should integrate productivity-enhancing technologies to boost agricultural output and welfare status. The combined benefits of enhanced crop resilience to water stress and improved soil fertility can contribute to sustainable agricultural practices. However, the success of this approach depends on the effective integration of these technologies into local farming systems and the consideration of socio-economic factors. Rural farmers should be encouraged to adopt integrated farming practices that involve the synergistic use of drought-resistant maize varieties and organic manure. This approach can enhance crop resilience, improve soil health, and contribute to sustainable agriculture and farmer's welfare status. Furthermore, government and stakeholders should facilitate the dissemination of high-quality drought-resistant maize varieties and organic inputs through agricultural extension services and public-private partnerships. Therefore, interventions promoting climate smartness in rural farming communities would have significant impacts on rural farm household welfare and agricultural output in South Africa.

5.6 Limitation of the paper

The findings may not be universally applicable to other regions due to varying agroecological conditions and socioeconomic contexts. Furthermore, the duration of the study and sample size may not represent the diverse farming system in South Africa and could impact the robustness and applicability of the results. The results are time-sensitive, influenced by climate variations or evolving agricultural practices, limiting the long-term generalizability of the findings. Additionally, external factors like weather patterns, market dynamics and socioeconomic conditions were not fully accounted for in the study and could influence the applicability of the findings beyond the study region

Chapter 6: Manuscript 6

This manuscript addressed objective 4, that being to Analyze the effects of CSA adoptions on food and nutrition security of smallholder maize farmers in South Africa. The manuscript, titled: Behavioural Intentions Toward Climate-Smart Practices and Rural Farmers' Food and Nutrition Security: Micro Economic-Level Evidence, has been prepared for the Journal of Climatic Change, submitted and already in press for publication

Behavioural Intentions Toward Climate-Smart Practices and Rural Farmers' Food and Nutrition Security: Micro Economic-Level Evidence

Abstract

The study examined the behavioural intention towards climate-smart agricultural practices (CSA) and its impact on the food-nutrition security (FNS) of farming households in South Africa. A multistage sampling procedure was employed in selecting rural maize farmers across some selected villages in South Africa. To understand the association between behavioural adoption of CSA and FNS of farming households, an endogenous switching regression model was employed while household dietary diversity score (HDDS) and household food insecurity access score (HFIAS) were used to determine the FNS status of the households. The findings indicate that the behavioural intentions of farmers had a significant influence on their desire to implement CSA practices, hence FNS status. Therefore, the findings emphasized the significance of socio-psychological variables (behavioural intentions) in elucidating the adoption decision of CSA practices and its impact on FNS in South Africa. The result indicates that households who adopt CSA observed a 27% and 23% increase in HDDS and HFIAS than those who do not adopt CSA practices, respectively. The outcome illustrates that the adoption of CSA practices substantially raises the HDDS and HFIAS of rural farming households in South Africa. Following this backdrop, a concerted effort to raise knowledge of CSA practices through the dissemination of pertinent information will exert influence on the farmers' adoption behaviour towards CSA practices which is capable of improving the FNS of the rural maize farmers.

Keywords: Behavioural dimension; Climate-smart; Extension delivery; Rural livelihoods

6.1 Introduction

The agricultural sector is currently experiencing a notable decrease in productivity as a result of the impacts of global climate change which severely affects productivity and food-nutrition-development in sub-Sahara Africa (SSA) (Kangogo et al., 2021; Maindi et al., 2020). Additionally, (FAO, 2021; Omotoso & Omotayo, 2024) regional assessment cautions that a temperature increase of more than 2 degrees Celsius would result in reduced yields for staple crops throughout much of SSA (for example, 20% - 40% lower maize yields in Southern Africa) leading to poor food-nutrition security (FNS) of the households (Akanbi et al., 2021; Omotoso et al., 2023; Tione et al., 2022). Notably, grain yields in South Africa especially maize which is the major staple food of the households have declined by 25% (Akanbi et al., 2021; Akano et al., 2023; Bahri et al., 2021). Thus, this situation had severe impacts on the livelihoods and FNS of rural farmers, who contribute around 65% of the country's food system (Akanbi et al., 2021).

More so, the impact of climate change on FNS is increasingly severe (Ali, 2021; Issahaku & Abdulai, 2020) while the impact is compounded by the country's socioeconomic, and environmental trends coupled with population growth, limited land and water resources, economic transformation, and challenges in agriculture and the food systems value chain (FAO, 2021). These trends have prompted food security experts to conclude that agriculture and FNS in South Africa will face significant challenges in a world where temperature is continually rising (Akano et al., 2023; Issahaku & Abdulai, 2020; Tione et al., 2022). This prognosis prompted the Food and Agriculture Organization (FAO) as well as other international multilateral organizations to contend that the implementation of climate-smart agriculture (CSA) practices is crucial for the country to enhance FNS (Akpan & Zikos, 2023; Omotayo et al., 2022; Ricart et al., 2022).

In South Africa, where maize farming is a vital component of the economy and livelihoods of rural dwellers, the increasing challenges posed by climate change threaten its production and the food-nutrition security (FNS) of farming households (Omotoso et al., 2023). It is anticipated that maize yields from rain-fed agriculture will decrease by as much as 50% by 2030, significantly impacting access to food by rural households (Daud et al., 2018; Worku et al., 2020). In light of these pessimistic projections, it is unsurprising that the implementation of CSA practices is crucial for sustaining food crop yields (Ali, 2021; Atta-Aidoo et al., 2022).

Consequently, there is increasing literature on CSA adoption and implementation on agricultural production in South Africa (Akanbi et al., 2021; Davis-Reddy, 2018; Omotayo et al., 2021; Shen et al., 2021). But there is paucity of research on its impact on food-nutrition security, creating a research gap in understanding the in-depth insights into the factors influencing farmers' behavioural intentions towards CSA and how these intentions translate into actual FNS. Notably, the adoption of agricultural practices is impacted by several elements, extending beyond socio-demographic considerations and economic incentives (Ali, 2019; Atta-Aidoo et al., 2022). Individual and intrinsic motives also known as behaviour intention, have a significant role in shaping these adoption decisions (Di Falco et al., 2011; Gwara et al., 2022). Understanding the behavioural intentions of farmers provide the most comprehensive explanation for these influences (Ado et al., 2020; Aidoo et al., 2021; Atta-Aidoo et al., 2022).

This research aims to make a scholarly contribution to the existing body of literature on climate change and its impact on agriculture through the provision of a micro-level analysis of the interplay between CSA and food-nutrition security. Specifically, this study examines the impact of behavioural intention of farm households' decision to adopt CSA, in response to long-term changes in key climatic factors like temperature and rainfall on household’s FNS. This research appears to be pertinent given that the predominant discourse around climate change in the agricultural sector has been focused on the consequences of climate change, rather than on the need of adaptation strategies and the behavioural intention in CSA adoption-decision. Despite the potential benefits of adopting CSA practices, there is a critical gap in understanding the behavioral intentions of farmers to adopt CSA and how this adoption impacts FNS. This gap hinders the development of effective strategies and policies aimed at promoting sustainable agriculture and enhancing the nutritional well-being of farming communities.

Conversely, micro evidence on the impact of rainfall, temperature, and climate related adaptation strategies on food production and FNS is very scanty. It has become apparent to gain insight into people's actions across contexts because it offers a socio-psychological foundation for understanding human behaviour in a variety of domains, as well as a platform for encouraging behaviour change towards adopting sustainable agricultural practice that would improve the households’ FNS (Atta-Aidoo et al., 2022). The study will add to the research on synergy between households’ FNS and CSA adoption by determining the relative importance of farmers' behavioural intention towards CSA practices in maize farming system. The insights would inform policymakers about potential household actions that might favourably affect farmers' behaviour intention towards the adoptions of CSA practices and its impact on FNS of the rural farming households in South Africa.

6.2 Behavioral Intention, Climate-Smart Agriculture and Food-Nutrition Security

Farmers in highly susceptible agro-climatic zones of SSA are perpetually deploying and reorienting agricultural systems to promote FNS in response to the new realities of climate change (Bahri et al., 2021; Paul et al., 2018). Climate-smart agriculture endeavours to enhance the adaptability of agricultural systems and livelihoods, while concurrently mitigating the vulnerability to FNS in both current and future contexts (FAO 2013; Lipper et al. 2014). In South Africa, CSA practices such as conservation tillage (minimal or zero-tillage), the adoption of enhanced and drought-tolerant cultivars, crop rotation, mixed-cropping, and crop diversification allow farmers to produce food in a sustainable manner, thus enhancing their food-nutrition security (Bahri et al., 2021; Paul et al., 2018). However, the overall transformation on the FNS is still not well established due to behaviour intentions of farmers towards CSA adoptions (Ali, 2019; Omotoso et al., 2022).

Behavioral intention which denotes individual's subjective intention and readiness to perform a specific behaviour plays a crucial role in driving the adoption of CSA practices in order to enhance their households’ FNS (Atta-Aidoo et al., 2022; Kangogo et al., 2021). Farmers' decisions to implement climate-smart practices are influenced by their attitudes, beliefs, and perceptions about these practices (Amadu et al., 2020; Outhwaite et al., 2022). Interestingly, if farmers have a positive attitude toward climate-smart practices, perceive them as beneficial for their farms, environment and household welfare, and believe they have the necessary resources and support, their behavioral intention to adopt these practices is more likely to be positive and strong (Atta-Aidoo et al., 2022; Outhwaite et al., 2022; Ren et al., 2018).

Thus, promoting positive attitudes and increasing knowledge about climate-smart practices can influence farmers' behavioral intentions in favor of sustainable agricultural practices and transformed to a better FNS households (Adesete et al., 2022; Gwara et al., 2022). Additionally, the synergy between farmers’ behavioral intentions, climate-smart agriculture, and FNS highlights the potential for positive impacts on both agricultural systems and human well-being (Akter et al., 2023; Jellason et al., 2021). Thus, fostering positive attitudes towards CSA adoption, promoting knowledge-sharing, and providing support for sustainable agricultural practices, can contribute to a more secure food supply, improved nutrition, and enhanced environmental sustainability. The findings from this study are anticipated to inform policies and interventions that are attuned to the unique challenges faced by farmers in South Africa.

6.2.1 Conceptual and Theoretical frame work: Theory of Planned Behaviour (TPB)

Following (Atta-Aidoo et al., 2022; Issahaku & Abdulai, 2020), the theory of planned behaviour (TPB) was used in this study in order to comprehend the various ways that the adoption of CSA practices has impacted on smallholder farmers' FNS. The TPB is predicated on the idea that people's judgements, choices, and actions are influenced by behavioural intentions when it comes to implementing certain technologies (Atta-Aidoo et al., 2022; Gwara et al., 2022). Thus, promoting a sustainable increase in agricultural productivity, preparing for the challenges posed by climate change, and reducing or eliminating greenhouse gas (GHG) emissions resulting from agricultural practices are the three objectives of CSA practices. In this framework (Figure 1), the CSA was designed to combine these three objectives in order to improve FNS and agricultural output of smallholder maize farmers in the face of climate change. The goal of the conceptual framework (TPB), as shown in Figure 6.1, is to explain how adopting climate-smart agricultural (CSA) practices might help smallholder maize farmers reduce the negative effects of climate change on their production and FNS.

The following eight parts make up the framework:

1. CSA framework: aims to decrease or eliminate greenhouse gas emissions, support a sustainable rise in agricultural output, and help people adopt a favourable attitude towards CSA activities. It also helps them adapt to the difficulties posed by climate change.
2. Past agricultural methods: Farmers' opinions about their capacity to direct and apply certain methods might be very important. They may stop using prior methods because of alleged obstacles, a lack of resources, or insufficient expertise. The identification of these controlling variables may aid in removing obstacles to the adoption of new agricultural technologies.

3. FNS: Farmers' intents to use sustainable farming methods in order to improve FNS may be evaluated using TPB. It may assist in comprehending the reasons behind farmers' selection of certain agricultural practices, crop types, or conservation strategies.

4. New CSA practices: Given farmers' enthusiastic attitudes and desire to embrace new technologies, interventions might concentrate on offering assistance, tools, and training to ease the adoption process.

5. The socioeconomic traits of farmers have a big impact on adoption behaviour, which includes embracing new methods, innovations, and technology.

6. Adoption of CSA (extension services): The adoption of new technology is a result of farmers being in touch with and receiving help from extension training, which has led to a favourable attitude towards new technology.

7. Adoption level: Subjective standards take societal influences on adoption behaviour into account. Adoption levels may be favourably impacted if people believe that significant others (such as peers, leaders, or experts) encourage the adoption of a certain behaviour. Adoption of an idea may be aided by the support of reliable people or organizations.

8. production of maize farmers: Considering climatic change and unpredictability, CSA implementation provides significant potential for increasing maize production.

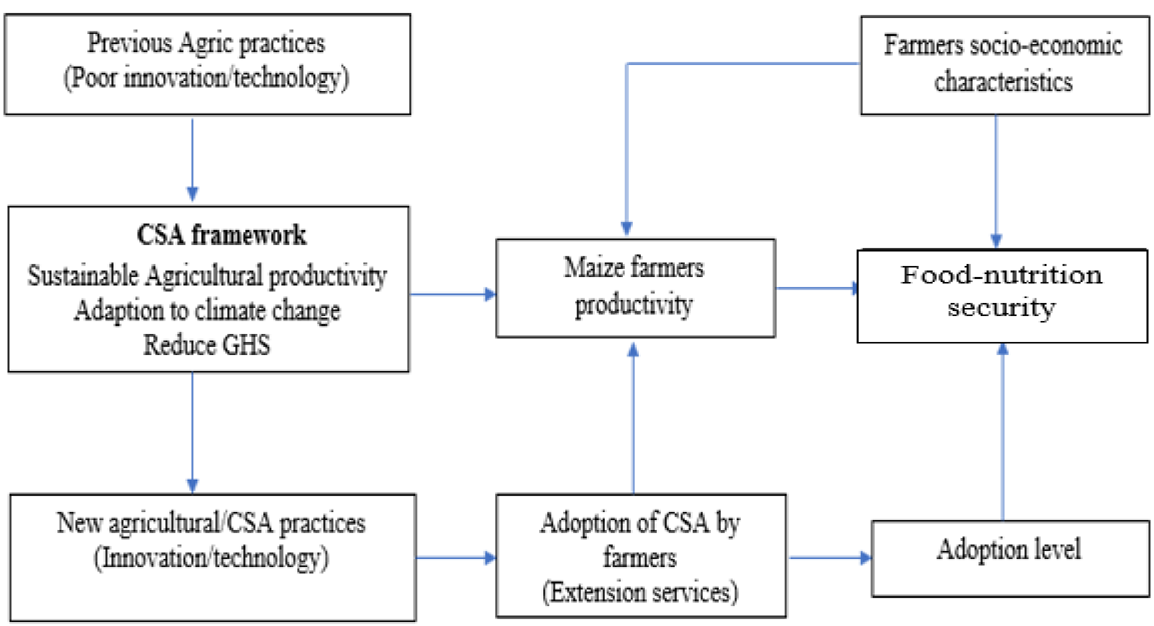

Fig. 6.1. Conceptual framework of the adoption impacts of Climate-Smart Agricultural Practices on smallholder's maize productivity and FNS

6.3 Research methodology

6.3.1 Study area

The study is conducted in North-West province (Figure 6.2), South Africa. The province accounted for about 9.0% of total geographical area, measuring 106,512 square kilometers. Consequently, ranks as the fourth smallest province in the nation (Akanbi et al., 2021). Mining and farming, notably maize production, provide significant contributions to the province's economy (Akanbi et al., 2021; Akpan & Zikos, 2023). Interestingly, maize farming is the backbone of the majority of South African rural farm households, and it is farmed in numerous places throughout the nation owing to its tolerance to varied climatic conditions (Akanbi et al., 2021; Issahaku & Abdulai, 2020). It is a staple food crop that accounts for about 70% of the country's total grain production, covers approximately 65% of cropping land area, and its cultivation is critical for ensuring FNS and supporting the livelihoods of many rural farm households through revenue generation and job creation (Aidoo et al., 2021; Ricart et al., 2022).

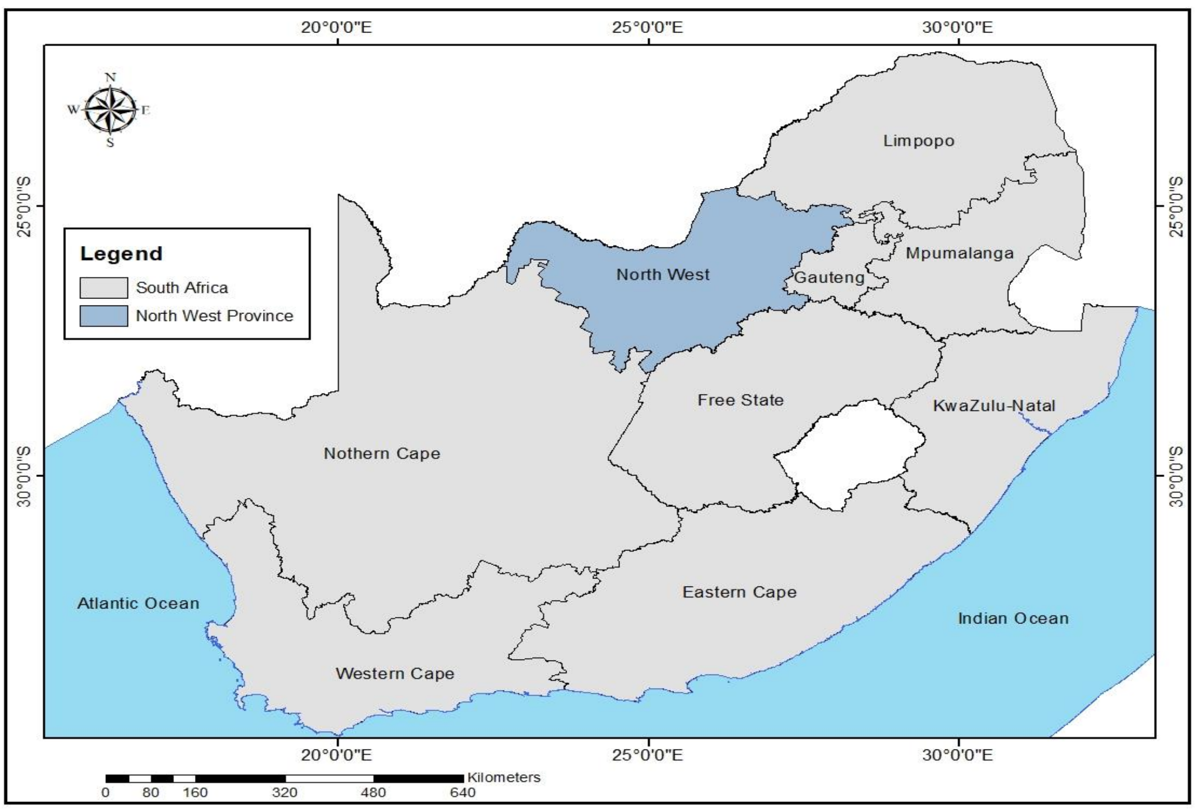

Fig. 6.2. South African map depicting the geographical location of the North-West province

North-West province has constantly been placed (third) among the top provinces in South Africa for maize cultivation owing to its favourable agroclimatic conditions, including rich soils and human capital, which make it appropriate for maize production (Akanbi et al., 2021; Maindi et al., 2020). Due to climate change, the province's ecological balance and biodiversity have been negatively impacted by the consistent temperature increases and erratic precipitation (Aidoo et al., 2021; Ricart et al., 2022). Notably, maize production contributes substantially to the province's economy and the residents' means of subsistence (Aidoo et al., 2021; Ricart et al., 2022). Research on the behavioural intention of smallholder maize farmers in adopting CSA would shed light on the potential economic consequences of climate change, such as changes in yield, farm incomes, FNS of the farm households. Local and national economic planning and decision-making can be informed by this data.

6.3.2 Sampling procedures and data analysis

For this study, primary data were used, and they were gathered via a cross-sectional field survey of smallholder maize farmers in the North West after the 2022 agricultural season. The data collected is suitable and adequate in assessing food diversity arising from dietary quality and adequacy as a result of output from farm and CSA practices adopted to improve farming operations. A total of 316 smallholder maize farmers that participated in extension training on improve agricultural technology from the province's four municipalities—Bojanala District, Ngaka Modiri Molema, Dr. Kenneth Kaunda, and Dr. Ruth Segomotsi Mompati District Municipality—were chosen using a multistage selection technique. To guarantee statistical representativeness, the initial step included choosing all four municipalities in the province of North West. With the help of the district extension staff, the second step entailed picking fifteen local communities that were well renowned for producing maize in North West.

With the assistance of local extension officials, two villages from each local municipality—a total of 30 villages—that are largely recognized for their subsistence maize growing were chosen at random. The 316 smallholder maize farmers in the villages were chosen at the end of the process from a list of all smallholder maize farmers kept by the district extension officers. Descriptive statistic was used to analyze the acquired data such as socioeconomic characteristics of the smallholder farmers, categories of food consume in the households, output from farm and various

CSA adopted in their farming operation in 2022 agricultural production season, resulting in the establishment of frequencies, means, and standard deviations (SD). The Endogenous Switching Regression Model (ESRM) was employed to analyze the impacts of adoption of CSA on the rural farmers' (adopters and non-adopters) FNS in South Africa. While HDDS and HFIAS were adopted to assess the food-nutrition security of the farmers.

6.3.3 Model Specifications

6.3.3.1 Adoption impact of CSA on FNS of farmers (adopters and non-adopters) – The Endogenous Switching Regression Model (ESRM)

Climate change adaptation is entirely optional and are based on individual self-selection (Atta-Aidoo et al., 2022). Farmers who adopted CSA may have systematically different traits than farmers who did not adopt, and they may have made the decision to adapt based on anticipated net benefits (Atta-Aidoo et al., 2022). Unobservable factors of farmers and their farms may influence both adaptation decisions and food output, leading to inconsistencies in estimates of the impact of adaptation on food security (Di Falco et al., 2011). To account for selection biases, we use an endogenous switching regression model (ESRM) in adoption-decision where farmers confront two regimes: (1) adapt or (2) do not adapt, which are defined as follow;

$$A_i^* = Z_i\alpha + \eta_i \rightarrow A_i = \begin{cases} 1 & if A^* > 0, \\ 0 & otherwise \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6.1)$$

Where farm household i choose to adopt CSA ($A_i = 1$) in response to climate change, if $A^* > 0$, and 0 otherwise. Thus, Z denote variables that affect the expected benefits of adopting CSA

In accordance with (Akter et al., 2023; Muñoz & Sandoval-Díaz, 2023), ESRM was selected as an impact model because it is able to control any bias that could obscure the output. This model consists of two sections. In the first part of the model, endogeneity resulting from self-selection is estimated by a Probit regression. This determines the adoption decisions of farmers regarding CSA. In this study, the decision of a farmer to adopt at least one CSA technique in response to impacts of climate change was expressed as a dummy variable (while 1 representing adopters and 0 representing non-adopters). The second section of the model depicts the CSA adopters' and non-adopters' FNS determinants. Smallholder farmers' likelihood of adopting CSA increases, if the anticipated benefit of adopting a CSA outweighs their likelihood of not adopting it. The expected benefits of adoption (latent variables $Y_{1i} - Y_{2i} > 0$) are higher than those of non-adoption.

The explicit formulation of ESRM is as follows:

Regime 1: $y_{1i} = x_{1i}\beta_1 + \varepsilon_{1i}$ *if* $A_i = 1$ (adopter) .... (6.2a)

Regime 2: $y_{2i} = x_{2i}\beta_2 + \varepsilon_{2i}$ *if* $A_i = 0$ (non-adopter) .... (6.2b)

Where Y_{1i} and Y_{2i} are the dependent variables (food-nutrition security) for adopter and a non-adopter of CSA, respectively, while X′ is the collective symbol for the vectors of the explanatory variables. To get a more robust identification, we employed a selection tool, as reported by (Atta-Aidoo et al., 2022; Maindi et al., 2020). As a consequence, we used behavioural attitude of the rural farmers as our selection tool. According to (Atta-Aidoo et al., 2022; Gwara et al., 2022), the factors motivating rural farmers in decision-making about adopting agricultural innovation goes beyond their socioeconomic characteristic and monetary incentive but sometimes the psychological state of mind (behavioural intentions).

A farmer's behavioural intentions depicts the desire and conscious decision-making process to expend effort in order to execute a certain strategy (Atta-Aidoo et al., 2022; Gwara et al., 2022). Having a positive behavioural intention encourages farmers to adopt new technology and increases their ability to utilize them successfully (Akano et al., 2023; Atta-Aidoo et al., 2022). This observation was also corroborated by the falsification tests (Appendix C1), where behavioural intention was adopted as selection instruments. In this study, we use selection instruments variables related to behavioural intention such as attitude, subjective norms, perceived behavioural control and intention of farmers to adopt CSA. The admissibility of these instruments is determined through a falsification test: in the case where a variable serves as a valid selection instrument, it will impact the decision regarding adoption; however, it will not have any influence on HDDS and HFIAS of non-adopting farm households.

As a consequence, Table C2 of the appendix provides evidence that the behavioural intention of farmers can be regarded as reliable selection instruments: they influence the decision to adapt or not to CSA practices (Model 1, $\chi 2 = 52.18$; $p = 0.00$), but not the HDDS (Model 2; F-statistic = 1.27, $p>0.10$) and HFIAS (Model 3, F-statistic = 1.09, $p = 0.35$) of non-adopting households. The results (Appendix A2) showed that the selected instrument is crucial in affecting the adoption behaviour of rural farmers in South Africa but not significant for those who did not adopt CSA.

Actual and counterfactual analysis: Average Treatment and Heterogeneity Effects estimation

After employing the ESRM framework to estimate the relationship between adoption-decision of CSA and FNS, we proceed to calculate the average treatment effect (ATT). This analysis, referred to as the actual-counterfactual analysis, provides estimates of the expected impacts for households that adopt CSA as well as those who do not (Akano et al., 2023; Issahaku & Abdulai, 2020). Four distinct estimations are conducted: (a) the observed effect of adoption on adopters; (b) the observed effect on non-adopters (c) the hypothetical effect of adoption on non-adopters, assuming they had adopted (counterfactual); (d) the hypothetical effect of adoption on adopters, assuming they had not adopted (counterfactual). Following (Akano et al., 2023; Atta-Aidoo et al., 2022), this approach allows us to create counterfactual outcomes for the two regimes (adopters and non-adopters), allowing us to compare the expected FNS outcomes (HDDS and HFIAS) of true adopters and their counterfactual (non-adopters). The conditional expectations for FNS in the four situations are shown in Table 1 and are defined as follows:

$$E(y_{1i} l A_i = 1) = X_{1i}\beta_1 + \sigma_{1\eta}\lambda_{1i} \qquad \text{.................................. (6.3a)}$$

$$E(y_{2i} l A_i = 0) = X_{2i}\beta_2 + \sigma_{2\eta}\lambda_{2i} \qquad \text{.................................. (6.3b)}$$

$$E(y_{2i} l A_i = 1) = X_{1i}\beta_2 + \sigma_{2\eta}\lambda_{1i} \qquad \text{.................................. (6.3c)}$$

$$E(y_{1i} l A_i = 0) = X_{2i}\beta_1 + \sigma_{1\eta}\lambda_{2i} \qquad \text{.................................. (6.3d)}$$

Consequently, the actual expectations that were seen in the sample are represented by Cases (a) and (b) along the diagonal of Table 6.1. While Cases (c) and (d) reflect the anticipated results of the counterfactual outcomes.

Table 6.1. Average Treatment and Heterogeneity Effects estimation for actual and counterfactual outcomes

	Adoption decision estimations[5]		
Household adoption categories	**To adopt**	**Not to adopt**	**Treatment effects**
Households that adopted	(a) $E(y_{1i} l A_i = 1)$	(c) $E(y_{2i} l A_i = 1)$	TT
Households that did not adopt	(b) $E(y_{1i} l A_i = 0)$	(d) $E(y_{2i} l A_i = 0)$	TU
Heterogeneity effects	BH_1	BH_2	HT

Following (Akano et al., 2023; Di Falco et al., 2011; Gwara et al., 2022), effect of treatment to adopt on treatment (TT) was measured as the difference between (a) and (c)

TT = $E(y_{1i} l A_i = 1)$ - $E(y_{2i} l A_i = 1)$ .... (6.5)

Equation (6.5) denotes the impact of CSA adoption on FNS of farm households that actually adopted the practices. Additionally, we estimated the effect of treatment on the untreated (TU) for households that actually did not adopt CSA, which is represented by the difference between (d) and (b), as expressed in equation (6.6)

TU = $E(y_{1i} l A_i = 0)$ - $E(y_{2i} l A_i = 0)$ .... (6.6)

Furthermore, we use the expected outcomes expressed as the difference between equation 6.3a – 6.3d to calculate the heterogeneity effects (HE) shown in equation 6.7. Following (Antwi-Agyei et al., 2021; Di Falco et al., 2011), HE denotes the scenario whereby households that adopt CSA could experience better FNS than households that did not adopt CSA irrespective of the fact that they decided to adopt because of their unobservable characteristics such as behavioural intention

[5] Noted: (a) and (b) symbolize the observed FNS, while (c) and (d) represent the counterfactual FNS of the farm households.

Ai = 1 if farm households adopted CSA; Ai = 0 if farm households did not adopt

Y_{1i} and Y_{2i} = FNS of farm households that adopted and did not adopt CSA, respectively

TT = impact of the adaptation treatment on the treated farm households

TU = signifies the adaptation treatment's effect on the untreated farm households

BH_i = impact of base heterogeneity on farm households (i = 1 for adopter; i = 2 for non-adopters)

HT = TU - TT, which represents transitional heterogeneity

(attitude, subjective norm, behavioural control and behavioural control)

$$\text{HT}_1 = E(y_{1i} l A_i = 1) - E(y_{1i} l A_i = 0) \quad \text{..................................} (6.7)$$

Likewise, "the effect of base heterogeneity" pertains to the group of farm households that opted not to adopt; it is calculated as the discrepancy between (c) and (b), shown in equation 6.8.

$$\text{HT}_2 = E(y_{2i} l A_i = 1) - E(y_{2i} l A_i = 0) \quad \text{..................................} (6.8)$$

Following (Antwi-Agyei et al., 2021; Di Falco et al., 2011), we examine the "transitional heterogeneity" (HT), which denote the difference between TT and TU (i.e., equation (6.5) and (6.6)) to see if the effect of adopting CSA is larger or smaller for FNS of farm households that actually adopted CSA or for farm households that actually did not adopt in the counterfactual case that they did adopt.

6.3.3.2 Behavioural intentions of rural farmers to Adopt CSA

Following (Gwara et al., 2022), the behavioural intentions of farmers to adopt CSA was based on their attitudinal dimensions assessed with through response score of $1<\mu<2$. Following (Atta-Aidoo et al., 2022; Gwara et al., 2022), values obtained about the attitudinal dimensions of smalholder farmers greater than 1.5 was indicative of a positive attitude, whilst scores below 1.5, denotes negative attitude. Following (Gwara et al., 2022; Issahaku & Abdulai, 2020), the attitudinal dimension of the rural farmers were assessed through the following;

i. Behavioural intension was assessed through a-four distinct criteria, aimed to investigate the farmers' decision to adopt CSA, either with or without assistance, as well as their readiness to overcome obstacles related to financial constraints and knowledge limitations.
ii. individual attitudes towards CSA adoptions was assessed through six distinct criteria with three of these criteria specifically examining the significance, convenience, and feasibility of CSA. The remaining three individuals considered the possible advantages of CSA in relation to enhanced crop yields, agricultural profitability, and reputation.
iii. Subjective norm was measured with four criteria, two of which concerned the motivation to use CSA and the remaining two addresses the perceptions of others regarding the adoption of CSA.
iv. Perceived behaviour control was assessed using four criteria. The criteria pertained to the level of control that a farmer has in relation to the requisite activities involved in CSA practices.

In addition, the latent construct of CSA adoption consisted of eight items that encompassed various CSA practices in South Africa; specifically, drought-tolerant varieties (DTV), cover cropping, zero/minimal tillage, mixed cropping, planting early maturing varieties (PEMV), water management/irrigation, mulching, and intercropping with legumes (IWL).

6.3.3.3 Food-Nutrition security (FNS) of rural farmers (adopters and non-adopters)

Given the multidimensional nature of FNS, we captured it using two measures. First, we utilize the household food insecurity access score (HFIAS) to capture the FNS. The HFIAS is a scale that quantifies and summarizes distinct behavioural and psychological dimensions of food insecurity (access) (Issahaku & Abdulai, 2020). Following (Tilahun et al., 2023), household with no reported food insecurity receives a minimum score of 0 (better food access). While food-insecure household with a high frequency of ingesting less preferred foods or foregoing meals due to inadequate access to food receives a maximal score of 27. Numerous research (Dlamini et al., 2023; Issahaku & Abdulai, 2020; Popoola et al., 2022; Teklewold et al., 2019) have been done to highlight the HFIAS of rural households in South Africa (Figure 6.3) but there is dearth of knowledge on behavioural adoption-impact of CSA on HFIAS in South Africa

The second metric is the household dietary diversity score (HDDS) which was used to measure the dietary-quality of the households. Following (Akter et al., 2023; Omotayo et al., 2022; Omotoso et al., 2022), food consumed by a household over the course of a week were classified into twelve distinct food categories, namely cereals, tubers and roots, vegetables, fruits, meat and poultry, eggs, fish, pulses and nuts, legumes, milk and milk products, oils and fats, sugar and honey, and miscellaneous items. This was used to compute the HDDS, which has been found to be a good predictor of households' nutritional status in South Africa (Figure 6.4) and thus will be a relevant indicator of dietary quality at the household level (Akter et al., 2023; Omotayo et al., 2022; Omotoso et al., 2022).

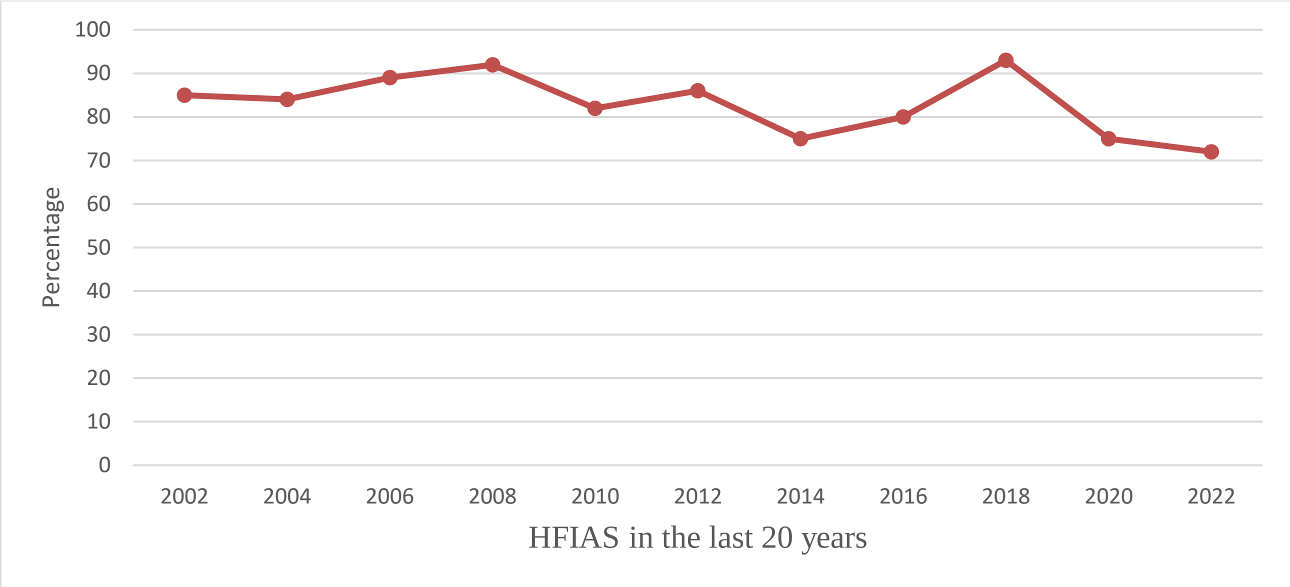

Fig. 6.3. Trends in HFIAS of rural households in South Africa in the last 20 years [adapted from (Akter et al., 2023; Dlamini et al., 2023)]

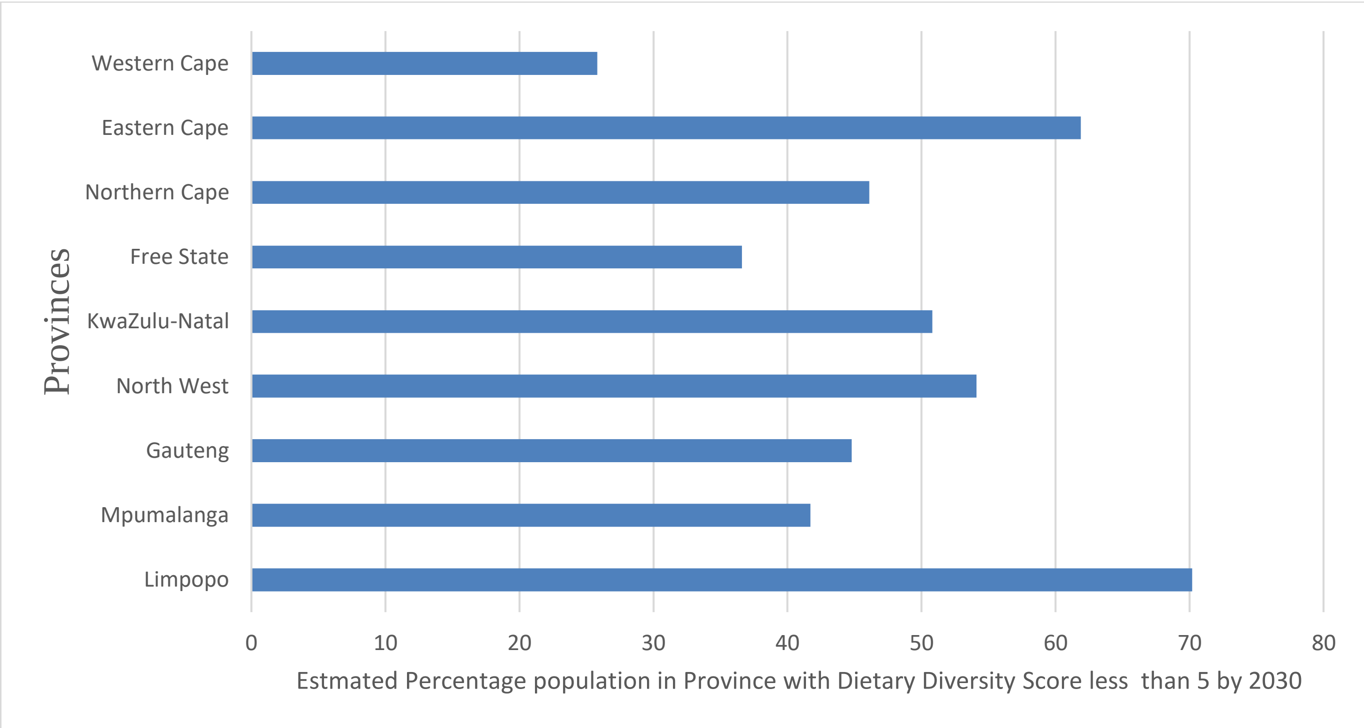

Fig. 6.4. Estimated percentage population in each province of South Africa having a dietary diversity score less than 5 by 2030 [adapted from (Bjornlund et al., 2022; Dlamini et al., 2023; Popoola et al., 2022)]

6.4 Results and discussions

6.4.1 Descriptive statistics

From Table 6.2, the average age of rural farmers in our sampled survey is 47.6 years old, which reflects the vitality of South Africa's population and the region's tremendous potential for agricultural development. Recent (FAO, 2021; Ricart et al., 2022) reports indicate that a larger proportion of the rural population in South Africa are over 45 years old. This indicates that individuals are expected to be productive with the resources at their disposal and conscious of their behavioural intentions toward adoption of improved technology. The average sampled household contains 6 persons, and cultivates less than 10 hectares of farmland, thus, illustrating the smallholder character of agriculture in the study area (Atta-Aidoo et al., 2022; Omotayo et al., 2022).

Regarding education (see Table 6.2), the majority (87.4%) of household heads are educated. Higher levels of education are indicative of robust human capital, which empowers farmers with the knowledge and skills necessary to make informed decisions regarding enhanced agricultural production practices (Bjornlund et al., 2022; Omotayo et al., 2020). With improved agricultural practices, rural farming households would experience increased crop yields and improved income generation, thereby contributing to poverty reduction and improved food-nutrition security in the households (Kangogo et al., 2021; Merga et al., 2023). Furthermore, the majority (71.9%) of rural producers interacted with extension agents. According to (Atta-Aidoo et al., 2022; Omotayo et al., 2022), found that contact with extension agents has a significant influence on adoption of agricultural technology and climate change adaptation strategies among rural farm families.

Additionally, extension agents play a crucial part in the dissemination of knowledge, provision of technical support, and assistance of farmers in making informed decisions regarding agricultural production (FAO, 2021; Ricart et al., 2022). As shown in Table 6.2, farm families with a greater diversity of income sources have the potential to adopt various CSA because they have a greater diversity of resilient livelihood alternatives, which influences their behavioural decision of households on CSA adoptions in South Africa. Similarly, remittances in the form of access to social safety will increase and diversify the sources of income for rural households, which would influence their behavioural intention towards CSA adoption in the study area.

Figure 6.5 illustrates the distribution of CSA adopted by smallholder maize farmers in South Africa. Farmers' comprehension of climate change has a substantial impact on their level of adaptation and the measures they take to combat the severe implications of climate change on their yields (Maindi et al., 2020; Mullins et al., 2018). Smallholder maize farmers in South Africa have devised a wide range of CSA strategies in response to the changing climate. Among them are mulching (66%), mixed cropping, zero tillage (60%), planting cover crop (51%), and irrigation (53%).

The reported HDDS of 9.10 (range from 2 to 11) and HFIAS of 3.412 (ranging from 1 to 25) in the previous seven days indicate that some degree of FNS exists among the studied families. Consequently, Figure 6.6 & 6.7 depicted the HFIAS and HDDS distribution of smallholder farmers respectively based on their adoption behaviour towards CSA. Figure 6.6 revealed the HFIAS values of 2.572 and 5.145 for adopters and non-adopters' categories of smallholder farmers, respectively. Following (FAO, 2021; Worku et al., 2020), these values (Figure 6.6) provide insights into the extent and severity of food insecurity of the rural farming households and can guide strategies and interventions to ensure food-secure households by 2030. Figure 6.7 depicts the HDDS values of 10.382 and 7.224 for adopters and non-adopters' categories of smallholder farmers, respectively. HDDS values (Figure 6.7) have implications for FNS and agricultural planning, aligning with the goals and objectives of FAO and other organizations working to improve global food security and nutrition outcomes.

Interestingly, the findings indicate that implementation of CSA practices by smallholder farmers has the potential to significantly enhance FNS in South Africa. In general, a rise in HDDS indicates an improvement in the household's dietary quality and nutrition security, while a drop in HFIAS indicates an improvement in the household's access to food (Omotayo et al., 2022; Pawlak & Kołodziejczak, 2020).

Table 6.2. Variable descriptions and statistical summaries used in the analysis

Variables	Descriptions	Total households		Farm households that adopted CSA		Households that did not adopt CSA	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Outcome variables							
Farm revenue	Estimated 2022/2023 agricultural season maize value per hectare (Rands/ha).	11289.551	8706.212	14895.021	9340.241	8503.732	5032.411
Household Food Insecurity Access Score (HFIAS)	An absolute food secure HH receives a score of 0, while a completely food insecure HH receives a score of 27.	3.412	1.593	2.572	1.131	5.145	2.772
Households Dietary Diversity score (HDDS)	Measured based on intake of 12 food groups consumes by the HH in the past 7 days	9.101	3.742	10.382	4.133	7.224	2.901
Treatment variables							
Adoption of CSA	Dummy; 1 if adopt any practices, 0 if otherwise	0.687	0.391	0.687	0.391	0.313	0.129
Socioeconomic characteristics							
Age	Actual age of household head	47.672	11.731	46.245	21.951	49.137	18.952
Gender	Dummy; 1=male, 0=female	0.751	0.393	0.812	0.573	0.288	0.115
Household size	Total member of household	6.101	2.612	7.423	3.111	5.329	2.602
Marital status of the head	Dummy; 1 if married, 0 if otherwise	0.810	0.529	0.903	0.430	0.791	0.516
Educational status of the household head	Dummy; 1 if educated, otherwise	0.874	0.317	0.812	0.537	0.895	0.491
Years of experience	Actual year (continuous)	11.542	6.711	14.952	6.153	9.742	3.634
Off-farm income	Dummy; 1 if yes, 0 if otherwise	0.573	0.202	0.673	0.286	0.527	0.317
Contact with extension	Dummy; 1 if yes, 0 if otherwise	0.719	0.361	0.812	0.594	0.588	0.202

Land ownership	Dummy; 1 if yes, 0 if otherwise	0.675	0.442	0.778	0.345	0.573	0.202
Total land used for cultivations of other crops	Actual farm size (Continuous)	8.701	4.352	11.304	7.928	6.631	3.852
Total land used for maize cultivation	Actual land area used for maize cultivation (Continuous)	5.142	1.972	7.562	3.982	4.207	0.196
Livestock farming	Dummy; 1 if yes, 0 if otherwise	0.458	0.221	0.398	0.203	0.542	0.221
Source of finance	Dummy; 1 if personal, 0 if otherwise	0.786	0.372	0.739	0.374	0.782	0.402
Membership of farm organization	Dummy; 1 if yes, 0 if otherwise	0.671	0.484	0.774	0.492	0.669	0.302
Access to credit	Dummy; 1 if yes, 0 if otherwise	0.381	0.130	0.118	0.183	0.487	0.205
Access to extension training	Dummy; 1=Yes to access to extension training on improved agricultural production practices, 0= otherwise	0.718	0.425	0.929	0.572	0.385	0.117
Social safety	Dummy; 1 if household members receive social grant, 0 if otherwise	0.585	0.309	0.601	0.335	0.391	0.196
Information on climate change							
Community meetings	Dummy; 1 if yes, 0 if otherwise	0.505	0.273	0.586	0.228	0.273	0.115
Flyers/Posters	Dummy; 1 if yes, 0 if otherwise	0.672	0.205	0.680	0.319	0.472	0.207
Radio	Dummy; 1 if yes, 0 if otherwise	0.791	0.289	0.927	0.504	0.305	0.135
Smartphone	Dummy; 1 if yes, 0 if otherwise	0.580	0.314	0.982	0.539	0.289	0.117
Local newspapers	Dummy; 1 if yes, 0 if otherwise	0.601	0.307	0.779	0.302	0.516	0.224
Sample size	Total number of sampled farm households	316		201 (63.6%)		115 (36.4%)	

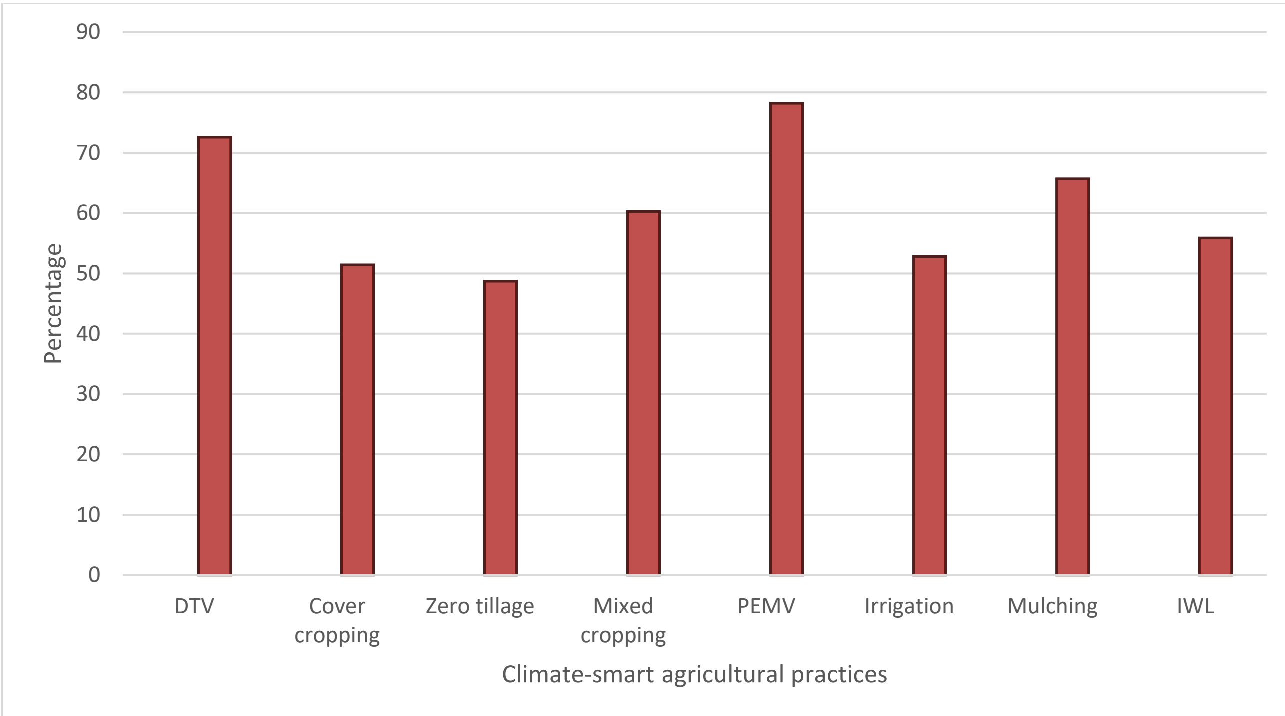

Fig. 6.5. CSA adopted by rural farmers in South Africa

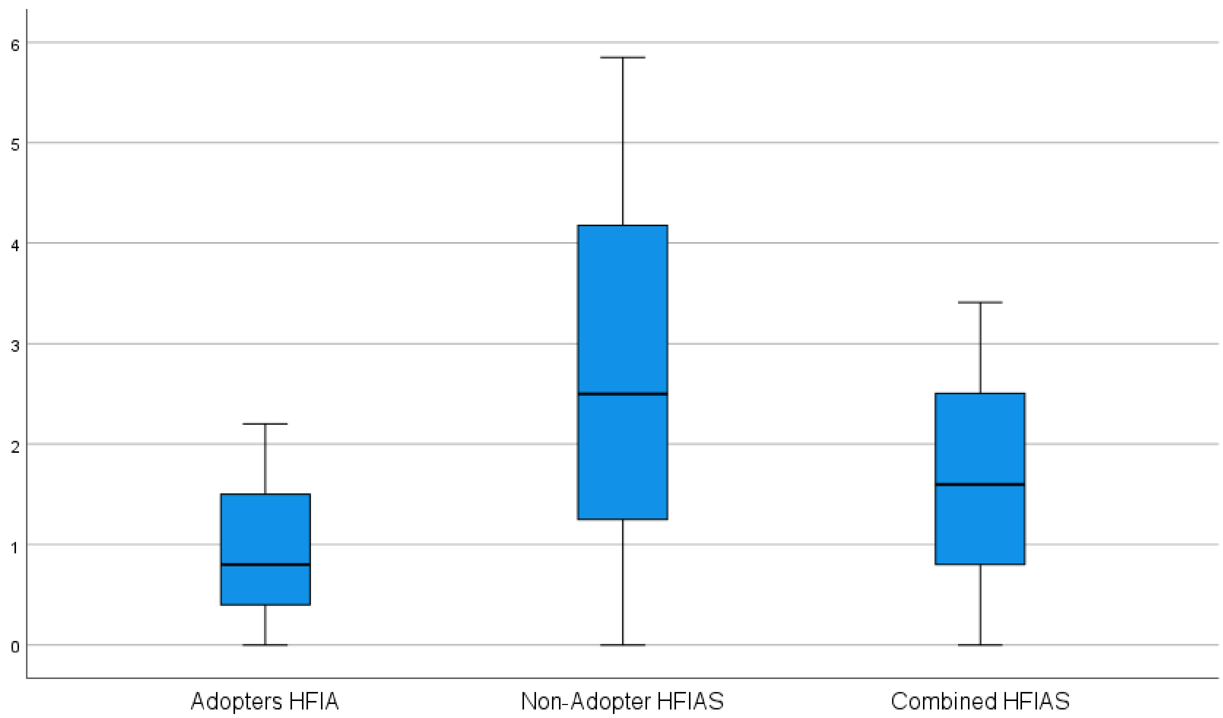

Fig. 6.6. HFIAS of smallholder farmers in SA (adopters and non-adopters of CSA)

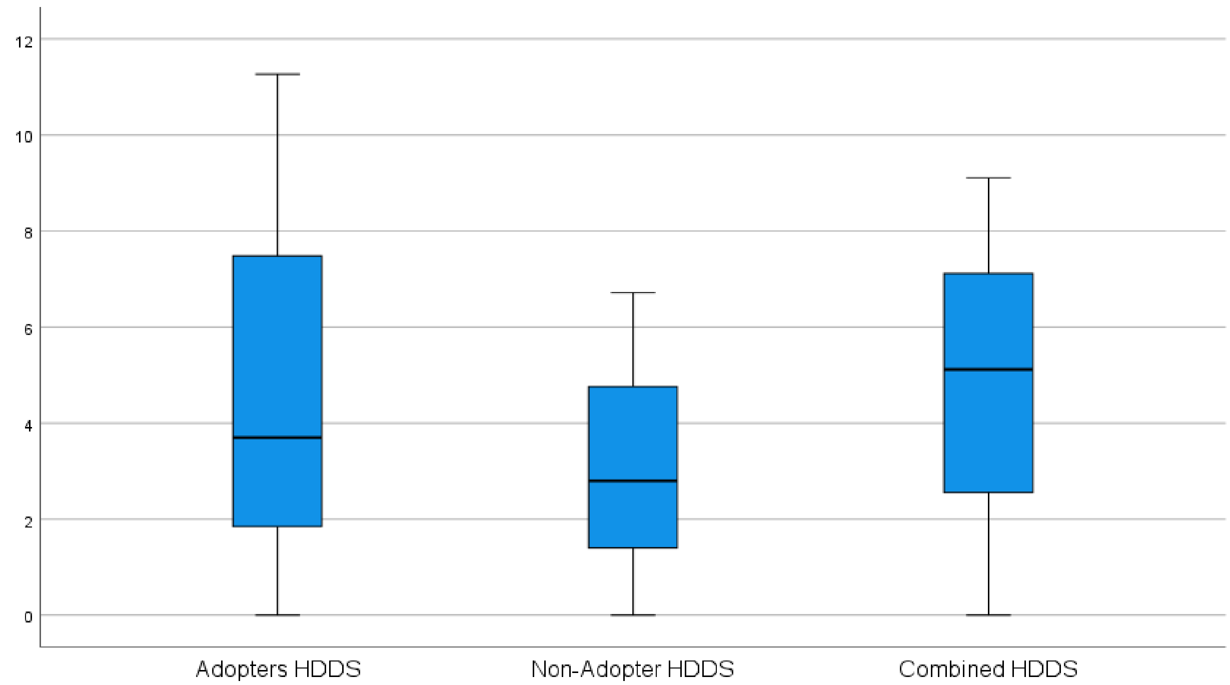

Fig. 6.7. HDDS of smallholder farmers in SA (adopters and non-adopters of CSA)

6.4.2 Behavioral dimensions of rural farmers toward the adoptions of CSA practices

The confirmatory factor analysis (Table 6.3) demonstrates that the observed variables highlighted were significant ($p<0.01$) and deemed adequate to explained the behaviour intentions of the rural farmers, with values ranging from 0.201 to 0.820. Additionally, it depicts that all the four constructs - individual attitude, subjective norm, perceived behaviour control, and behavioural intention, are significant, denoting that were internally consistent and reliable for assessing farmers behavioural attitudes toward CSA adoption in South Africa. From Table 6.3, the behaviour intention score was favourable (1.651), showing that farmers were eager to adopt CSA in the farming operation. The individual attitude score also denotes a positive response (1.631) to adoption of CSA.

Consequently, the subjective norms were not as dissuasive as the other behaviour dimension (1.582), which showed that farmers would adopt CSA, if benefit of CSA adoptions is well established by other farmers. Potential hurdles were indicated by perceived behavioural control (1.433), which showed that farmers thought adopting CSA in agriculture was risky and that they lacked the necessary skills and self-efficacy to utilized it. This research was in accordance with (Atta-Aidoo et al., 2022; Gwara et al., 2022; Mutengwa et al., 2023), reported that not only financial incentives can motivate farmers' adoption behaviour, but the behavioural dimension has been useful in illuminating farmers' decision-making processes. This is due to the fact that farmers aren't only profit-maximizing entities, but may also be impacted by other intrinsic and human incentives, particularly when a choice might have social and environmental repercussions.

The result predicts farmers' attitude towards CSA adoptions on the supposition that their behavioural attitude, which govern their adoption-decision, are influenced by individual attitudes, subjective norms, perceived behavioural control and intentions. The analysis revealed a noteworthy and statistically correlation between the attitude of farmers and their inclination to embrace CSA. The results obtained in this study align with the conclusions drawn in other research (Atta-Aidoo et al., 2022; Gwara et al., 2022; Mutengwa et al., 2023), indicating that behavioural intentions serve as the most effective first factor for initiating decision-making process. The influence of farmers' mindset on behavioural dimension towards conservation agriculture has documented by (Kangogo et al., 2021; Maindi et al., 2020; Mullins et al., 2018), revealed that behavioural intention has a significant role in influencing farmers' decision making in adopting new technology, which would have a significant impact on their households' FNS.

Table 6.3. Summary statistics of the attitudinal dimensions of the smallholder farmers

Attitudinal dimensions	Mean	Std. Dev.	Factor loading
Behavioural intention	1.651^	1.021	
a. Willing to adopt CSA with or without financial support	0.613	0.225	0.201***
b. Willing to access to credit to overcome financial barrier to CSA adoption	0.701	0.382	0.482***
c. Willing to source information about CSA practices	0.582	0.198	0.751***
d. Willing to learn more about CSA	0.732	0.521	0.283***
Individual attitudes	1.631^	1.131	
a. CSA practices are necessity approach to improve productivity	0.850	0.392	0.503***
b. CSA practices convenient to implements	0.753	0.441	0.481***
c. CSA practices implementation on farm is practicable	0.892	0.381	0.453***
d. CSA practices will enhance farm yields	0.714	0.521	0.684***
e. CSA practices will increase farm income	0.608	0.339	0.535***
f. CSA practices will increase my reputation in the community	0.525	0.275	0.764***
Subjective norm	1.582^	1.183	
a. Expected of me to adopt CSA since all other farmers have adopted it	0.587	0.207	0.571***
b. Want to be like other farmers when it comes to new technology adoption	0.612	0.406	0.661***
c. Motivation/pressure from extension agent about adopting CSA	0.784	0.372	0.345***
d. Pressure from community to adopt since others have already adopted CSA	0.550	0.185	0.226***
Perceived behaviour control	1.433^	1.072	
a. I am able to practice at least one of the CSA practices	0.504	0.202	0.574***
b. Resources to implement CSA practices on farm is available	0.408	0.198	0.820***
c. All the information needed to adopt CSA has been provided	0.536	0.275	0.421***
d. Risky and unprofessional	0.525	0.176	0.304***

Note: *** significant at 1%; ^ weighted mean score (for constructed attitude)

6.4.3 Empirical analysis of determinants of CSA adoption – ESRM

The outcomes of the empirical analysis of ERSM are presented in this section. To begin, we investigated the determinants that impact the CSA adoption. As previously stated, the ESRM estimates two distinct but related outcome equations, one for each group (adopters and non-adopters), in conjunction with an adoption selection equation. The second estimates revealed the determinants of food-nutrition security outcomes (HDDS, and HFIAS) of the smallholder farmers.

6.4.3.1 Drivers of Adoption of CSA - First stage ESRM

The adoption predictors of CSA by smallholder farmers in South Africa are shown in the second column of Table 6.4, illustrating the obtained findings. In general, the findings indicate that the adoption of CSA is significantly influenced by household factors (education level, household size, and sex), resource restrictions (farm size, access to credit and off-farm income), institution variables (access to extension training, members of cooperative society and sources of climate information – radio, smartphones and community meetings), and their perceived attitudinal dimensions (individual attitude, subjective norms, behaviour intension and control) of the smallholder farmers.

The coefficient for the household size variable is positive and substantially distinct from zero, suggesting that households with larger prospective labour force are more likely to employ CSA. The coefficient for the variable education is also positive and substantially distinct from zero, suggesting that producers with a higher level of education are more likely to implement CSA. According to (Akpan & Zikos, 2023; Omotoso et al., 2022), education helps farm families grasp the benefits of new agricultural technology by boosting awareness and improving adoption decisions. The adoption of CSA is more prevalent among female farmers, as seen by the statistically significant negative coefficient associated with the gender variable, a result aligns with (Aidoo et al., 2021; Popoola et al., 2022) findings. Off-farm income is also a significant variable that influences the adoption of CSA suggesting that adoption decision on farm and off-farm income activities are complementary. This suggests that engaging in off-farm income-generating activities liberates farmers from financial constraints that might prevent them from implementing new agricultural technology (Daud et al., 2018; Kangogo et al., 2021).

Another intriguing finding is the estimate of access to extension variable. We discovered that farmers' extension interactions improve their likelihood of adoption. Farmers may acquire relevant information regarding climate-smart practices via extension contacts. Similarly, (Daud et al., 2018; Kangogo et al., 2021), posited that rural households' confidence in the abilities of extension agents has a significant influence on their propensity to employ agricultural technologies. CSA adoption was shown to have a favourable correlation with increased access to climate information through radio, community meetings and smartphone. This suggests that the respondents would be more likely to use adaption techniques if they had appropriate awareness about climate change. The adoption of CSA was also found to be positively correlated with membership in agricultural cooperatives. According to (Akpan & Zikos, 2023; Omotoso et al., 2022), membership in agricultural cooperative societies has a positive and statistically significant impact on the adoption of agricultural technology and the productivity of farm households.

Cooperatives facilitate member access to inputs, credit, and markets (Akpan & Zikos, 2023; Daud et al., 2018; Omotoso et al., 2022). The results also demonstrated that South African smallholder farmers with constrained credit access are less likely to adopt CSA. This implies that adoption of novel agricultural technologies requires a monetary investment. Prior research (Omotayo et al., 2022; Pawlak & Kołodziejczak, 2020), has demonstrated that rural households are more likely to implement agriculture innovations if they have access to credit. Additionally, this study discovered a consistent positive influence of behavioural attitude of rural farmers on CSA adoptions in South Africa. This could be attributed to the endogeneity of behavioural dimension of smallholder farmers in the propagation of CSA practice. Due to fact that CSA are frequently knowledge-intensive and require reassurance regarding usage and management procedures, therefore smallholder farmers' positive attitude play a significant role in CSA adoption in South Africa.

Consequently, the presence of a positive and statistically significant correlations among the adoption of CSA and farmers' behavioural intention suggests that holding favourable attitudes about CSA enhances the likelihood of farmers intending to adopt these practices. The development of favourable attitudes towards CSA practices is contingent upon farmers seeing the favourable effects that CSA practices have on agricultural productivity and households' food-nutrition outcomes (Atta-Aidoo et al., 2022; Gwara et al., 2022; Mutengwa et al., 2023). Specifically, it was found that individual attitude, subjective norms and behavioural intensions have been the most substantially behavioural intentions influencing farmers' decision-making in adoption of CSA. This also verifies the validity of the ESRM model's instrumental variable (behavioural dimension of smallholder farmers – behavioural intension, individual attitude, subjective norms and behaviour control)

6.4.3.2 Determinants of HDDS and HFIAS of adopter and non-adopter of CSA

The column 3 and 4 (Table 6.4) displays the HDDS and HFIAS determinants for adopters and non-adopters of CSA. As reported, certain important household characteristics (household size, gender, and off-farm income) are notably significant in the HDDS and HFIAS outcomes. In the HDDS outcomes, coefficient associated with household size negative and demonstrate statistical significance for adopters of CSA while positive and statistically significant for HFIAS outcome, indicating that, all other things being equal, a larger family size is associated with poor dietary quality. The positive and statistically significant coefficient of the variable representing education suggests that a higher level of education may be associated with a higher HDDS intake. This is consistent with earlier research that found a positive and statistically significant correlation between household education and dietary quality (Jellason et al., 2021; Omotayo et al., 2022). This could be attributed to fact that education improves farmers' understanding of food and nutrition security (Kangogo et al., 2021).

The coefficient associated with gender variable is statistically significant (negative for HDDS and positive for HFIAS), indicating that female-headed households are associated with increased dietary diversity among adopters. This finding aligns with previous research that linked empowered female household heads to heightened dietary diversity in SSA (Akter et al., 2023; Asravor, 2022). It is important to note that in many regions of Africa, women are typically in control of food preparation and therefore tend to influence dietary quality. This finding reaffirms the importance of gender in food and nutrition security, as outlined in the South Africa National Food-Nutrition Policy for 2023.

The coefficient associated with off-farm employment has a positive relationship with the HDDS but a negative relationship with the HFIAS. Moreover, this coefficient is statistically significant, suggesting that involvement in off-farm employment is likely to result in enhanced dietary variety and quality (HDDS) as well as improved access to food (HFIAS). The observed results may be attributed to the income effect stemming from engagement in non-farm work, whereby families use their earnings from non-farm employment to improve their food-nutrition security. Access to credit has significant effect on HDDS but not on HFIAS. Intriguingly, extension contact and extension training has the anticipated indications in both HDDS and HFIAS, indicating that extension service plays a significant role in enhancing food-nutrition security in South Africa.

Table 6.4. ESRM for determinant of CSA adoption and HHDS and HFIAS of adopters and non-adopters

	CSA adoption	HDDS		HFIAS	
Variables		**Adopters**	**Non-adopters**	**Adopters**	**Non-adopters**
Constant	0.125*** (0.055)	0.365*** (0.101)	0.561*** (0.129)	0.278*** (0.087)	0.056 (0.049)
Age	0.296*** (0.103)	-0.387 (0.853)	0.154 (0.164)	0.175 (0.243)	0.040* (0.022)
Gender	-0.075** (0.038)	-0.056*** (0.022)	-0.186 (0.264)	0.198*** (0.058)	-0.111 (0.085)
Household size	0.115*** (0.031)	-0.152* (0.080)	0.063 (0.321)	0.088* (0.047)	0.105 (0.096)
Marital status of the head	-0.116 (0.283)	0.187 (0.439)	-0.107** (0.040)	0.190 (0.165)	0.724 (0.773)
Educational status of the household head	0.198*** (0.053)	0.036** (0.018)	0.147* (0.081)	0.065 (0.109)	-0.476 (0.392)
Years of experience	0.286 (0.789)	0.368 (0.472)	0.075 (0.379)	0.308 (0.281)	0.197 (0.209)
Off-farm income	0.387*** (0.092)	0.037** (0.018)	0.078 (0.195)	-0.157** (0.082)	0.050 (0.103)
Contact with extension	0.043** (0.022)	0.177** (0.082)	0.186 (0.291)	-0.082** (0.041)	0.272 (0.185)
Land ownership	-0.184 (0.263)	-0.178 (0.654)	0.306*** (0.101)	0.074 (0.106)	0.007 (0.013)
Total land used for cultivations of other crops	0.459 (0.653)	0.642 (0.539)	-0.007 (0.038)	0.039 (0.051)	-0.602 (0.592)
Total land used for maize cultivation	-0.096 (0.185)	-0.363 (0.378)	0.023** (0.011)	0.178 (0.195)	0.102** (0.049)
Livestock farming	0.187 (0.259)	0.439 (0.653)	0.017 (0.018)	0.209 (0.194)	-0.012 (0.028)
Source of finance	-0.471 (0.389)	0.153 (0.118)	-0.188 (0.175)	0.059 (0.104)	0.307 (0.294)
Membership of coop organization	0.183* (0.097)	-0.276 (0.197)	0.907 (0.865)	0.204 (0.213)	0.018 (0.175)

Access to credit	0.049* (0.026)	0.086** (0.043)	-0.084 (0.175)	-0.609 (0.421)	0.028** (0.011)
Access to extension training	0.654** (0.307)	0.209** (0.097)	0.261 (0.334)	-0.056*** (0.021)	-0.037 (0.164)
Radio	0.034*** (0.015)	0.981*** (0.321)	-0.085 (0.155)	-0.106* (0.062)	0.098 (0.082)
Smartphones	0.007** (0.003)	0.159*** (0.045)	0.032 (0.186)	-0.087* (0.047)	-0.027 (0.118)
Community meetings	0.208** (0.097)	0.226** (0.096)	0.024 (0.183)	-0.102** (0.051)	0.197 (0.229)
Flyers/Posters	0.872 (0.923)	0.006 (0.108)	0.107 (0.098)	0.046 (0.078)	-0.106 (0.140)
Local newspaper	0.112 (0.108)	0.048 (0.113)	0.038 (0.011)	-0.085 (0.118)	0.088* (0.047)
Social safety	-0.1874 (0.181)	0.108 (0.265)	0.096 (0.165)	-0.004 (0.013)	0.066*** (0.029)
Behaviour intention	0.052** (0.028)				
Individual attitude	0.116*** (0.031)				
Subjective norms	0.024** (0.010)				
Behavioural control	0.011* (0.006)				
Rho_1		0.184*** (0.028)	0.033 (0.105)	-0.158 (0.103)	-0.107 (0.099)
Rho_2		0.095*** (0.031)	-0.164 (0.119)	0.078** (0.022)	0.072 (0.102)
Wald test χ^2 (75) = 198.67, p < 0.001,					
Log-likelihood = -285.402					

Note: *, **, and *** denotes 10%, 5%, and 1% significance level, respectively

Values in parentheses are robust standard error

6.4.4 Average Treatment (ATT) and Heterogeneity Effects estimation - Impacts of CSA adoption on HDDS and HFIAS

The primary aim of this research is to assess the impact of implementing CSA on the results related to FNS (HDDS and HFIAS) of rural farm households in South Africa. The ESRM allows for the acquisition of anticipated results pertaining to FNS, contingent upon the act of adoption of CSA (Ewunetu et al., 2023). The term "average treatment effect on the treated" refers to the discrepancy between the expected output of those who have chosen to adopt (adopters) and the counterfactual outcomes if they had not made that decision (non-adopters) (Ewunetu et al., 2023; Njuguna et al., 2022). The average treatment effect and heterogeneity of CSA adoption on household food-nutrition security in South Africa is shown in Table 6.5. Noteworthy, heterogeneity effects which accounts for the potential heterogeneity in the sample rural households, indicates that in the counterfactual case, farm households that adopted CSA would have produced considerably more than those that did not adopt CSA. This observation highlights the presence of significant heterogeneity factors that distinguish adopters as "better food secure households" than non-adaptors, in the context of climate change issue. Despite this, farm households in South Africa that adopted CSA still experienced a better FNS than those that did not.

The result presented in Table 6.5 indicates that household heads who adopt CSA observed a 3.156 (27%) increase in HDDS than those who do not adopt CSA practices. Subsequently, HDDS would have increased by 2.115 (23%) had non-adopters implemented CSA practices. The outcome illustrates that the adoption of CSA practices substantially raises HDDS of rural farming households in South Africa. The results are comparable to those of (Akano et al., 2023; Antwi-Agyei et al., 2021; Di Falco et al., 2011), who discovered that the HDDS of rural farmers in SSA was enhanced by adopting CSA practices. Additionally, the result demonstrates that the adoption of CSA practices has also yielded a noteworthy impact in mitigating the extent of food insecurity within the rural farming households in South Africa.

Interestingly, adopting CSA practices decreases the probability of household food insufficiency and HDDS by 2.576 (35%). The household food gap and HFIAS would have been reduced by 3.515 (41%) if non-adopters had implemented CSA practices on their farm. Consistently, CSA practices contributes to the resilience of ecosystems, making smallholder farmers less susceptible to extreme weather events and other climate-related challenges, optimizes agricultural productivity and reduces the risk of food insufficiency (Ali et al., 2020; Omotoso & Omotayo, 2024). By adopting practices that make agriculture more resilient to climate-related challenges, households are better positioned to maintain stable food production despite environmental variations. Thus, higher crop yields contribute to increased food availability within the household, reducing the likelihood of food shortages and improving overall food security (Hasan et al., 2018). Consequently, the results of the study confirmed that the adoption of CSA substantially improved household food-nutrition security (as measured by household dietary diversity score and household food insecurity access score). Recent empirical research conducted by (Ewunetu et al., 2023; Njuguna et al., 2022) bears resemblance to the current investigation, which revealed that the adoption of CSA practices such as crop diversification, soil and water management resulted in greater utility returns for rural households' welfare.

Table 6.5. Average Treatment and Heterogeneity Effects estimation for actual and counterfactual FNS (HDDS and HFAS) outcomes

FNS outcomes		Adoption decision estimations		
		To adopt	**Not to adopt**	**Treatment effects**
HDDS	Adopters	9.177 (4.036)	6.021 (3.011)	3.156*** (1.024)
	Non-adopters	7.265 (2.861)	5.149 (2.853)	2.115*** (0.087)
	Heterogeneity effects	-1.852*** (0.372)	0.872*** (0.211)	1.041** (0.578)
HFIAS	Adopters	2.851 (1.962)	5.427 (2.439)	-2.576*** (0.073)
	Non-adopters	4.702 (1.628)	8.217 (3.872)	-3.515*** (1.003)
	Heterogeneity effects	1.851	-2.790	-0.939*** (0.124)

Note: ***, ** and * denote significant at 1%, 5% and 10%; Standard errors are in parentheses

6.5 Conclusion and policy implication

This research investigated the behavioural intentions of smallholder farmers to implement CSA in South Africa and the subsequent impacts of adoption on food-nutrition security (HDDS and HFIAS). The study made use of cross-sectional data obtained via field survey from rural farmers in South Africa. We used ESRM to address possible selection bias that may result from both observable and unobserved sources. Furthermore, we conducted an estimation of the impacts of adoption on FNS (proxied by HDDS and HFIAS) outcomes in order to evaluate the distributional consequences of adoption. The present study has presented empirical data on the influence of individual attitude, subjective norm, perceived behaviour intention and control on the intentions and eventual adoption of CSA practices among rural farmers in South Africa. The findings indicate that there is a positive correlation between behavioural attitude of farmers and their adoption-decisions of implementing CSA on their farm. Furthermore, ESRM indicate that there are some household characteristics (age, household size and educational status), farm-level factors (off-farm income, and access to credit) and institutional factors (access to extension training on improved agricultural practices, and climate information through radio, phones and community meetings) that have a substantial impact on farmers' choices to adopt CSA. Consequently, the behavioural intentions (such as subjective norms, individual attitude and behavioural control) positively and significantly influence CSA adoption by smallholder farmers in South Africa. Additionally, adoption of CSA had a positive and significant impacts on FNS of smallholder farmers. The result herewith depicts that CSA adopting increase the HDDS of the rural farmers by 23% and decrease their HFIAS by 35%. The study concluded that farmers who cultivate more positive attitudinal dimension are more likely to enhance their desire to implement CSA practices. Overall, given that farmers' attitudinal dimension towards CSA adoption is linked to improvement in agricultural productivity, we draw the conclusion that it is responsive to FNS of smallholder farmers in South Africa. Therefore, policy interventions should be focused on raising awareness among rural farmers in order to foster a more favourable attitude towards CSA practices. Farmers' favourable behavioural intentions toward CSA practices could be enhanced through the updated extension services and the integration of climate change sensitization into extension delivery method through radio, smartphone, local newspapers as well as flyers/posters, this would boost the adoption of climate-smart practices, hence improving the resilience of farmers to climate change and FNS in the rural households. Furthermore, future perspectives in this field should aim to address emerging challenges, embrace technological advancements, and contribute to the development of sustainable and climate-resilient agricultural systems. Collaborative efforts involving researchers, policymakers, and local communities will be essential for shaping a more sustainable and food-secure future in the face of climate change.

CHAPTER 7: CONCLUSION AND RECOMMENDATION

This chapter addressed the extent to which the Aim was achieved and the problem addressed by reviewing the findings of each Objective. It details the significance of the findings, the limitations that may have affected the results, and presents recommendations for practice and research.

7.1 Summary of Major Findings

The agricultural sector in sub-Saharan Africa (SSA) is witnessing a notable decrease in productivity as a result of the impacts of global climate change, which have implications for productivity and food-nutrition-development. Additionally, the FAO and WHO regional assessment cautions that a temperature increase of more than 2 °C would result in reduced yields for staple crops throughout much of SSA. Ascribed to the current manifestations of climate change in SSA, agricultural production is being affected by the prospect of reduced yields, attributed to the relatively shorter length of the growing season and increase temperature, which affects the availability, accessibility and price of food products.

Evidence from the systematic literature review (manuscript 1, 2 and 3) conducted to highlight the trends in climate change in SSA, its impact on agricultural production and influence of agriculture energy-use on GHGs emission revealed the prevailing consensus that the countries of the SSA that are suffering the impacts of climate change have landed in an extremely vulnerable position. Without swift action, emissions of GHGs in agriculture, land, and energy-use will continue to rise and lead to the overheating of the ozone layer. Understanding GHG emissions by sources and removal by sinks in agriculture is essential for devising effective GHG reduction and adaptation strategies. Furthermore, while projections concerning the degree, magnitude and the regional pattern of climate change, are unpredictable, the impact of climate change on vulnerable households would indeed prove to be extreme if adequate measures are not implemented timeously in SSA.

In the context of South Africa (evidence from manuscript 4, 5 and 6), cereal productions, particularly maize, which serve as the country's primary staple meal, decreased by 25% from 2000 to 2022 due to climate change, resulting in low productivity, decreased incomes and increased poverty, especially among the rural smallholder farmers. As a result, an understanding of farmers' adaptation techniques to offset the negative impacts of climate change is crucial for agricultural development of the nation.

Objective 2 is addressed in manuscript 4, which examined the complementary relationships among climate change adaptation strategies (CCAS) adopted by smallholder maize farmers and their adoption impacts on productivity in North West Province, South Africa. The results reveal that all of the adopted CCAS are mutually complementary, and all contributed to the farmers' productivity. Additionally, age of the household head, household size, access to extension service and climate information (through smartphones, newspaper and radio broadcast) were found to enhance the probability of adopting mixed cropping, crop rotation, mulching and agroforestry. The average treatment effect (ATT) revealed that the adoption of CCAS significantly improved the net farm income of smallholder maize farmers in South Africa by R3689.19/ha.

Manuscript 5 addressed Objective 3, and examined the impacts of the concurrent adoptions of drought-tolerant maize varieties (DTMVs) and organic manure on the productivity and welfare outcome of rural farmers in South Africa. Conversely, the cross-sectional data collected from 316 smallholder maize farmers were analyzed using propensity-score matching (PSM) and multinomial endogenous switching regression model (MESR). The results of the PSM revealed that DTMVs and organic manure adoptions had a significant impact on productivity and welfare outcomes, with joint adopters experiencing a 28% and 8% increase in their productivity and welfare outcomes, respectively. The per capita household expenditure for the joint adopters of DTMVs and organic manure was 4% higher than DTMVs adopters alone, and 8% higher than organic manure adopters only. MESR demonstrated that the estimated coefficients of age of the household head, education level, access to credit, farm and household size, and years of farming experience varies considerably across the various adoption packages of DTMVs and organic manure, and significantly influenced their concurrent adoption. The behavioural intention (BI) of adopting CSA practices by smallholder maize farmers in South Africa plays and important role in efforts to mitigate the adverse impacts of climate shock on farmers' households' food-nutrition security (FNS).

Manuscript 6 addressed Objective 4 and examined the BI of adopting CSA and its impact on the FNS of farming households in North West Province. In order to determine the relationship between behaviour adoption of CSA and FNS of smallholder maize farmers' households, an endogenous switching regression model was used, with household dietary diversity score (HDDS) and household food security score (HFIAS) serving as measures of FNS. The findings indicate that there is a positive correlation between BI, as described by the planned behaviour model, with subjective norms, individual attitude and behavioural control contributing to the farmers making decisions to implement CSA on their farm. The result indicate that CSA adoption increase the HDDS of the rural farmers by 21.3% and decrease their HFIAS by 30.7%.

Research on the impact of adopting climate-smart agriculture on agricultural productivity and food security serves a wide range of goals, including addressing climate change challenges, promoting sustainable agriculture, improving food access, and informing policy decisions. This research is critical for building a resilient and sustainable agricultural system in the face of a changing climate.

7.2 Significance

The study addresses critical issues of food security, sustainability, resilience to climate change, and socioeconomic development of South Africa, making it a valuable area of research and policy consideration. The study makes a number of significant contributions to the field of agricultural science and sustainable agricultural development of the nation, including the following:

- The study provides empirical evidence of the effects of CSA adoption on agricultural productivity and food security in a specific context, which can serve as a reference for future research and policy development. Likewise, it contributes to understanding the sustainability of agricultural practices, demonstrating how CSA can reduce soil degradation, conserve water, and promote biodiversity.
- The study shows how CSA practices enhance climate resilience in agriculture, which is increasingly important in the face of climate change and extreme weather events.
- The research sheds light on how CSA practices improve soil health and fertility, adding to the body of knowledge on soil management. Recommendations for policy changes or incentives to promote the adoption of CSA practices can influence agricultural policies in South Africa and beyond.
- The results highlight the impact of CSA adoption on farmer incomes and livelihoods, which is critical for understanding the socio-economic implications of sustainable farming.

- The study offers valuable insights into how to effectively transfer knowledge and promote the adoption of sustainable agricultural practices among farmers through proper funding of extension services.
- The findings can be applicable to other regions with similar agricultural and environmental challenges, making a contribution to the global understanding of sustainable agriculture. They could also serve as educational material for agricultural institutions, NGOs and extension services, and thereby help to train farmers and agricultural professionals in sustainable practices.

7.3 Limitations

A number of limitations may have affected the study findings, and therefore their applicability to elsewhere in North West Province and the rest of South Africa.

- The sampled farmers may not be representative of the broader farming population of the province or country, making the findings less generalizable. As only 46.1% women farmers were included, this may not reflect the breadth of opinions from this cohort.
- Establishing a causal relationship between CSA adoption and increased productivity or food security can be challenging. Other factors, such as access to credit, education, and infrastructure, can also influence outcomes.
- Farmers participating in the study may provide biased information based on their perceptions of CSA practices, potentially over-estimating their effectiveness.
- The study may not account for variations in CSA adoption rates among different farmers, potentially skewing the results.
- The study did not explore potential unintended consequences of CSA adoption, such as changes in pest dynamics or shifts in labor requirements, which in the long-run could have an impact on agricultural productivity in the study area.

7.4 Conclusion

The South Africa’s agricultural sector is failing, with production falling short of global standards and farm households living in impoverished conditions. This is largely due to adverse impacts of climate change on agricultural productivity of rural households, which results in inadequate food production and consumption. This circumstance had grievous effects on the livelihoods and FNS of rural producers, who contribute approximately 65% to the nation's food system. As a result, the study evaluates the impacts of CSA adoptions on the productivity and food security of smallholder maize farmers employing a multinomial endogenous switching regression technique. We concentrated on maize production since it is the most important staple food in terms of production volume, land allocation, and farmer involvement in the nation. This research employs the conceptual framework developed by FAO to identify areas of knowledge deficiency, promote innovative ideas, and inspire concrete measures aimed at using CSA to enhance the HDDS, HFIAS, and overall agricultural productivity of smallholder farmers in the country.

The findings of the study (manuscript 4) concluded that CCAS can have a significant impact on farm productivity of smallholder maize farmers in South Africa. Thus, in achieving FAO's sustainable agricultural goals and creating a world free hunger by 2030, South Africa's farmers must develop in term of their resilience to climate change by adopting CCAS, such as mulching, organic manure, improved seeds and agroforestry to augment their agricultural productivity.

Additionally, the finding of the research (manuscript 5) emphasized the importance of the simultaneous adoption of CSA practices, specifically DTMVs and organic manure, on smallholder maize farmers' productivity and welfare outcomes in South Africa. The findings concluded that the adoption of DTMVs and organic manure alone, or in combination, significantly increases the productivity and welfare outcomes of smallholder maize farmers. However, the returns are greatest for joint adopters of DTMVs and organic manure, indicating that concurrent adoption of DTMVs and organic manure is the optimal strategy.

Furthermore, given that farmers' attitudinal dimension towards CSA adoption is linked to improvement in agricultural productivity, we draw the conclusion (manuscript 6) that smallholder maize farmers who cultivate more positive attitudinal dimension are more likely to enhance their desire to implement CSA practices and it is responsive to their households' FNS.

7.5 Recommendations

The following recommendations are made as a result of the study findings:

- Farmers should integrate productivity-enhancing technologies to boost agricultural output and FNS status, as adopting technology in isolation may not provide the desired results.

Interventions promoting climate smartness in rural farming communities would have a significant impact on rural farm household welfare and agricultural output in South Africa.

- Farmers' favourable behavioural intentions toward CSA practices could be enhanced through updated extension services and integrating climate change sensitization into extension delivery method through radio, digital media, local newspapers as well as flyers/posters. This would boost the adoption of climate-smart practices, hence improving the resilience of farmers to climate change and FNS in the rural households
- Government, non-governmental organizations and all stakeholders should promote and apply a variety of climate mitigation techniques, such as dispersing seeds of maize and other food crops that are drought-tolerant, and prioritize the dissemination of climate-related information through platforms like radio, digital media and neighbourhood newspapers to enhance CSA adoption-decision and implementation.
- Instruction in minimal tillage practices and the use of organic manure to enhance farmers' productivity should be disseminated across the nation by extension village outreach through adequate funding by the government
- Farmers need to be provided with more reliable and constant supplies of water, such as through building dams or sinking boreholes, to enable irrigation when rainfall changes affect their crop production. The public agricultural financing system must be improved by the government through appropriate funding and monitoring to enhance maize farmers in embracing climate-smart farm practices and lessen the impacts of climate change.
- Ongoing monitoring of climate related changes need to occur throughout the country to prepare farmers for seasonal variations in rainfall and temperature, and to therefore enable them to plan for modifications in their farming practices in conjunction with the agricultural extension services.

The study findings suggest the following areas for further research:

- Further studies are required to assess the economic viability and cost-effectiveness of climate-smart practices in comparison to conventional farming methods, and to consider the short- and long-term returns on investment regionally.
- Nutritional and agro-ecological analysis need to be conducted to determine the impact of climate-smart practices on the nutritional quality of maize farmers, will further enhance

results on how these practices contribute to improved dietary diversity and micronutrient intake for farming households.

- Qualitative studies on small groups of farmers are needed to better understand issues raised in this study, such as their credit needs, inadequate climate information, poor extension service and training on improved agricultural production
- The findings of this study need to be analyzed within districts to establish if the farmers need differ in terms climate information, input and extension services.
- Inter-disciplinary research with environmental scientists, agronomists, economists, and social scientists, will provide a holistic approach to addressing complex agricultural and food security issues.

These areas of research can provide valuable insights into the specific challenges and opportunities faced by smallholder maize farmers in South Africa as they adapt to changing climatic conditions while striving to enhance both productivity and food nutrition security. Interdisciplinary collaboration and participatory approaches involving farmers locally and regionally could help ensure the relevance and impact of research findings in the field.

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Appendixes

Appendix A. Second stage of ESRM of smallholder farmers and falsification test of instrument

Table A1. Test of validity of the selection instrument

Variables	**Coef.**	**Std. Error**
Gender	0.199*	0.106
Age of household head	0.047***	0.010
Educational status	0.139***	0.042
Household size	0.082	0.194
Marital status	0.083	0.070
Main occupation	0.174***	0.039
Farm size	0.088	0.197
Years of farming experience	0.779**	0.403
Off-farm income	0.008	0.023
Membership of organization	0.042	0.142
Access to Credit	0.117	0.095
Extension agents	0.108***	0.031
Climate information	0.088	0.173
Access to extension training	0.185	0.191
Constant	0.274***	0.063

Note: *, **, and *** denote 10%, 5%, and 1% significance level, respectively

Table A2. Poisson regression of maize farmers' adoption intensity of CCAS in the study area

Variables	Coefficient	Robust Std. Err.	Marginal effect
Gender	-0.057***	0.021	-0.032
Age of household head	0.073***	0.018	0.093
Educational status	-1.061	0.891	-0.048
Household size	0.057	0.061	0.063
Main occupation	0.047**	0.021	0.057
Farm size	0.187**	0.093	0.053
Farming experience	0.573***	0.213	0.034
Off-farm income	0.155*	0.081	0.073
Membership of organization	-0.079	0.084	-0.108
Credit	0.137**	0.051	0.031
Extension agent	0.373	0.527	0.028
Climate information	0.148***	0.036	0.025
Access to extension training	0.106	0.875	0.011
Constant	1.531***	0.591	
Pseudo R^2	0.657		
Chi-square	129.21		
Number of observations	316		
McFadden	0.034		
AIC	1402.06		
BIC	1370.31		
Prob > chi^2	0.000		

Note: *, **, and *** denote 10%, 5%, and 1% significance level, respectively

Appendix B. Second Stage of MESRM and Productivity of smallholder farmers

Table B1. Productivity structure of maize farmers in South Africa (ton/ha)

Description	**D_0M_1**		**D_1M_0**		**D_1M_1**	
	Mean	**Std. dev.**	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**
Revenue (R)						
Value of Maize	226211.34	16547.59	165615.5	14396.78	345890.67	178523.92
Variable Cost Items (R)						
Labour cost	81455.21	34872.56	64914.1	34278.90	112903.34	56792.78
Transportation cost	3535.73	2387.07	2498.44	1785.34	5421.19	3479.06
Cost of Planting materials	9000.17	7805.56	10062.5	4569.08	13890.54	4590.54
Cost of Herbicides	18670.21	11234.56	18971	9067.45	7851.23	2315.86
Cost of Organic manure	15619.79	10986.75	19984.38	11354.79	2418.87	890.56
Cost of Tractor service	16200.76	7853.23	16021.42	13578.73	15490.45	10653.41
Rent on knapsack sprayer	3012.89	2389.56	2000.42	1390.34	1050.87	345.42
Total Variable Cost (R)	147494.76	87214.63	134451.8	6721.65	159026.49	103762.43
Gross Margin (R)	78716.58	34823.90	31163.61	12096.45	186864.18	111352.89
Fixed Cost Items (R)						
Rent on Land	15906.67	11654.12	9109.38	4562.65	15680.87	7632.89
Depreciation	11900.06	6782.34	3663.28	1204.54	12764.78	8745.86
Total Fixed Cost	27806.73	15906.70	12772.66	6974.56	28445.65	12549.07
Total Cost	175301.49	149531.90	147224.51	124734.67	187472.14	57986.45
Net Farm Income (R)	50909.85	30856.45	18390.95	17532.81	158418.53	98431.23
Total Factor Productivity (TFP)	1.29	0.76	1.13	0.26	1.85	1.02
Productivity	9675.00	1154.15	8475.00	3434.52	13875.34	9853.73

Note: Maize value = R7500.15/ton of maize

Table B2. Test of validity of the selection instrument

Variables	**D_0M_1**		**D_1M_0**		**D_1M_1**	
	Coef.	**Std. SE**	**Coef.**	**Std. SE**	**Coef.**	**Std. SE**
Socio-economic characteristics						
Age	-0.0231	0.0580	-0.0001	0.0028	-0.0039	0.0028
Gender	0.5168***	0.1141	0.0093	0.0060	0.0099	0.0060
Household size	0.1277***	0.0614	0.0128	0.0357	0.0393	0.0358
Marital status	0.0593	0.1153	0.0781	0.0523	0.0767	0.0534
Educational status o	-0.1287	0.1169	0.0508	0.0547	0.0797	0.0549
Years of experience	0.1091	0.1644	0.0767***	0.0304	0.0554*	0.0305
Off-farm income	0.2321	0.1079	-0.1946***	0.0489	-0.1703***	0.0491
Contact with extension	0.1942	0.1740	0.0283	0.0793	0.0145	0.0796
Access to extension training	0.0932	0.1842	0.2741	0.2092	0.1734	0.2891
Land ownership	0.0089	0.3495	0.0165	0.0168	-0.0147	0.0168
Total farm size in hectares	0.1491	1.7406	-0.0083	0.0366	-0.0095	0.0367
Total land used for maize cultivation	0.3285	1.7328	0.1222	0.3590	0.0756***	0.0294
Livestock	0.0145	0.6035	0.6304**	0.3848	0.1402	0.3865
Source of finance	0.0580	0.0744	-0.1920	0.1704	-0.0687	0.1711
Membership of cooperative society	0.0231	0.7532	-0.1572	0.1333	-0.1901	0.1339
Access to credit	0.0194	1.7005	-0.3355	0.2988	0.0932	0.3002
Information on climate change	-0.1497	0.6033	-0.0102	0.0283	0.0212	0.0284
Social safety	0.3285	1.0483	0.0391	0.0570	-0.0544	0.0573
Constant	0.0867***	0.0311	0.0707***	0.0292	2.2054	0.6606

Note: ***, **, and * denotes significant at 1%, 5% and 10% respectively. D_0M_0 is the reference category

Table B3. Productivity outcome: second-stage estimates of MESR

Variables	**D_0M_1**		**D_1M_0**		**D_1M_1**	
	Coef.	**Std. SE**	**Coef.**	**Std. SE**	**Coef.**	**Std. SE**
Socio-economic characteristics						
Age	0.1964	0.6521	0.3192***	0.1006	0.5837***	0.5044
Gender	0.3461	0.7190	0.4123***	0.0824	-0.4824***	0.0815
Household size	-0.2786*	0.1067	-0.0083	0.1117	0.0295	0.0440
Marital status	0.4701	0.4217	0.2071	0.1268	-0.0621	0.0909
Educational status	0.6419*	0.2494	-0.2741*	0.1105	0.1172**	0.0212
Years of experience	-0.1378	0.3720	0.5173***	0.0656	0.0406**	0.0255
Off-farm income	0.1219	0.3824	0.0284	0.0220	0.2310	0.1179
Contact with extension	-0.1042	0.2124	0.0037	0.0305	0.1715	0.2341
Land ownership	0.1038	0.5540	-0.0487	0.0884	0.1270	0.1554
Total farm size in hectares	0.1280	0.3414	0.1914	0.5003	-0.7761*	0.3812
Total land used for maize cultivation	-0.1735	0.1172	0.0700	0.0848	0.2138	0.2372
Livestock	0.0841	0.1275	-0.0667	0.2879	0.2751	0.2095
Source of financing farm operation	0.5122**	0.2550	0.1389**	0.0791	0.1014	0.2496
Membership of cooperative society	0.3223	0.2041	0.2490	0.2027	0.2020	0.4210
Access to credit	0.1288	0.2688	0.2085**	0.0938	0.5431**	0.4678
Information on climate change	0.4933**	0.1190	0.0822	0.2400	0.3126	0.5727
Social safety	0.2736	0.9310	-0.0558	0.1167	-0.2492	0.2660
Sigma2	5.1396	7.0521	2.9061*	1.0752	1.0961***	0.0094
Rho 1			0.1863	0.3419	0.3062	0.1747
Rho 2	0.2947	0.1075			0.6705	0.2089
Rho 3	0.1842**	0.0976	0.1297	0.9831		
Constant	2.5981***	0.3803	1.0982***	0.0742	2.7826***	0.2344

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

Table B4. Per capita household expenditure (total) outcome: second-stage estimates of MESR

Variables	D_0M_1		D_1M_0		D_1M_1	
	Coef.	**Std. SE**	**Coef.**	**Std. SE**	**Coef.**	**Std. SE**
Age	-0.0065	0.1458	0.0315	0.0386	0.0012	0.0001
Gender	0.0192	0.2568	-0.0247	0.0057	0.0136	0.0265
Household size	0.0579	0.1257	0.1541	0.0353	-0.0139***	0.0016
Marital status	-0.0203	0.2569	0.2610	0.1514	0.1207***	0.0112
Educational status	0.0655	0.1415	0.2019	0.1073	-0.0238	0.4341
Years of experience	0.0799	0.2307	0.1275	0.1091	0.1145	0.1062
Off-farm income	0.1007***	0.0369	0.3124	0.5602	0.0584***	0.0100
Contact with extension	-0.2060**	0.0931	0.1441	0.1054	0.1197	0.0391
Land ownership	0.1545	0.1116	0.4316	0.1702	0.0285	0.1062
Total farm size in hectares	0.0087	0.1234	0.1370	0.3051	0.0981**	0.0408
Total land used for maize cultivation	0.0251	0.0422	0.0546	0.0486	0.0061	0.6721
Livestock	0.0682	0.1772	-0.1159**	0.0469	0.0091	0.0619
Source of financing	0.1009*	0.0534	0.3773***	0.0644	-0.0415	0.0419
Membership of cooperative society	0.1968	0.0164	0.0181	0.0162	0.0238	0.1735
Access to credit	0.0892***	0.0042	0.0783***	0.0058	0.0884	0.0215
Information on climate change	0.1175	0.4405	0.6217**	0.2361	0.0249	0.0503
Social safety	0.4682***	0.0971	-0.1741	0.1197	0.0072	0.3885
Sigma2	4.2287***	0.1599	5.0476	4.1005	2.0616*	0.7391
Rho1			0.2862*	0.1084	0.3705*	0.1971
Rho2	0.1852	0.2711			0.3891	0.1785
Rho3	0.2380	0.1042	0.1967	0.1053		
Constant	0.9842***	0.1742	0.2696***	0.0348	0.1027*	0.0469

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

Table B5. Per capita expenditure on food outcome: second-stage estimates of MESR

Variables	**D_0M_1**		**D_1M_0**		**D_1M_1**	
	Coef.	**Std. SE**	**Coef.**	**Std. SE**	**Coef.**	**Std. SE**
Age	-0.0211	0.0522	0.1150***	0.0235	0.0689**	0.0258
Gender	0.0186	0.1117	-0.0663	0.0768	0.0961	0.1553
Household size	0.2507	0.2621	0.3225*	0.1470	-0.1008	0.3289
Marital status of the household head	0.1932*	0.0984	0.0674	0.0512	0.0221	0.0576
Educational status of the household head	-0.2486	0.0105	0.0509**	0.0261	0.0152	0.0681
Years of experience	0.1505***	0.0563	0.0761	0.0584	0.5752	0.7124
Off-farm income	-0.0108	0.0997	0.0788	0.1164	-0.2357	0.1521
Contact with extension	-0.0825***	0.0147	-0.5008	0.4294	0.0260	0.2028
Land ownership	0.0301	0.3112	0.0047	0.0081	0.0056	0.2217
Total farm size in hectares	0.2987***	0.0679	0.1867	0.0247	0.0148	0.1052
Total land used for maize cultivation	0.2642	0.5442	0.0914	0.5420	0.0331	0.0245
Livestock	0.5423	0.8713	-0.0269	0.0203	0.0729*	0.3092
Source of finance	-0.1483	0.3160	0.0707	0.0678	0.8743	0.7530
Membership of cooperative society	-0.0844	0.2471	0.0668	0.0593	0.1387	0.2691
Access to credit	0.0419	0.0316	0.4351	0.3347	0.5421	0.5022
Information on climate change	-0.0524*	0.02743	0.0592	0.0733	0.0752	0.2683
Social safety	-0.3668	0.05255	0.0513	0.0435	0.3512	0.2139
Sigma2	2.3785***	0.01509	4.0511	3.1267	2.1298**	0.9924
Rho1			0.0963*	0.0407	0.1034*	0.0452
Rho2	0.4592	0.5826			0.0754	0.1907
Rho3	0.1657	0.1094	0.1773	0.1852		
Constant	0.7783***	0.3382	0.4086***	0.0981	0.7775***	0.1153

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

Table B6. Robustness test using NNM

	Productivity		**Per capita household expenditure**		**Per capita expenditure on Food**	
	Coefficient	Std. Er	Coefficient	Std. Er	Coefficient	Std. Er
D_0M_1	664.56**	365.14	319.62	450.35	86.39***	35.66
D_1M_0	165.87**	76.60	908.22*	468.83	75.94	58.26
D_1M_1	51.89**	23.08	171.32*	90.72	32.12	39.34

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

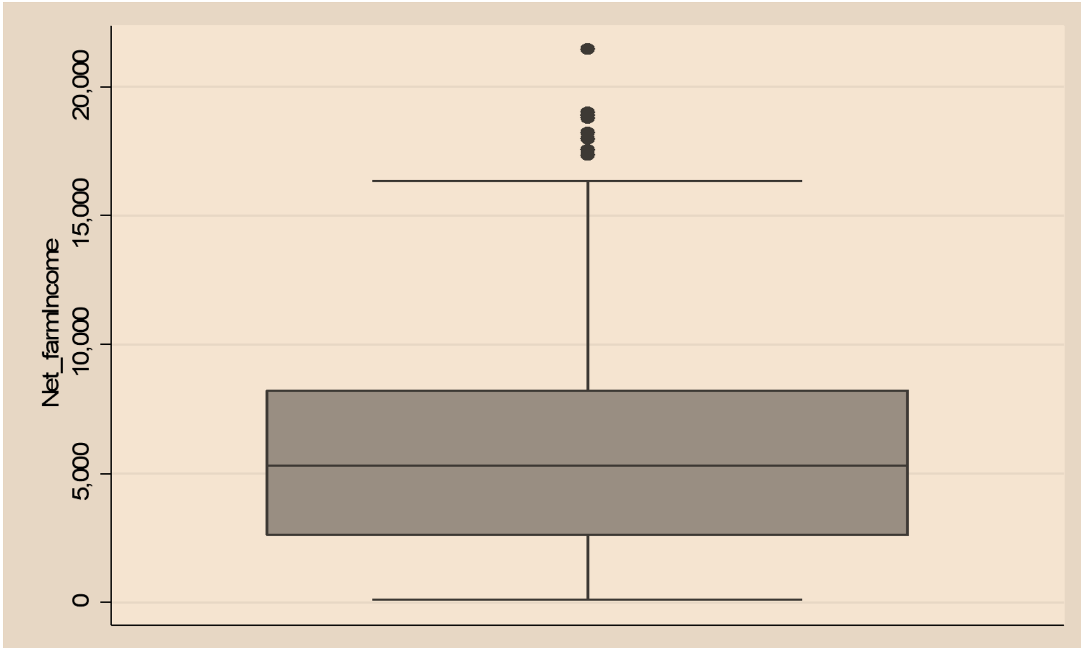

Figure B. Graph of productivity outcome of smallholder farmers in South Africa

Appendix C. Falsification test of instruments

Table C1. Falsification test of instruments

Variables	**Coefficient**	**Std. Error**
Constant	0.0561***	0.0223
Age	0.0034	0.039
Gender	-0.1907**	0.0987
Household size	0.0226	0.0251
Marital status of the head	0.3901***	0.1165
Educational status of the household head	0.7612	0.4981
Years of experience	0.0087	0.0761
Off-farm income	0.0065	0.1752
Contact with extension	0.0011	0.0261
Land ownership	0.3362	0.2776
Total farm size in hectares	-0.5422*	0.2908
Total land used for maize cultivation	0.0673	0.1087
Livestock farming	0.652	0.4979
Source of finance	0.1822	0.2438
Membership of coop organization	-0.0023**	0.001
Access to credit	0.1775**	0.0845
Access to extension training	0.8642	0.7709
Radio	0.0345	0.1983
Smartphones	-0.1904***	0.0664
Community meetings	0.0057	0.0203
Flyers/Posters	-0.0885	0.079
Local newspaper	0.0226**	0.0099
Social safety	-0.9075	0.8808
Behaviour intention	0.1183	0.2381
Individual attitude	0.0982	0.1093
Subjective norms	-0.2692	0.2995
Behavioural control	0.0896	0.1175

Note: *, **, and *** denotes 10%, 5%, and 1% significance level, respectively

Appendix C

Table C1. Test of validity of the selection instrument

Variables	**D_0M_1**		**D_1M_0**		**D_1M_1**	
	Coef.	**Std. SE**	**Coef.**	**Std. SE**	**Coef.**	**Std. SE**
Socioeconomic characteristics						
Age	-0.0231	0.0580	-0.0001	0.0028	-0.0039	0.0028
Gender	0.5168***	0.1141	0.0093	0.0060	0.0099	0.0060
Household size	0.1277***	0.0614	0.0128	0.0357	0.0393	0.0358
Marital status	0.0593	0.1153	0.0781	0.0523	0.0767	0.0534
Educational status o	-0.1287	0.1169	0.0508	0.0547	0.0797	0.0549
Years of experience	0.1091	0.1644	0.0767***	0.0304	0.0554*	0.0305
Off-farm income	0.2321	0.1079	-0.1946***	0.0489	-0.1703***	0.0491
Contact with extension	0.1942	0.1740	0.0283	0.0793	0.0145	0.0796
Land ownership	0.0089	0.3495	0.0165	0.0168	-0.0147	0.0168
Total farm size used in cultivating other crops	0.1491	1.7406	-0.0083	0.0366	-0.0095	0.0367
Total land used for maize cultivation	0.3285	1.7328	0.1222	0.3590	0.0756***	0.0294
Enterprise diversification	0.0145	0.6035	0.6304**	0.3848	0.1402	0.3865
Source of finance	0.0580	0.0744	-0.1920	0.1704	-0.0687	0.1711
Membership of cooperative society	0.0231	0.7532	-0.1572	0.1333	-0.1901	0.1339
Access to credit	0.0194	1.7005	-0.3355	0.2988	0.0932	0.3002
Information on climate change	-0.1497	0.6033	-0.0102	0.0283	0.0212	0.0284
Social safety	0.3285	1.0483	0.0391	0.0570	-0.0544	0.0573
Constant	0.0867***	0.0311	0.0707***	0.0292	2.2054	0.6606

Note: ***, **, and * denotes significant at 1%, 5% and 10% respectively. D_0M_0 is the reference category

Table C2. Productivity outcome: second-stage estimates of MESR

Variables	**D_0M_1**		**D_1M_0**		**D_1M_1**	
	Coef.	**Std. SE**	**Coef.**	**Std. SE**	**Coef.**	**Std. SE**
Socioeconomic characteristics						
Age	0.1964	0.6521	0.3192***	0.1006	0.5837***	0.5044
Gender	0.3461	0.7190	0.4123***	0.0824	-0.4824***	0.0815
Household size	-0.2786*	0.1067	-0.0083	0.1117	0.0295	0.0440
Marital status	0.4701	0.4217	0.2071	0.1268	-0.0621	0.0909
Educational status	0.6419*	0.2494	-0.2741*	0.1105	0.1172**	0.0212
Years of experience	-0.1378	0.3720	0.5173***	0.0656	0.0406**	0.0255
Off-farm income	0.1219	0.3824	0.0284	0.0220	0.2310	0.1179
Land ownership	0.1038	0.5540	-0.0487	0.0884	0.1270	0.1554
Total farm size used in cultivating other crops	0.1280	0.3414	0.1914	0.5003	-0.7761*	0.3812
Total land used for maize cultivation	-0.1735	0.1172	0.0700	0.0848	0.2138	0.2372
Enterprise diversification	0.0841	0.1275	-0.0667	0.2879	0.2751	0.2095
Source of financing farm operation	0.5122**	0.2550	0.1389**	0.0791	0.1014	0.2496
Membership of cooperative society	0.3223	0.2041	0.2490	0.2027	0.2020	0.4210
Access to credit	0.1288	0.2688	0.2085**	0.0938	0.5431**	0.4678
Information on climate change	0.4933**	0.1190	0.0822	0.2400	0.3126	0.5727
Social safety	0.2736	0.9310	-0.0558	0.1167	-0.2492	0.2660
Sigma2	5.1396	7.0521	2.9061*	1.0752	1.0961***	0.0094
Rho 1			0.1863	0.3419	0.3062	0.1747
Rho 2	0.2947	0.1075			0.6705	0.2089
Rho 3	0.1842**	0.0976	0.1297	0.9831		
Constant	2.5981***	0.3803	1.0982***	0.0742	2.7826***	0.2344

Table C3. Per capita household expenditure (total) outcome: second-stage estimates of MESR

Variables	D_0M_1		D_1M_0		D_1M_1	
	Coef.	**Std. SE**	**Coef.**	**Std. SE**	**Coef.**	**Std. SE**
Socioeconomic characteristics						
Age	-0.0065	0.1458	0.0315	0.0386	0.0012	0.0001
Gender	0.0192	0.2568	-0.0247	0.0057	0.0136	0.0265
Household size	0.0579	0.1257	0.1541	0.0353	-0.0139***	0.0016
Marital status	-0.0203	0.2569	0.2610	0.1514	0.1207***	0.0112
Educational status	0.0655	0.1415	0.2019	0.1073	-0.0238	0.4341
Years of experience	0.0799	0.2307	0.1275	0.1091	0.1145	0.1062
Off-farm income	0.1007***	0.0369	0.3124	0.5602	0.0584***	0.0100
Land ownership	0.1545	0.1116	0.4316	0.1702	0.0285	0.1062
Total farm size used in cultivating other crops	0.0087	0.1234	0.1370	0.3051	0.0981**	0.0408
Total land used for maize cultivation	0.0251	0.0422	0.0546	0.0486	0.0061	0.6721
Enterprise diversification	0.0682	0.1772	-0.1159**	0.0469	0.0091	0.0619
Source of financing	0.1009*	0.0534	0.3773***	0.0644	-0.0415	0.0419
Membership of cooperative society	0.1968	0.0164	0.0181	0.0162	0.0238	0.1735
Access to credit	0.0892***	0.0042	0.0783***	0.0058	0.0884	0.0215
Information on climate change	0.1175	0.4405	0.6217**	0.2361	0.0249	0.0503
Social safety	0.4682***	0.0971	-0.1741	0.1197	0.0072	0.3885
Sigma2	4.2287***	0.1599	5.0476	4.1005	2.0616*	0.7391
Rho1			0.2862*	0.1084	0.3705*	0.1971
Rho2	0.1852	0.2711			0.3891	0.1785
Rho3	0.2380	0.1042	0.1967	0.1053		
Constant	0.9842***	0.1742	0.2696***	0.0348	0.1027*	0.0469

Appendix D

RESEARCH QUESTIONNAIRE

Questionnaire number: ……………....

Province, Municipality, Village: ……………...

Dear Sir/Ma,

This household survey questionnaire is designed for the study on **'Climate-smart agricultural practices, productivity, and food security among smallholder maize farmers in North West Province, South Africa"**. The questions are strictly for the purpose of this research. All information obtained will be treated confidentially. Please answer each question honestly and accurately, as your participation in this exercise is important to the success of community development. Thank you for your anticipated cooperation.

Please Fill and Tick(✓) in the appropriate place where necessary.

SECTION (A): SOCIO-ECONOMIC CHARACTERISTICS OF PARTICIPANTS

(A1) Age (Years) ________________________________

(A2) Marital Status (a) Married [ ] (b) Single [ ] (c) Divorced (d) Widowed [ ]

(A3) Gender (a) Male [ ] (b) Female [ ]

(A4) Educational status (a) Standard [ ] (b) Matric [ ] (c) Diploma [ ] (d) Degree [ ] (e) None [ ]

(A5) Race (a) Black [ ] (b) White [ ] (c) Coloured [ ] (d) Indian [ ]

(A6) Religion (a) Christianity [ ] (b) Islam [ ] (c) Traditional worshipper [ ] (d) Others, specify _______

(A7) Household size ____________________ (b) Number of working member(s) _________________

(A8) What is your secondary occupation? (a) Indigenous plant farming (b) Arable crop farming (c) Civil servant (d) Entrepreneur (e) Others, specify _______

(A9) Years of farming experience in maize cultivation? ______________________

(A10) Land tenure in maize cultivation: (a) Owned [ ] (b) Leased [ ] (c) Communal [ ] (d) Inherited [ ]

(A11) What is your farm size for maize cultivation? …………………………….

(A12) Are you a member of a farmers' cooperative society or association? (a) Yes (b) No

(A13) Do you have access to credit facilities? (a) Yes (b) No

(A14) Do you have Off-farm activities and income? (a) Yes (b) No

(A15) Do you have access to extension services? (a) Yes (b) No

(A16) Do you have access to agricultural and climate change training? (a) Yes (b) No

(A17) What is the source of financing your "maize farm" enterprise (a) personal saving [ ] (b) friends & relation [ ] (c) Cooperative loan [ ] (d) bank loan [ ] (e) others ________________________

(A18) Do you have access to social safety nets (a) Yes (b) No

SECTION (B): CLIMATE CHANGE PERCEPTION, ADAPTATION STRATEGIES

(B1) Are you aware of climate change? (a) Yes (b) No

(B2) Do you have access to climate information? (a) Yes (b) No

(B3) Has the annual rainy season temperature changed? (a) Yes (b) No
(B4) Has the winter season temperature changed? (a) Yes (b) No
(B5) Did you know the annual rainy season precipitation (a) Yes (b) No
(B6) Did you know the summer season precipitation (a) Yes (b) No
(B7) Are you susceptible to climate change (a) Yes (b) No

(B8) Dimensions of perceived impact of climatic change **(**Kindly tick appropriately)

Perceived climate change intensity	**Yes**	**No**
Plant date changes		
Variations in seasonal changes		
Increased rainfall		
Increased temperature, sunlight intensity, and heat waves		
Precipitation is reduced		
Changes in relative humidity		
Crop and animal pest and disease outbreaks		
They reduced the yield of plants		
Crop failure		
Forest resource decline		
Crop diversity changes		
Reduced soil moisture and soil fertility		
High rate of weed growth on the farm		
Frost hails and heavy rains		
The flooding problem increased with storm surges		
Erosion of the surface soil of the farm		
Increased incidence of drought		
Heavy winds which affect farm produce		
Early drying up and rotting of farm produce		
Loss of farmland		
Livelihood changes		
Poverty and food insecurity increased		
Migration aggravated and displacement of farmers		
Income decline		
High food costs		

SECTION C

(B11) Climate-Smart Agriculture: Kindly tick the various CSA practices that you have adopted

S/N	**CSA Practices**	**Yes**	**No**
1.	Use of Improved crop varieties		
2.	Use of legumes in crop rotation		
3.	Use of Cover crops		
4.	Changing Planting dates		
5.	Efficient use of Inorganic fertilizer		
6.	Use of Terraces		

7.	Planting Trees on cropland		
8.	Use of live barriers		
9.	Diversified crop and animal breeds		
10.	Irrigation		
11.	Use of Improved livestock breeds		
12.	Use of Organic fertilizers		
13.	Planting crops on tree land		
14.	Use of mulching		
15.	Use personal experience to predict weather events		
16.	Received education/training on how to access weather information		
17.	Take Index-Based Insurance (IBI) to protect my farm		
18.	Access to weather information on the internet		

SECTION D: Perceived constraints affecting CSA Practice adopted Please tick appropriately

S/N	Factors	Disagreed	Undecided	Strongly Agreed
1.	Expensive to manage			
2.	Time-consuming			
3.	Inadequate sustainable agricultural technologies			
4.	Inadequate Resources			
5.	Lack of labour			
6.	Infertile land			
7.	High demand for farm produce			
8.	Drought occurrence			
9.	Land tenure system			
10.	Availability of CSA funds by the government			
11.	Poor access to roads and markets			

SECTION (E): HOUSEHOLDS FOOD SECURITY STATUS (Kindly tick appropriately)

	Food group conmsume	**Yes**	**No**
1	Cereal		
2	Roots and tuber		
3	Vegetables		
4	Fruits		
5	Meat, poultry, offal		
6	Eggs		
7	Fish and seafood		
8	Pulses, legumes and nut		
9	Milk and milk products		
10	Oli/fats		

11	Sugar/honey		
12	Miscellaneous		

SECTION F: Household food insecurity coping strategies: identify the food insecurity coping strategies of your household in the last 7 days.

	Food insecurity coping strategies	Tick	No. of Days
a	Rely on less preferred and less expensive foods		
b	Borrow food, or rely on help from a friend or relative		
c	Purchase food on credit		
d	Gather wild food, hunt, or harvest immature crops		
e	Send household members to eat elsewhere, such as neighbours, friends, or relatives		
F	Send household members to beg		
g	Consume seed stock held for next season		
h	Limit portion size at meal times		
I	Restrict consumption of adults in order for small children to eat		
J	Feed working members of HH at the expense of non-working members		
k	Ration the money you had and buy prepared food		
L	Reduce the number of meals eaten in a day		
m	Skip entire days without eating		

SECTION G: Total household expenditure

(D3) How many times do you eat in a day? Once ( ), Twice ( ), Thrice ( ), More ( )

(D4) What is your source of drinking water (i) Well (ii) Borehole (iii) River (iv) Tap (v) Rain (vi) Others?

(D5) Do you and or your household run out of money to buy food during the past year (a) Yes (b) No

(D6) The total monthly expenditure of the household.......................................

(D7) The amount spent on food for the household in the last month …………………

(D8) On which class of food does the household spend the most (a) Cereal, root and tubers, and staple grains [ ] (b) processed food [ ] (c) meat, fish, egg, and milk [ ] (d) fresh fruit and vegetables [ ] (e) others, specify...................

(D9) Did you or anyone in your household eat any food OUTSIDE the home yesterday? Yes [ ], No [ ] , if yes

(D10) Where did the person eat from (a) street food [ ] (b) Restaurant [ ] (c) local food kiosk [ ] (d) food relief/ aid project [ ] (e) Others ....

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ETHICS APPROVAL LETTER OF STUDY

Based on approval by the **Faculty of Natural and Agricultural Sciences Ethics Committee (FNAS-REC)**, the Faculty of Natural and Agricultural Sciences Ethics Committee hereby **approves** your study as indicated below. This implies that the North-West University Senate Committee for Research Ethics (NWU-SCRE) grants its permission that, provided the special conditions specified below are met and pending any other authorisation that may be necessary, the study may be initiated, using the ethics number below.

Study title: Climate-smart agricultural practices, productivity and food security among smallholder maize farmers in North West Province, South Africa
Study Leader/Supervisor: Prof SS Letsoalo
Student: AB Omotoso

Ethics number: NWU-01267-23-A9 (Institution: NWU; Study Number: 01267; Year: 23; Status: A9)

Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Application type: Single **Risk Category: Minimal**

Commencement date: 25/05/2023
Expiry date: 25/08/2024

Approval of the study is initially provided for a year, after which continuation of the study is dependent on receipt and review of the annual (or as otherwise stipulated) monitoring report and the concomitant issuing of a letter of continuation.

Special in process conditions of the research for approval (if applicable):

- The following documentation are archived by FNASREC and should be complete and kept up to date:
  - Research proposal
  - Signed approval from the scientific committee indicating the proposed risk category
- All researchers involved in the study should submit signed NWU code of conduct statements annually.
- All researchers of low risk studies should submit proof of relevant ethics training every two years.
- All researchers that take part in activities that pose a safety and security threat to the researchers or the environment should submit a risk assessment form annually.
- All research involving human interaction should follow best ethical practise and keep documents as proof. This includes informed consent, questionnaires, incorporation of risk-benefit, and responsible data management.
- Any research at governmental or private institutions, permission must still be obtained from relevant authorities and provided to the FNASREC. Ethics approval is required BEFORE approval can be obtained from these authorities.

Durban
South Africa
2nd November, 2023

To whom it may concern

Title: Climate-smart agricultural practices, productivity and food security among smallholder maize farmers in North-West Province, South Africa

Student: Abeeb Babatunde Omotoso (43120075)
Department of Agricultural Economics and Extension,
North-West University, South Africa.

To whom it may concern:
I have provided extensive comments on the grammar, table formatting and general structure for this thesis. I have also briefly scanned the student reworking of my comments, and am confident that should he have addressed them, the document will be suitable for submission. The student has clearly put a lot of effort into this study, and I have therefore tried to respect their voice in the representation of their work.

Regards

Ms Carrin Martin
Academic Editor
MSocSci, PGDPH

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