

**MODELLING CLIMATE CHANGE IMPACTS ON SELECTED
INDIGENOUS CROPS IN MARGINALISED COMMUNITIES OF
SOUTH AFRICA**

by

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Agrometeorology, School of Agricultural, Earth and Environmental Sciences, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the Water Research Commission of South Africa, funded through WRC Project No. K5/2717//4 on “Developing a guideline for rainfed production of underutilised indigenous crops and estimating green water use of indigenous crops based on available models within selected bio-climatic regions of South Africa”, the uMngeni Resilience Project (URP, funded by the Adaptation Fund) and the Sustainable and Healthy Food Systems – Southern Africa (SHEFS-SA) Programme, supported by the Wellcome Trust [Grant No 227749/Z/23/Z].

The contents of this work have not been submitted in any form to another university, and except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.



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DECLARATION 1: PLAGIARISM

I, Mendy Ndlovu, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
 - a. Their words have been rewritten, but the general information attributed to them has been referenced
 - b. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks and referenced.

This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections



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Date: 27 March 2026

DECLARATION 2: PUBLICATIONS

The following is the list of publications in this thesis. The following manuscripts have been published:

Chapter 2: Publication 1

Ndlovu, M., Scheelbeek, P., Ngidi, M. and Mabhaudhi, T., Underutilised crops for diverse, resilient and healthy agri-food systems: A systematic review of sub-Saharan Africa. *Frontiers in Sustainable Food Systems*, 8, p.1498402. **Published**

The Following manuscripts have been submitted for publication:

Chapter 3: Publication 2

Ndlovu, M., Schütte, S., Nhamo, L., Scheelbeek, P., Ngidi, M., and Mabhaudhi, T. Understanding Climate Risks for Water and Agri-Food Systems: Implications for Smallholder Farmers. Submitted to: *Frontiers in Climate*.

Chapter 4: Publication 3

Ndlovu, M., Ngidi, M., Scheelbeek, P., and Mabhaudhi, T. Pathways to resilience: coping strategies to climate risks and food security outcomes among smallholder farmers in rural South Africa. Submitted to: *Climate Services*

The following manuscript is under preparation to be submitted to a journal:

Chapter 5: Publication 4

Ndlovu, M., Kunz, R., Carr, T., Scheelbeek, P., Ngidi, M., and Mabhaudhi, T. Nutritional Yield and Nutritional Water Productivity of Underutilised Crops for Climate-Resilient Agri-Food Systems. In preparation for submission to *Science of the Total Environment*.

In all the above papers and manuscripts, the conceptualisation of the idea was undertaken by M. Ndlovu (student) and Prof. T. Mabhaudhi, Dr P. Scheelbeek, and Prof. M. Ngidi

(supervisors). M. Ndlovu conducted the research and the write-up, while the supervisors corrected and proofread the manuscripts.



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DECLARATION 3: ARTIFICIAL INTELLIGENCE

I, Mendy Ndlovu, declare that I made use of generative AI in this thesis in the following areas:

- (i) For language editing.
- (ii) To generate a graphic abstract for Chapter 3, I made use of Napkin ([Napkin AI - The visual AI for business storytelling](#)).

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ABSTRACT

Climate projections indicate a drier and hotter environment for the Sub-Saharan Africa (SSA) region, including South Africa (SA), under different emission scenarios. These changes present climate and environmental risks which have multifaceted consequences on agri-food and water systems, socio-economic and ecological systems, livelihoods, and food and nutrition security, particularly for rural smallholder farming households. Under these circumstances, promoting locally adapted, multi-risk resilient, and nutrient-dense crops is touted as a plausible adaptation strategy. This thesis integrates results from various numerical models to conduct interdisciplinary research, highlighting the interconnected challenges of climate risk, food insecurity and resource management in SA. This work highlights the transformative potential of and gaps in the utility of neglected and underutilised crop species (NUS) through a systemic literature review (chapter 2) while exploring their potential to transform South African agri-food systems (chapters 2 and 5) for environmental sustainability and human health within safe planetary boundaries under climate change (chapter 3). For chapter 3, changes in rainfall [Climate Moisture Index (CMI)], and air temperature [Thermal Heat Index (THI)], across three time periods [the present (1961-1990), near future (2015-2044) and distant future (2070-2099)] are computed and assessed using an ensemble of six GCMs forced by RCP 8.5 in three Hydro-climatic zones (HCZs 1,2 & 5) in South Africa. Chapter 4 assesses the relationship between the climate risk coping strategies of smallholder farming households and food and nutrition security outcomes among households in rural areas, focusing on the three poorest provinces in South Africa. We provide a comparative analysis of the Nutritional Yields (NY) and Nutritional Water Productivity (NWP) of Mainstream and NUS crops across the three time periods in the 5th chapter. In this chapter, the AquaCrop Model was used to determine crop yields and water use efficiency for selected NUS and Mainstream crops across 5838 South African sub-catchments. The simulations covered the years 1960 to 2100, divided into three 30-year timelines. The overall findings of the study underscore the necessity for climate-informed, context-specific interventions and support systems to facilitate the adoption of appropriate, effective and scalable multi-risk adaptation strategies. Such strategies are essential for agri-food systems transformation and for strengthening their long-term climate resilience and sustainability, within a food- and nutrition-sensitive framework that prioritises social equity, ecological integrity, and planetary health.

DEDICATIONS

To both my fathers in heaven and my late grandparents: I carry with me the warmth of your encouragement and the strength of your belief in me. We are done with school now, (I think).

For my son, K.E.

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Above all, I would like to acknowledge the grace and divine favour of God over my life.

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The HSRC for granting me access to the data used in Chapter 4.

My heart overflows with gratitude to my family and friends, whose unwavering faith in me has been the quiet force behind every page I’ve written and every milestone I’ve reached.

NIV-Revelation 3:8

I know your deeds. See, I have placed before you an open door that no one can shut. I know that you have little strength, yet you have kept my word and have not denied my name.

NIV-2 Timothy 4:17

But the Lord stood at my side and gave me strength, so that through me the message might be fully proclaimed, and all the Gentiles might hear it.

NIV-Psalm 107

Give thanks to the Lord, for he is good; his love endures forever.

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Background and Rationale

South Africa, like several other nations in Sub-Saharan Africa (SSA), is a hotspot for climate- and water-related risks. The country experiences highly variable rainfall patterns, an increasing frequency and intensity of extreme weather events, and is significantly vulnerable to droughts, floods, and temperature extremes. These factors represent a trio of critical challenges that impede the sustainability of natural resources and agricultural activities in the country (Du Preez and Van Huyssteen, 2020; Ndlovu et al., 2021; McBride et al., 2022). Alterations in weather and climatic regimes further exacerbate these risks, with the sectors associated with water, agriculture, and the environment being the most adversely affected (Calzadilla et al., 2014; Ziervogel et al., 2014; Meza et al., 2021; Bonetti et al., 2022).

Alongside changes in the weather and climate of South Africa, the country is experiencing a burgeoning population alongside diminishing natural resources, such as water and land, two critical resources for agricultural production and productivity, particularly in smallholder contexts (Du Preez and Van Huyssteen, 2020; Tantoh and McKay, 2023). Consequently, there are numerous concerns and increasing pressure regarding the sustainability of natural resource utilisation, especially within agri-food systems that must maintain productivity sustainably, without expansion, to meet growing food demands and achieve food and nutrition security, particularly in marginalised environments (Çakmakçı et al., 2023). The existing agri-food systems in the SSA region, including South Africa, are characterised by inefficient water usage, unsustainability, and a lack of adaptability to remain productive under changing local environmental conditions (Ndlovu et al., 2024). In this context, the strategic deployment of locally adapted and nutrient-dense crops is increasingly recognised as a necessary, transformative, and viable climate and multi-risk adaptation strategy.

1.1.1 Climate Change, Climate Risks and South African Agri-Food Systems: An Overview

The frequency and severity of extreme weather and climate events have increased over the past decade in the SSA, including South Africa. This has multifaceted consequences on local agri-food and water systems, livelihoods and food and nutrition security of poor rural households (Kruger and Nxumalo, 2017; Oxford, 2017; Ndlovu et al., 2021; Ayanlade et al., 2022;

Engelbrecht *et al.*, 2024). The South African climate is becoming increasingly susceptible and vulnerable to hydrometeorological and climatological extremes, including heatwaves, droughts, and floods. These phenomena are often exacerbated by the El Niño-Southern Oscillation (ENSO) phenomenon and localised pressure systems (Ndlovu *et al.*, 2021; Sikhwari *et al.*, 2022; Rouault *et al.*, 2024).

To address these challenges, smallholder farmers in rural areas have historically relied on diverse local agricultural practices to sustain food production stability and ensure food security for local communities (Mabhaudhi *et al.*, 2018; Malapane *et al.*, 2024). However, colonialism, along with the policies and systems that supported it, altered these agricultural systems, leading to a shift from diversified, locally adapted crop cultivation towards an over-dependence on a limited number of mainstream crops. This transition was driven by yield-centric monocultural approaches (Mabhaudhi *et al.*, 2017; Agulanna, 2020).

This shift, however, has been shown to be neither efficient nor sustainable, and it lacks adaptability to local environments. The agricultural sector currently represents one of South Africa's largest consumers of natural resources, particularly water. Approximately 80% of the total land area in South Africa is utilised for agricultural purposes, predominantly for mainstream agriculture (Johnston *et al.*, 2024). Furthermore, sixty percent (60%) of the available freshwater in the country is allocated to commercial irrigation, whereas smallholder farmers, primarily situated in marginalised settings, engage in rainfed agriculture (Nhamo *et al.*, 2020).

1.1.2 Food and Nutrition Insecurity as a Challenge in South Africa

South Africa is considered a food-secure nation; however, food insecurity remains a significant challenge at the household level with the growing population (Chakona, *et al.*, 2019; HSRC, 2024). Currently, 26.7% of the population experiences moderate food insecurity, 19.3% face mild food insecurity, and 17.5% suffer from severe food insecurity (HSRC, 2024). Furthermore, inadequate dietary intake and poor dietary quality are particularly present in low-income communities (HSRC, 2024). The impact of climate change, particularly on agricultural production and productivity of current agri-food systems, exacerbates these challenges, particularly in resource-poor communities. Addressing these issues requires urgent actions to develop context-specific, climate-informed adaptation strategies that build climate resilience and sustainability and ensure positive food and nutrition security outcomes under climate change. Neglected and Underutilised crops (NUS) have been proposed as a potential multi-risk solution to

some of these challenges, owing to their potential to sustainably intensify local agri-food systems and improve dietary diversity and food and nutrition security.

1.1.3 Overview of Underutilised Crops and Their Potential in South African Environments Under Dryland Rainfed Conditions

NUS, also known as orphan, indigenous or traditional crops, are local crop varieties that have been cultivated and consumed by local communities for generations. However, their prominence has been diminished due to the rise of monoculture-based food production systems and the dominance of staple crops (Padulosi et al., 2011; Mayes et al., 2012; Tedebe, 2018; Mabhaudhi et al., 2019). NUS can significantly enhance access to diverse, nutritious food sources and reduce reliance on staple crops such as maize and wheat, in an environmentally sustainable way. However, their full potential remains largely unrecognised and underutilised (Padulosi et al., 2011; Mayes et al., 2012; Kour et al., 2018; Tedebe, 2018). It is additionally recognised that NUS are particularly abundant in various micronutrients and essential vitamins that can enhance nutritional status and improve the quality of life within communities, particularly in resource-limited contexts (Padulosi et al., 2011; Kour et al., 2018; Tedebe, 2018). Furthermore, NUS have the potential to address community-based cultural, social, and economic requirements (Padulosi et al., 2011; Kour et al., 2018; Tedebe, 2018).

NUS are well-adapted to low-input agriculture while providing high-quality food and enhancing diversification and resilience of agroecosystems (Padulosi et al., 2011; Kour et al., 2018). In South Africa, integrating NUS into mainstream agriculture has been proposed as a key strategy to diversify agricultural and food systems (Mabhaudhi et al., 2019; Ndlovu et al., 2024). This stems from reports of abiotic and biotic stress tolerance and nutrient-dense properties of these crops, as well as their suitability and adaptability to marginal agricultural production niches, which typify rural landscapes (Padulosi et al., 2011; Mayes et al., 2012; Kour et al., 2018; Tedebe, 2018; Mabhaudhi et al., 2019). This approach is further supported by evidence suggesting that, as a sub-component of agrobiodiversity, NUS offer sustainable intensification opportunities allowing agricultural expansion in marginal areas without exceeding environmental limits (Mayes et al., 2012; Mabhaudhi et al., 2019). However, while there are pockets of evidence within disciplines, there remains a lack of integrated evidence to comprehensively demonstrate their potential in addressing food and nutrition insecurity (Mabhaudhi et al., 2019; Ndlovu et al., 2024).

1.1.4 Justification for the Study

SSA is one of the main climate change “hotspot” regions, with a high prevalence of food and nutrition insecurity, which is increasing faster than anywhere else in the world (Wudil *et al.*, 2022; Ouko and Odiwuor, 2023; Engelbrecht *et al.*, 2024). Although agriculture is highly sensitive to climatic changes, its role in achieving food and nutrition security cannot be overstated in the region, including in countries such as South Africa. South Africa is among the driest countries in the world, and climate projections forecast drier and hotter climates for most provinces (Engelbrecht *et al.*, 2024). Given this and recognising the interdependence between agricultural production and food and nutrition security, particularly among resource-constrained farming households, innovative strategies are needed to improve the efficiency, sustainability, and productivity of the country's agri-food systems. Coping mechanisms and adaptive capacity should be founded on a comprehensive understanding of localised climate risks, existing coping strategies, and their limitations.

While adaptation and coping strategies play a considerable role in buffering households from food and nutrition insecurity, there is still a gap in research regarding their suitability, contextual variations and long-term effectiveness under different climatic scenarios in South Africa. Furthermore, assessing climate risk and advancing natural resource management are pivotal to achieving efficient, resilient, and sustainable agri-food systems in the country in the context of climate change. The main motivation of this research is to explore and emphasise the utility and potential of NUS as a viable and context-specific climate change and multi-risk adaptation strategy. Despite their potential, NUS remain under-integrated into climate adaptation strategies, which limits their contribution to sustainable and resilient agri-food systems. By integrating NUS into existing climate-sensitive agri-food systems, I explore pathways to strengthen local agri-food systems by leveraging locally available, adapted, and diverse crops that respond to current and future challenges in water, food, and nutrition. To develop context-specific and spatially explicit adaptation solutions, I first explored the climate risks to water and agri-food systems. Following that, I explored existing climate risk coping strategies and their implications on food and nutrition security outcomes in vulnerable communities. The objective was to understand the alignment, feasibility and sustainability of these climate risk coping strategies. Lastly, to address the overall goal, I integrated the understanding of climate risks and the existing gaps in food and nutrition to align NUS into target environments under current and projected

climate change. The promotion of NUS bodes well for the transformation of agri-food systems within the context of sustainability, resilience, and equity for people and the planet.

1.2 Research Questions:

The current research sought to answer the following questions:

1. To what extent are underutilised crops currently integrated into local agri-food systems in Sub-Saharan Africa, and how can their broader adoption serve as an adaptation strategy to strengthen resilience, enhance food security and nutritional health?
2. What are the main climate risks for water and agri-food systems in Hydro-Climatic Zones 1, 2, and 5, and what implications do they have for smallholder farmers?
3. What climate risk coping strategies exist among smallholder farming households, and how do they impact food and nutrition security outcomes?
4. How do NUS and mainstream crops perform under rainfed environments in terms of Water Use Efficiency (WUE), Nutritional Yields (NY) and Nutritional Water Productivity (NWP) in the present, near future and distant future climates?

1.3 Aims and Objectives

The overall aim of this research is to conduct interdisciplinary research to assess the current utilisation of NUS, the existing climate risks to water and agri-food systems in South Africa, and the ability of NUS crops to transform these systems to support ecosystem and human health within safe planetary boundaries under climate change.

The presented research is divided into four specific objectives structured as four sequential chapters:

- Examine the state of knowledge on the application, utilisation of NUS, as well as the existing constraints to their adoption, in promoting diverse, sustainable, and resilient agri-food systems and food sovereignty in sub-Saharan Africa under climate change.
- Examine climate risks and their effects on water and agri-food systems among smallholder farmers in the Eastern Cape (HCZ 5), KwaZulu-Natal (HCZ 2), and Limpopo (HCZ 1) provinces of South Africa.

- Assess the relationship between the coping strategies of smallholder farming households and food and nutrition security outcomes using the Household Food Insecurity Access Scale (HFIAS) and Household Dietary Diversity Score (HDDS).
- Provide a comparative analysis of Water Use Efficiency (WUE), Nutritional Yield (NY) and Nutritional Water Productivity (NWP), specifically focusing on Iron, Zinc, vitamin A, Energy, and Protein, between Mainstream crops and underutilised crops in South Africa under climate change.

1.4 Outline of the thesis

This thesis is organised in paper format as a set of interlinked, coherent, but independent, successive chapters, formatted as manuscripts for submission to journals. Chapters 2, 3, 4, and 5 are self-contained and address the interconnected challenges of climate risk, food insecurity, and natural resource management in South Africa. The systematic review (Chapter 2) provides integrated evidence on the potential of NUS as a multi-risk adaptation strategy and anchors the work conducted in Chapters 3 and 4, which expose biophysical and social realities on the ground, and Chapter 5 presents an empirical solution to the identified challenges. The outline of the thesis showing how each objective is linked to a specific research chapter is presented in Figure 1.1. and outlined below:

Chapter 2 provides a synthesis of available literature on the application of NUS. The chapter discusses the utilisation of NUS and the challenges associated with their adoption in Sub-Saharan Africa. This discussion is framed within the context of agri-food system development under climate change. The purpose of this chapter is to provide background information and identify existing gaps in the use and potential of locally adapted, nutrient-dense crops, which are increasingly recognised as a viable multi-risk adaptation strategy for the region's agri-food systems. This chapter lays a foundation for confronting the legacy of monoculture systems.

Chapter 3 focuses on advancing the quantification of climate risks to water and agri-food systems and their implications for smallholder farmers. The chapter assesses changes in rainfall [Climate Moisture Index (CMI)] and air temperature [Thermal Heat Index (THI)] across three time periods [the present (1961-1990), near future (2015-2044) and distant future (2070-2099)]. These

were computed and assessed using an ensemble of six GCMs forced by RCP 8.5 across three Hydro-climatic zones (HCZs 1, 2, and 5) in South Africa.

Chapter 4 presents an assessment of the relationship between the coping strategies of smallholder farming households and food and nutrition security outcomes using the Household Food Insecurity Access Scale (HFIAS) and Household Dietary Diversity Score (HDDS). This assessment is crucial to building on context-specific, transformative mitigation and adaptation frameworks to safeguard smallholder farming resilience and food and nutrition outcomes under climate change.

Chapter 5 is the final results chapter. It presents a comparative analysis of the Water Use Efficiency, Nutritional Yields and Nutritional Water Productivity of mainstream crops and NUS across three time periods: 1960-1990, 2015-2044, and 2070-2099 under rainfed conditions across 5838 sub-catchments in South Africa. This analysis provides empirical evidence of the potential of NUS to enhance South Africa's agri-food systems under different climatic conditions.

Chapter 6 is the final chapter of this research, providing a comprehensive synthesis of key findings, concluding remarks, and recommendations for future research.

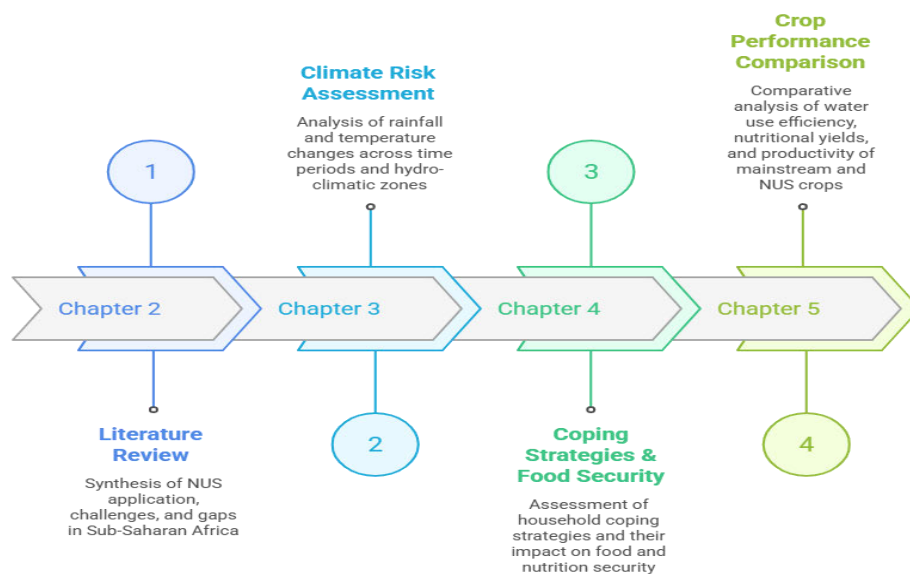


Figure 1.1 An outline of the flow of publishable chapters in the thesis.

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CHAPTER 2: UNDERUTILISED CROPS FOR DIVERSE, RESILIENT AND HEALTHY AGRI-FOOD SYSTEMS: A SYSTEMATIC REVIEW OF SUB-SAHARAN AFRICA

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Keywords: future crops, nutrition, sustainable diets, food sovereignty, agrobiodiversity, and climate change adaptation

2.1 Abstract

Sub-Saharan Africa (SSA) faces increasing water scarcity, food and nutrition insecurity, poverty and inequality under climate change. Under these circumstances, promoting locally adapted and nutrient-dense crops is touted as a plausible climate adaptation strategy. We reviewed the utility of neglected and underutilised crop species (NUS) as a climate change adaptation strategy to diversify local food systems and diets and improve nutritional health and environmental outcomes in SSA. We conducted a systematic literature review using Web of Science and Scopus research databases. Of the 1545 studies retrieved, 75 were included following a multi-level screening process on Covidence guided by the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines. The review consolidates fragmented knowledge on the application of NUS in different contexts. Despite growing interest, NUS remain gendered and stigmatised crops, marginalised and fragmented in research, development, and marketing efforts and lack explicit support from policy and decision-makers. Despite rhetoric purporting to support them, there is a worrying rise in policies and regulations that inadvertently hinder the development of these crops and reinforce dependence on a narrow basket of crops for food and nutrition security, undermining food sovereignty. Some NUS have received increasing recognition for their potential in the past decade. However, this is neither universal nor systematic, which makes scaling up necessary but challenging. Consequently, progress in mainstreaming NUS in local food systems continues to lag. Despite these challenges, NUS remain sub-Saharan Africa's better-bet option for diversifying food systems and transitioning them to be equitable, inclusive, resilient and healthy; hence, NUS provide positive outcomes for people and the planet under climate change.

2.2 Introduction

Underutilised crops, also referred to as orphan, indigenous, traditional crops, or neglected, underutilised species (NUS) (1), are local crop varieties that communities have utilised for generations. However, they have been rendered neglected due to the promotion and dominance of a few major/staple crops and an industrial monoculture-centred agri-food system (1,2,3,4,5,6,7). Consequently, the value chains of NUS in Sub-Saharan Africa (SSA) are currently poorly developed, and smallholder farmers, especially women, in marginalised settings are currently the main conservators of these crops (1,8,9,10,11,12,13). As a result, some NUS are at risk of abandonment (14).

NUS are typically more resilient to localised environmental stress, including drought, salinity, and extreme heat, generally have richer nutritional composition and require fewer resources than their “mainstream” counterparts (15,16,17,18). SSA has significant, underutilised potential to increase production, utilisation, and niche-specific competitiveness, and to commercialise underutilised crops. Inclusion of these crops can improve the resilience, sustainability, and inclusiveness of current agricultural and food systems, address hunger and food and nutrition insecurity, and support local development goals and livelihood strategies (1,19). Therefore, the continued underutilisation of NUS could be a major missed opportunity to contribute to SSA’s agri-food systems transformation and human and environmental well-being.

Food systems, human well-being, and planetary health are interlinked (20,21). Poor agri-food systems development and lack of diversity contribute to poor dietary composition, malnutrition, and negative health and food security outcomes (15,22,23). The number of hungry people has been increasing globally since 2014, particularly in SSA, where 31 of the top 36 countries have the highest hidden hunger index, indicating a lack of access to essential nutrients (9,24,25,26). This is a reversal of the progress made through food-security-specific interventions, such as introducing existing agri-food systems, which reduced global hunger levels between 1990 and 2014 (27). However, micronutrient deficiencies of iron, vitamin A, and iodine remain widespread in SSA, affecting the health and well-being of many of the population, particularly women and children (28,29). Further, suppose no necessary adaptation strategies are employed urgently, by the year 2050, the world is expected to see a 20% increase in hunger, and close to 65% of those experiencing hunger will reside in SSA (29).

The existing agri-food system challenges in SSA stem from the region's dependence on agriculture (mainly rainfed), alongside its inherently low adaptive capacity, widespread poverty with about 40% of the population living below the international poverty line in 2019, high socio-economic inequality rates, failing governance and a fast-growing population (2,3,10,24,27). Often, SSA countries rely extensively on climate-sensitive, misaligned, outdated and vulnerable mainstream agri-food systems, leading to food production insecurity, low yields, limited availability of food, poverty, and increasing food and nutrition insecurity as the climate changes (2,3,4,8,24,30,31). These challenges coexist with the lack of appropriate-scale food and agricultural interventions, technologies and infrastructure to inform the region's development and environmental, socioeconomic and policy-related barriers (2,19,29,30).

While there have been major strides made in improving agricultural productivity in SSA, the current agri-food systems in the region are not resilient. The COVID-19 pandemic, alongside widespread global conflicts, climate crises and rising levels of malnutrition, have exposed its vulnerability to external shocks (23,32,33,34). These agri-food systems lack inclusion, equality and equity and embrace the production of a select few high-yielding, climate-sensitive mainstream crops with limited nutritional value, lacking in micronutrients and healthy proteins and have low dietary composition and diversity (9,11,24,30,35,36,37). By design, the existing agri-food systems suppress crucial local agricultural systems that have previously informed diverse agri-food systems and could still contribute to sustainable and inclusive agri-food systems (16,34,38). These agri-food systems were shaped by the Green Revolution's framework, colonialism, and the widespread capitalisation of pre-existing agri-food systems (32,34,35). This approach inadvertently undermines the importance of indigenous knowledge and farming systems and locally adapted agri-food systems (32,34,38,39). In its various versions, despite its successes, the framework failed to acknowledge and incorporate context-specific natural capital and localised systems to inform ethical, feasible and appropriate transformation (34,37). Uncertain environmental conditions, including climate change, further exacerbate these challenges. Sub-Saharan Africa mostly has a drought-prone, semi-arid climate and highly variable hydrometeorological regimes (1,8,40). The region is among the global climate change hotspots due to repeated exposure to extreme weather events and underlying factors known to contribute to vulnerability (2,24). Climate change, higher frequency and intensity of weather extremes and hydrometeorological challenges, pests and diseases, soil degradation and erosion form additional challenges for agricultural production and productivity, leading to further declines in yields and increased crop failures across SSA (2,21,24).

The central role of agriculture as a determinant of food and nutrition security and diet and health outcomes cannot be questioned, and innovative measures must be taken to improve agricultural

systems to be food-and nutrition-sensitive in SSA. The different pathways through which NUS have been applied or promoted to address such challenges in SSA have not been comprehensively examined, particularly in the context of agri-food systems development under climate change. In this review, we examine the state of knowledge on the application, utilisation and existing constraints around adopting NUS to promote diverse, sustainable, and resilient agri-food systems and food sovereignty in SSA under climate change. Understanding the utility and importance of NUS crops will help guide agricultural policy pathways in the region towards productive, resilient, food- and nutrition-security-centred approaches. While this review advocates for food systems diversification through incorporating NUS, it does not advocate for the replacement of current major crops but argues that there is value to be gained from broadening the current basket of crops.

2.3 Methods

2.3.1 Defining NUS

In this systematic review, we collectively refer to the crops being spotlighted as Neglected and Underutilised crops (NUS), as explained by Chivenge et al. (10) and Akinola et al. (30). In short, this includes generational and historically important crops that have been a crucial part of native or local smallholder agricultural systems and played a role in contributing to agrobiodiversity, socio-cultural outcomes, food and nutrition security and food sovereignty at different localities during adversities. Most of these crops were primarily sidelined following the introduction of the current “major crops” focused agri-food systems.

2.3.2 Identification of studies: Inclusion and exclusion criteria

The search strategy used combined three main concepts or specific key terms: indigenous OR neglected OR traditional OR orphan OR native OR underutilised crops AND climat* change OR climat* variability OR global warming OR extreme weather OR greenhouse effect AND Sub-Saharan Africa OR SSA OR Sub Saharan Africa, including Comoros, Madagascar, Mauritius, and Seychelles island states in the strings tailored to conduct a search within Title-Abstract-Keyword on the Scopus database and inclusive Topic search (TS) on Web of Science (see Text 1 on the Supplementary Information). All qualifying peer-reviewed research published in English, between January 2000 and December 2023 was considered and included if qualifying. The overall inclusion and exclusion criteria

used in the review are presented in Table 2.1. Specific authors were contacted for all full-text articles we were unable to retrieve.

Table 2.1: Study inclusion and exclusion criteria.

<u>Inclusion Criteria</u>
- Full-text article available online in English and published in peer-reviewed journals
- Articles that have Indigenous (food) crops (and synonyms) as their primary subject
- Articles that have Indigenous (food) crops and climate change adaptation as subjects or climate change and Indigenous (food) crops
- Articles documenting the application of Indigenous crops and climate change in the SSA region
- Articles published between Jan 2000 and December 2023
<u>Exclusion Criteria</u>
- Articles focusing on different geographical settings, outside SSA
- Articles that do not focus on Indigenous (food) crops
- Articles offered in other languages and not available in full-text and English
- Articles focusing only on chemical compositions, horticulture, crop-physiology, atmospheric sciences and or soil, crop and other environmental and climate change aspects and not the application of NUS

2.3.3 Data Extraction, synthesis and analysis

All references from Scopus or Web of Science research databases (1545) were exported as RIS files to import into Covidence for deduplication and screening following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Figure 2.1). Screening on Covidence was performed by two authors to manage bias, while one author completed full-text screening, critical appraisal, and data extraction using Microsoft Excel and a form generated using Microsoft Word. All authors reviewed and validated critical appraisal, data extraction and analysis. The year of publication, country of focus within the region, reported use and potential application of NUS, NUS and their prioritisation in research, research outcomes and gaps in NUS prioritisation, and barriers to NUS adoption were extracted as emerging themes and mutually inclusive categories identified, and studies were grouped according to these themes. The secondary review of extracted data and the data analysis protocol for all included studies were conducted by all authors. Data analysis

and initial reporting were conducted by a single author and shared with the team for collaborative data cleaning, refinement, validation, insights, and examination for potential biases and human errors.

2.3.4 Thematic and statistical analyses

Given the wide range of available literature on the subject, we adopted both narrative and quantitative approaches for data analysis and synthesis. We performed thematic coding and analysis of all included studies, categorising them into mutually exclusive categories (articles with similar study outcomes, reported use/potential use of NUS for health and wellbeing outcomes, and environmental and socio-cultural outcomes). The included articles were independently coded using a descriptive/thematic/analytical analysis approach by one researcher and independently reviewed by three researchers as secondary coding. Information extracted for quantitative analysis included year of publication, prioritised NUS crops in research and prioritised outcomes for NUS application in research, allowing for a synthesis of priorities, reported uses, research focus, and potential of NUS to strengthen climate change adaptation strategies at different levels for improved agricultural and food production sustainability, and food, nutrition and health outcomes according to existing research. The statistical analysis of this data was conducted using percentage calculations of extracted information, for example, percentages of publications prioritising NUS for a specific outcome, such as enhancing food security, across the entire database of included studies.

2.3.5 Critical Appraisal

The research objective, inclusion and exclusion criteria, and the PRISMA systematic review guidelines guided the evidence synthesis for the current study. For the final screening stage, we performed content analyses. We adapted the Critical Appraisal Skills Programme's checklist (see supplementary material, table 2) using only questions that applied to this review to qualify articles that formed a part of this study. We considered specific questions to exclude poor-quality studies instead of conducting a full critical appraisal, which doesn't apply to this type of study. Responses to our adapted/modified critical appraisal questions informed the final inclusion or elimination of full-text articles that had passed through different PRISMA-guided screening phases. Each article was independently appraised by one author, and all authors approved the appraisal. We excluded articles that had:

- unclear or absent methodology sections

- an unclear or absent synthesis of findings
- did not have formulated research questions.

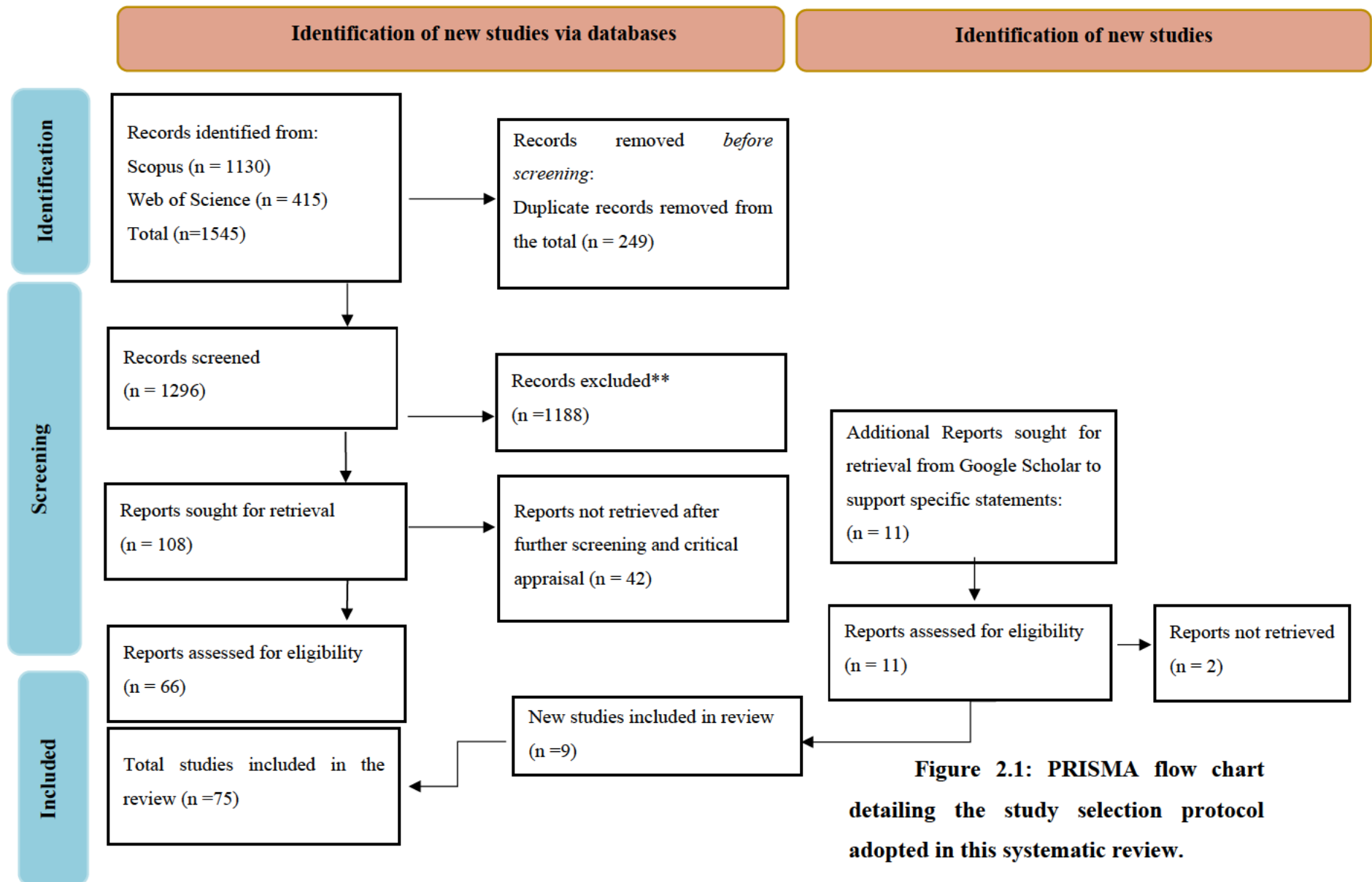


Figure 2.1: PRISMA flow chart detailing the study selection protocol adopted in this systematic review.

2.4 Results

2.4.1 Literature search

Publications from Scopus and Web of Science research databases totalled 1545 (1130 and 415) papers, and a total of 66 articles were included in this synthesis following a multi- stage comprehensive screening process on Covidence, as summarised in Figure 1. Following comments from an internal review, nine additional articles were added to support statements in the introduction and discussion sections. The literature included in the review synthesis totalled 75 publications. Research on the application of NUS and barriers hindering their use and adoption has increased over the past decade. Approximately 56% of the articles included in the review were published between 2020 and 2023 (Figure 2.2), and the year with the most published literature on the topic was the year of the COVID-19 pandemic 2020. South Africa had the most published literature on the subject matter, followed by Ethiopia, Kenya and other countries in SSA. Some publications, however, focused on the SSA region instead of individual countries (Figure 2.3). This section presents the results of the study qualitatively and quantitatively.

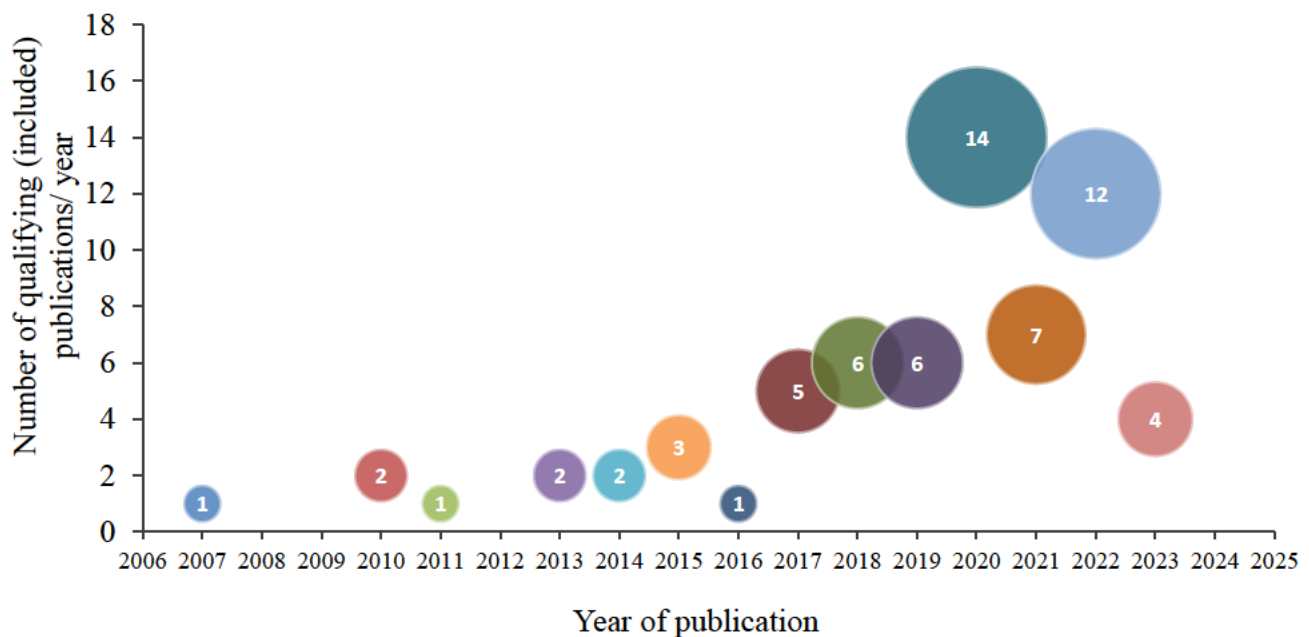


Figure 2.2:The number of publications on NUS over the years. Studies included in this research were published between January 2000 and December 2023. The bubble size correlates with the number of publications per year.

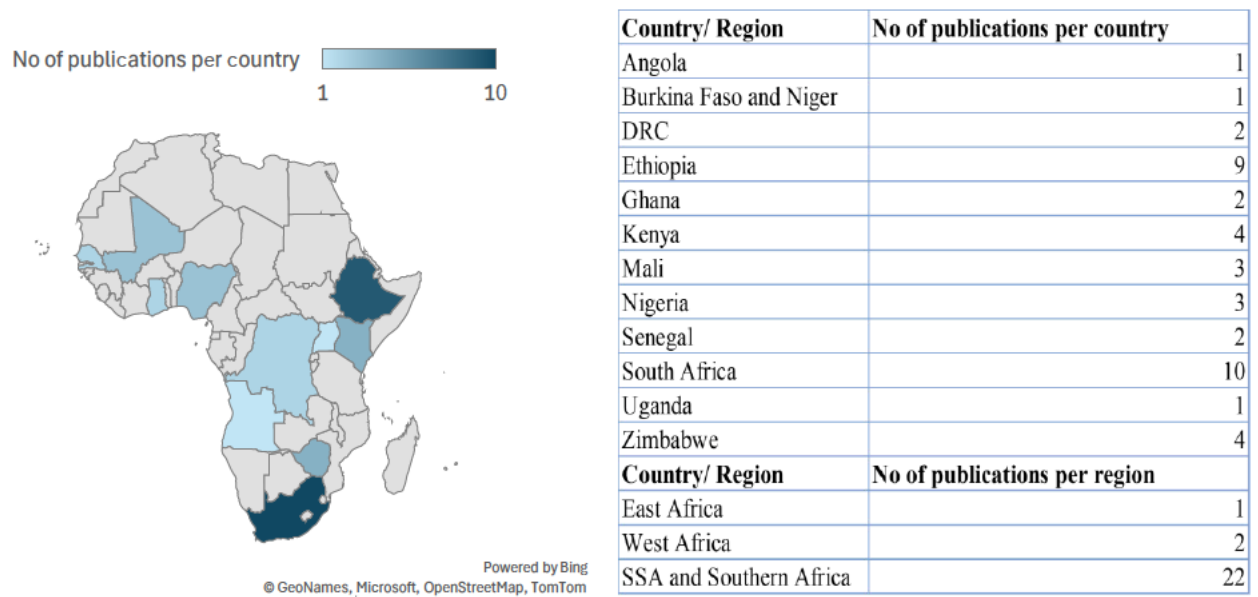


Figure 2.3: Visualisation of the number of qualifying publications focusing on NUS from each country across SSA.

2.4.2 An analysis of the utilisation and potential of NUS and NUS-inclusive local agrifood systems

2.4.2.1 Food and Nutrition Security

Central to the reported importance of underutilised crops is their use and potential to be sustainable and intergenerational sources of food and affordable nutrition, especially in marginalised smallholder settings(1,8,9,10,11,13,18,19,26,30,31,35,36,39-52). As a result, NUS were acknowledged as directly contributing to improving food security in 81.8% of the reviewed literature. This was supported by reports from 37.9% and 86.4% of the publications, which also acknowledged that these crops can indirectly enhance food security. NUS do so by enabling marginalised communities to engage in activities that improve their livelihoods and local agricultural systems, respectively, thereby positively impacting their food security outcomes.

NUS crops are acknowledged to contribute towards the different pillars of food security, especially the availability of food, access and stability of the food systems as well as utilisation, which, in enabling environments, supports positive nutritional outcomes (9,10,12,13,14,19,26,35,36, 41,43,45,46,47,48,53,54). It is also explicitly documented that in rural settings, NUS are known to improve socio-cultural outcomes (1,11,30,55), aid with fighting against hunger (2,26,19,35,42,43,45,56,57,58) and supplement or have potential to aid climate change adaptation

through improving production and productivity of agri-food systems, particularly under harsh conditions (86.4%)(e.g. 1,8,10,12,13,16,18,34,40).

NUS are reported to be natural insurance for food security in times of adversity. Authors like Yemata (2019) have gone as far as to report that communities that plant NUS species are generally food secure and have “*never*” known famine and that they are not exposed to extreme hunger or food insecurity even during harsh seasons in places like Ethiopia (45). This claim was linked to the characteristics and abilities of underutilised crops to enhance food security and sufficiency by diversifying and intensifying local agri-food systems, particularly in water-scarce environments (1,17,28,29,46,49,53,59,60,61). In this way, NUS crops are strategic as it is well documented and acknowledged that reduced agricultural diversity has adverse consequences for food access, availability and security (8,29,30,40,43,59). Collectively, most NUS have been labelled as food security crops for rural farmers, particularly women, in settings where the main obstacle for agri-food systems and policymakers at different scales is to provide strategic solutions to the challenge of granting the growing population access to sustainable, healthy diets and ensuring food security, especially in rural areas (1,8,10,12,13,40,47,48).

2.4.2.2 Food Sovereignty

Progress towards designing and reinforcing quality food and nutrition-sensitive initiatives and approaches has been slow (6,62). Such approaches, for example, would be inclusive and people-centred to inform equitable, sustainable agri-food systems transformation towards nutrition-sensitive systems that support food sovereignty and aim to reduce hunger and malnutrition and boost local economies, thus contributing to the five pillars of the SDG agenda, people, planet, prosperity, peace, and partnerships (6,62). Rural communities have relied on NUS to provide food systems stability, food sovereignty, dietary support, nutritional safety nets, food security and medicinal support for local communities for centuries during adverse climatic conditions (35,42).

Food sovereignty is essentially the right of people to define their own food systems (62,63). Central to the principle of food sovereignty is the people's right to healthy, culturally appropriate, high-quality foods produced sustainably in accordance with ecologically sound values (62, Declaration of Nyéléni, 2007(63)). The principle is inclusive and people-driven, with a mission to include local people as stakeholders in their agricultural food systems. Of the articles analysed, 12.12% reported on the potential of underutilised crops to catalyse the efforts to reinforce food sovereignty and positive socio-cultural outcomes (16,20,60,64).

Underutilised crops not only have the potential to strengthen existing agri-food systems through agricultural crop diversification, but they can also strategically reinstate food sovereignty at local levels and promote dietary diversity, leading to better food and nutrition security outcomes (15,24,49). NUS crops that remain in informal, indigenous smallholder farming systems are a product of intergenerational farmer selection and are supported by informal seed systems (6,28). The farmers' right to self-informed production knowledge, crop selection, and preferences remains crucial to transforming existing systems.

2.4.2.3 Nutrition and Health

Sub-Saharan Africa has among the world's highest levels of hunger and micronutrient deficiencies, and this situation is worsening in the region faster than anywhere else in the world (2,9,24,26,65). Of the 36 countries with the highest scores of micronutrient deficiencies, 86% are in SSA (9,24). Further, non-communicable diseases (NCDs), malnutrition, stunting, and hidden hunger are all conditions that have been increasing in SSA following the shift to monoculture agri-food systems, and monotonous diets post the introduction of the Green Revolution and its framework (23,32,34). The Green Revolution and supporting frameworks and policies failed and continue to fail to account for food quality and nutrition security, leading to a decrease in agricultural and dietary diversity and neglected nutritional requirements of local populations in SSA (9,11,19,28,35,66). The agri-food systems must be transformed and contextualised to cater to local needs (19,28,36). The reintroduction of indigenous crops to the broader population can be a strategic step to help address poverty and caloric and nutritional deficiencies (1,5,11,12,28,29,30,35,36,42,45,46,67).

2.4.3 NUS and their prioritisation in research

SSA has a rich agrobiodiversity of NUS, which could be incorporated into transformed and contextualised agri-food systems that are food and nutrition security sensitive (10,11,15,30,35,46,61). The richness of NUS in nutrients, proteins, dietary fibre, healthy carbohydrates and proteins, vitamins, active compounds, antioxidants, and minerals contributed to and could continue to contribute to improving the health status of people at different scales (Figure 2.4) (9,10,13,35,42). Underutilised crops have the potential to improve access to and availability of diverse, nutritious, and healthy foods, thereby enhancing nutritional and health outcomes and quality of life across populations at different life stages and regional scales (9,11,42).

Underutilised crops can be considered strategic foods to solve numerous challenges in SSA under current and future conditions (3,5,9,14,30). In the literature included in this synthesis, several NUS were reported to be more important and strategic due to their characteristics and potential to help solve the region's prevailing problems. This section reports on the “strategic” NUS crops currently prioritised in research for their specific characteristics and potential to improve adaptive capacity and sustainability under climate change and food and nutrition security outcomes. However, processing constraints bottleneck their sustainable deployment in mitigating food and nutrition insecurity (31,48). The existing literature indicates that post-harvest handling and processing techniques for NUS species are limited to traditional methods and lack innovation to improve shelf life and taste without compromising the nutritional value of the end products (31,43,48).

2.4.3.1 Priority underutilised crops

The studies reviewed highlight the importance and potential of Bambara groundnut (*Vigna Subterranea*) as a strategic NUS crop in 18.18% of the reviewed publications. Significant evidence also highlighted the importance of ensete (*Ensete ventricosum*) in 10.66% of the literature reviewed. In comparison, modest evidence on amaranthus and other African leafy vegetables (9.09%), cowpea (*Vigna unguiculata*), sorghum and yam (*Dioscorea L*) (6.06% of the publications each) highlighted the potential and benefits of including these crops in local agricultural systems as a climate change, food and nutrition security, and local livelihood adaptation strategy. Cassava (*Manihot esculenta Crantz*), fonio (*Digitaria exilis*) and teff (*Eragrostis tef*) (4.54% of publications each) and millet (*Pennisetum glaucum*) and taro (*Colocasia esculenta*) were also included among the underutilised crops with the potential to aid in addressing existing challenges in the region with limited evidence base (3.03% of included publications) supporting them as strategic crops. Twenty-four (24) publications included in this synthesis grouped these NUS crops and reported on them collectively. Collectively, these crops were identified as having the potential to sustainably contribute towards enhancing agri-food systems productivity and stability, thereby improving food and nutrition security and socio-economic, socio-cultural and environmental outcomes in SSA (Figures 2.4-2.5) (3,5,7,10,12,14,15,18,19,34,35,38,40,41,43,46,50,53,58,60,64,68,69,70).

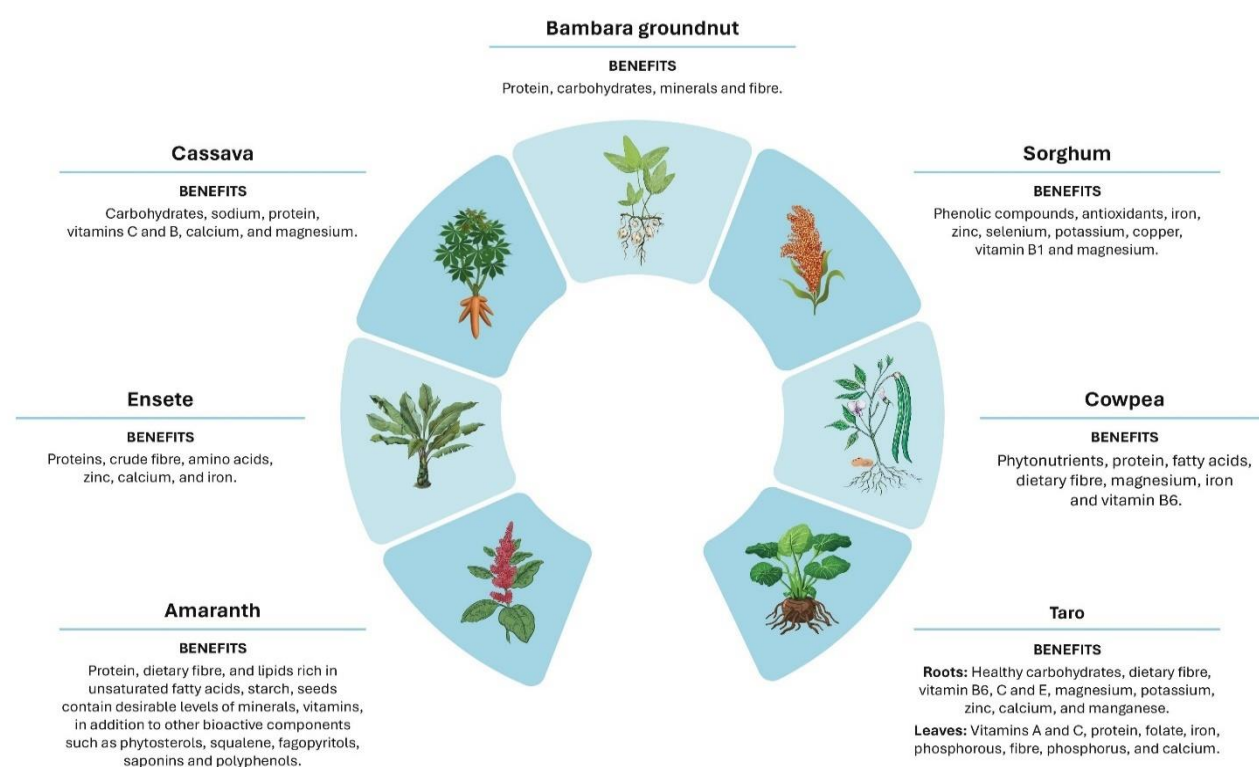


Figure 2.4: Nutritional benefits associated with several NUS presently prioritised in research.

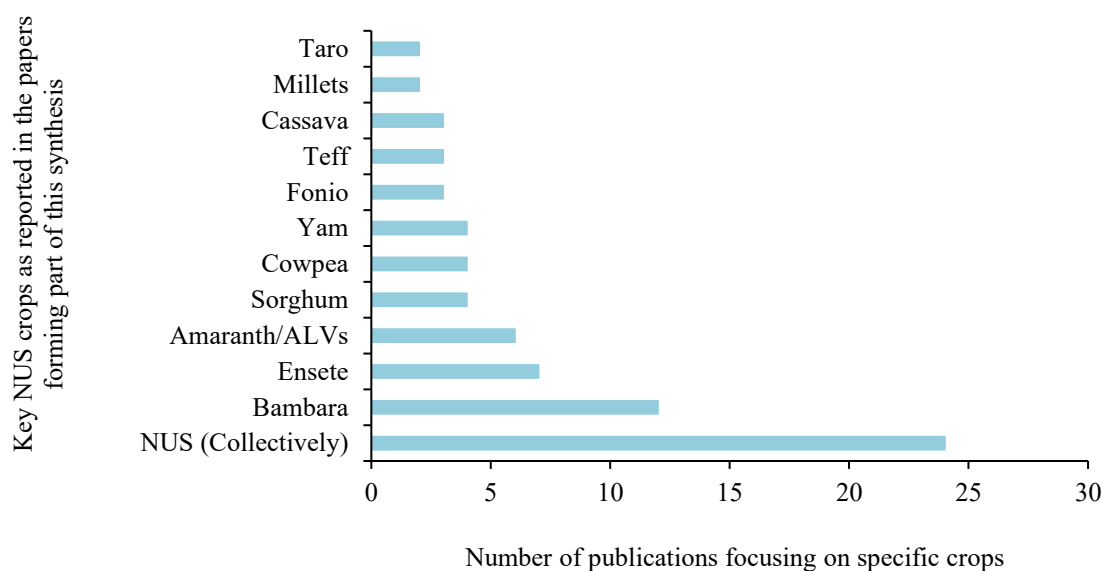


Figure 2.5: Top 11 most researched NUS based on the reviewed literature published between 2000 and 2023.

NUS crops have also been reported to have numerous cultural and medicinal properties. They can contribute to the stability and diversity of agri-food systems at different scales, re-informing food sovereignty, environmental sustainability and ecosystem services through improving agro-biodiversity (49,53,60,64,70). Through their different properties, underutilised crops are strategic to catalyse the region's progress toward achieving SDGs, particularly SDGs 1, 2,3 and 15 and contributing to the five pillars of the SDG 2030 agenda, through informing and intensifying:

i. Building resilient agri-food systems

A selected few major crops dominate current agri-food systems, with three specific major crops reported to utilise up to 40% of all arable land globally post-2011 (24). Increasing agricultural biodiversity can minimise the risk and vulnerability of local agri-food systems and livelihoods, reinforce production stability and resilience, and minimise risks to food and nutrition security in the region (49,71,68). Research has reported on the potential NUS for the past years, such as those in Figure 2.5, have to contribute towards agricultural improvements and mitigation and adaptation measures in the agri-food systems and the resilience of these systems given climate change and environmental changes (1,26,30,40,41,43,51). Their potential expands from reports on their adaptability to change and adversity, suitability to a wide range of environments, ease of maintenance, and lower input requirements (1,3,5,12,14,16,28,43,50,51,58,59,69). These crops are also favourable due to their tolerance to biotic and abiotic stressors and ability to withstand harsh conditions and intensify agri-food systems, especially in rural areas (8,17,30,40,41,70). Some of these crops, for example, Bambara groundnut, can further contribute to nitrogen fixation and encourage yield increase in farming systems that would otherwise struggle (14,29).

Underutilised crops can also contribute to improvements in agri-food systems through genetic advancement of some major crops, helping them become more adaptable and resilient to future and present climatic and environmental changes (5,7,9,36,40,41,42,46,47,59). Because of this, some publications highlight the importance of conserving some NUS, particularly those mentioned above, for example, Bambara groundnut, which was said to be at risk of abandonment and genetic erosion as a result of their marginalisation and elimination from agri-food systems despite their potential because of their poorly defined value-chains and informal seed systems (10,40,41,42,43). However, like most NUS, these crops have been neglected in developmental agendas, food systems policies, and formalisation efforts for seed systems (14,36).

One of the main strategies to improve existing agri-food systems and agricultural adaptation and resilience to shocks is perceived to be the development of more resilient crop varieties of some major crops using genetic traits of NUS, as well as diversification of agrobiodiversity through the inclusion and promotion of NUS crops (36,40,41,42,59). However, there are limited efforts to support this. Genomics breeding, molecular breeding, genetic engineering and using traits of NUS to improve some major crops genetically and promote phenotypic diversification for improved food-nutrition security have potential as strategies for agricultural climate change adaptation (5,9,14,36,40,41,59,72,73,74). NUS have phenotypic diversity to support agricultural production and improve agricultural diversification under climate change conditions (10,30,40,41,42,59).

ii. Socio-economic benefits

Sub-Saharan Africa's share in the global food system, agricultural exports, and local food sovereignty drastically decreased following the Green Revolution and supporting systems (1,9,11,26,30,60,68). The Green Revolution improved productivity and production of specific crops, largely "cash crops", and seemed to have contributed towards progress made to achieve food security and suppressing global hunger levels between 1990 and 2014 (27). However, the Green Revolution systems largely failed in SSA due to their oversight to address context-specific requirements of a sustainable and holistic food system, local socio-economic value chains, sidelining the role of local climates in the sustainability of agri-food systems, existing ways of life, and other socio-economic and socio-cultural requirements (9,11,35). Existing local and traditional agricultural value chains were primarily displaced by the efforts and framework of the Green Revolution, even though the objective of improving productivity and intensification of food production through streamlining the food system and mainstreaming higher-yielding crops was achieved (9,11,12,28,66).

Post the Green Revolution, reduced agricultural diversity and monocultural cropping systems that support input-driven major crops that are not as locally suited and adaptable as landraces and previously grown varieties, are the single most prominent challenges threatening socio-economic statuses, livelihoods, food security, human health and nutrition sectors in SSA (916,30,33,34,66). The system exacerbated inequality, poverty, food and nutrition insecurity and environmental challenges. However, climate change impacts will be more severe in developing nations where poverty, malnutrition and food insecurity are already problematic and adaptive capacity is low, with limited resources to cope with external threats and shocks (65,68).

Most NUS are healthier alternatives to staple crops, have multiple socio-economic and socio-cultural benefits, and can be produced in an ecologically friendly way (6,15,23,32,50,52). For generations, these species have been reported as “natural insurance” against hunger and food insecurity (9,19,30,35,42,43,45). Underutilised crops are also comprehensively reported as sources or potential sources of income generation, poverty eradication, and natural insurance for local livelihoods, which means their incorporation can assist the region’s efforts to achieve SDG 1 (zero poverty), and SDGs 2, 3 and 15. (1,8,11,12,30,35,41,43,44,53). People who currently benefit from using NUS for socio-economic reasons are primarily women from poor, marginal areas. They are considered significant in the current value chain of NUS and are labelled as guardians and conservators of NUS and their seed systems (8,12,14,35). This highlights gaps where the government needs to step in to support local efforts to ensure the conservation and utilisation of NUS crops. Table 2.2 summarises some of the reported socio-economic values of NUS.

Table 2.2: Some socio-economic values of NUS crop species reported in the reviewed literature.

Socio-Economic value	Explanation	Examples of published literature
-Enhancing local agri-food systems diversifies food sources and promotes food sovereignty and nutritional benefits	NUS are widely culturally acceptable and have a broader range of genetic variation. Promoting NUS as strategic crops will support the multi-stakeholder inclusion, agricultural diversity, resilience, and sustainability of local food systems. These crops could also be used to genetically enhance mainstream crops, resulting in increased resilience, adaptability and productivity of local agri-food systems.	(14,26,28,29,35,36,40,43,46,66)
-NUS requires fewer inputs and are easier to cultivate	NUS are highly adaptable and require fewer resources to grow. Promoting NUS to be mainstreamed into current agri-food systems could help communities achieve more stable production systems at lower production costs.	(1,26,8,10,35,40,43)
-NUS can be buffer crops: avoiding hunger and poverty during lean seasons	NUS are better adapted to their local environments and changes to climatic and environmental conditions (71). These crops, therefore, can serve as safety nets to protect communities from poverty and hunger during adversity.	(1,19,30,41,44,38,71)
-NUS are healthier alternatives	NUS are generally richer in healthy fats and carbohydrates, nutrients, micronutrients, minerals and proteins, which could help local communities bridge the existing nutritional gaps and sustainably achieve improved nutritional health.	(8,26,44,66)

-NUS can improve Gender inclusivity in agri-food systems, particularly under climate change	Women are the primary guardians of NUS and their seed systems in rural areas. Promoting these crops will enable women to participate as stakeholders in local agri-food systems and economies.	(35,41)
-NUS inclusion can enhance economic opportunities and value chains for local people, especially women and youths	NUS crops aimed at specific niche markets at a local level have socio-economic and cultural potential. If local farmers are involved in such value chains, sustainable employment creation and autonomous pathways out of poverty could be created.	(12,23,52)
-NUS can improve Local agri-food systems' resilience, adaptability and stability	NUS are resilient and adaptable to climate and environmental changes, and therefore more stable in food systems compared to major crops. These crops, in this way, can ensure sustained and resilient production and agri-food systems value chains at different levels.	(16,18,30,38,39,50)
-NUS can improve environmental health	Underutilised crops have been reported to have immense potential to rehabilitate, improve and strengthen local environments. Such environmental benefits include, but are not limited to, nitrogen fixation and improving environmental biodiversity.	(14,30,41,44,71)

2.4.4 Research outcomes and gaps in NUS prioritisation

Most of the publications reviewed advocate for NUS as a solution to the region's food and nutrition insecurity challenges and highlight the characteristics that make NUS an important component in informing agri-food systems transformation. Mabhaudhi et al. (28) highlighted existing gaps and provided recommendations to address them and proposed realigning policy focus to promote NUS prioritisation and application; however, efforts towards this remain stagnant (5,7). This review further advanced these gaps by identifying that health and well-being, and environmental outcomes were prioritised in research involving NUS, while sociocultural outcomes, although acknowledged, were not prioritised. The studies that collectively reported on NUS focused primarily on health and well-being outcomes, poverty reduction and strengthening livelihoods, nutrition and food security and environmental outcomes, respectively (Figure 2.6-2.7). Root vegetables and legumes were specifically linked to research prioritising health outcomes, while grains were largely linked to environmental and socio-cultural outcomes. This reflects a focus on promoting NUS based on their environmental and nutritional benefits and less on their socio-cultural importance. A gap therefore exists in addressing social stigmas associated with NUS to realise the potential of these crops (28). Policy revisions need to be undertaken to widen the scope of NUS prioritisation in research and enable their acceptance and application at different scales.

		Health and Wellbeing outcomes				Environmental outcomes		Socio-cultural outcomes
		Reducing hunger	Improving food security	Improving nutrition security	Reduced poverty/ improved livelihoods	Improved yields/agri-food system stability/productivity/ diversity/improved environmental sustainability	Crop breeding/ modelling	Socio-cultural outcomes
Grains	Millet		1			2	2	4
	Sorghum	1	1	2	1	4	4	
	Teff		3	1	1	3	3	1
	Fonio	1	2	2	3	3		1
Legumes	Bambara	2	11	7	6	11	6	2
	Cowpea	1	3	3	2	4	4	1
Vegetable	Amaranth/ALVs	1	6	5	4	5	2	1
Root Vegetable	Taro	1	2	1	2	2	1	
	Cassava		2			2		
	Ensete	2	7	3	3	6	1	1
	Yam	1	4	3	2	2	1	
NUS (collective)	Orphan/underutilized/ traditional/neglected crops	7	19	20	21	19	3	5

Figure 2.6: Evidence heat map showing the prevalence of outcomes within included publications focusing on NUS in SSA. The health, wellbeing and environmental outcomes present a collection of specific sub-outcome proportions.

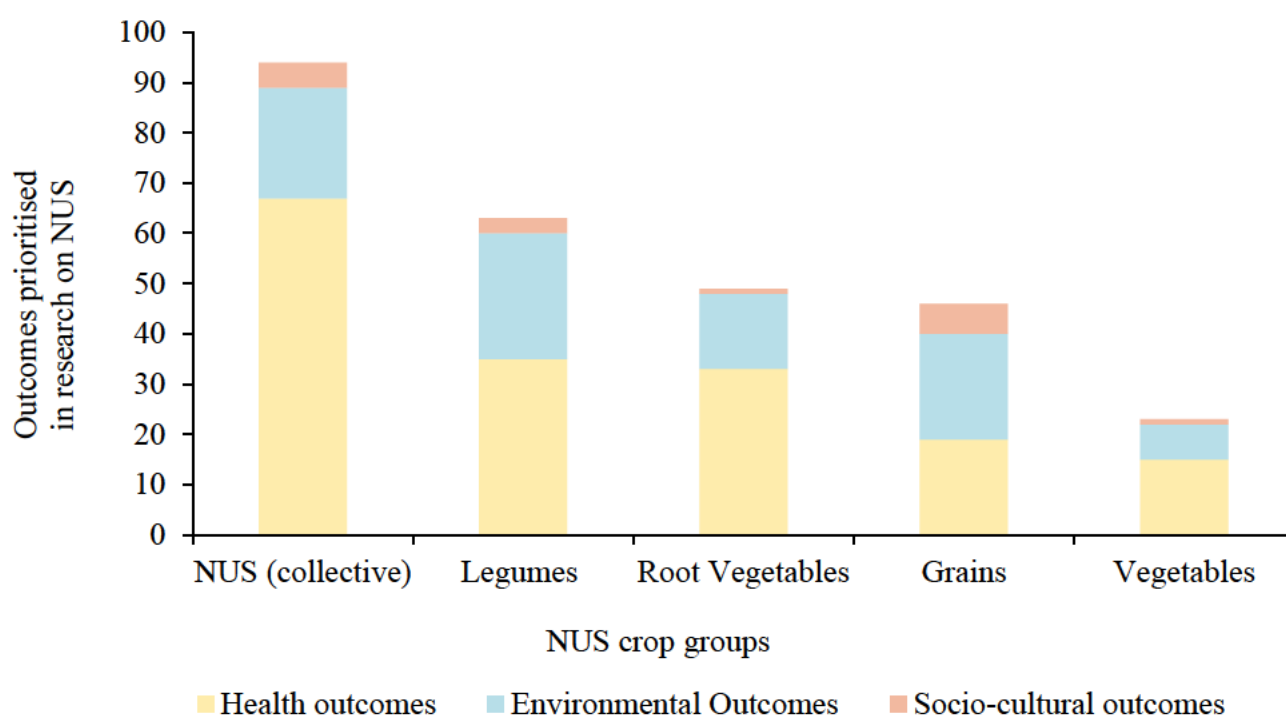


Figure 2.7: Frequency of each reported outcome per NUS group.

2.4.5 Barriers to the adoption and utilisation of NUS

NUS are comprehensively reported to have the potential to address several socio- economic and cultural challenges (e.g. Table 2.2). The potential of NUS stems from their characteristics, which presents them strategically as a constituent solution to catalyse efforts to address food and nutrition challenges and contribute towards resilience of local agri-food systems and livelihoods (14,16,24,43,56,69,72,74). However, several barriers currently exist and prevent NUS from transitioning from being underutilised crops towards becoming more mainstream. These systematic and entrenched barriers make translating the goodwill of NUS into actionable outcomes difficult. On the other hand, these barriers are enabled by the marginalisation of these crops in research, production and developmental initiatives. Existing barriers are further enabled by limited data availability on NUS production and processing techniques, misaligned research and policy priorities, their neglect of genetic improvement efforts and lack of efforts promoting them as a potential key component to agri-food systems transformation, particularly under climate change (44). The main barriers are highlighted below:

i. Insufficient agricultural innovation

The correlation between NUS and climate change mitigation and adaptation within the agricultural and food systems to support food security and stability, nutrition security and health exists (12,14,26,29,40,41,59,70). However, research and data on the indigenous and genetic characteristics of NUS remain scattered and limited (2,5,12,43). Management strategies and production information of these crops are often passed down through local generations in vernacular systems rather than published and conserved systems (18,68). This translates into a lack of knowledge of these crops, misaligned research, breeding, and seed-testing priorities, the marginalisation of NUS crop species in research and development agendas, and missed opportunities to utilise these crops to solve regional challenges (10,24).

Further, informal, variable and inequitable seed systems, alongside the capitalised seed bills and frameworks which criminalised seed exchange and free will when it comes to seed selection of some “unregistered crop varieties”, which are primarily underutilised crops, are other major production and adoption bottlenecks for these species (10,14,57). Additionally, reports of NUS being less yielding and less commercially viable due to limited uses and ill-defined and underdeveloped value chains and seed systems are obstacles to adopting these crops (2,3,8,14,24).

The ideological, structural and institutional barriers put in place to support the production of major crops post the Green Revolution discourage local communities from incorporating and embracing NUS crops into their agri-food systems. Transforming local agri-food systems requires ethical consideration of traditional knowledge systems, cultural needs, climate and general inclusivity. Therefore, these barriers need to be overcome. Traditional and scientific knowledge systems and innovations on NUS agronomic requirements and processing must align to promote NUS. Additionally, well-developed seed systems, markets, and efforts to destigmatise these crops are necessary to enable their adoption and to create competitiveness for NUS cultivators in the agri-food systems value chains at different scales (10,14,26). These efforts, however, are currently limited.

ii. Gendered restrictions

Women, especially in rural areas, are reported to be the primary guardians and stewards of NUS species (41). They, however, lack support and inclusion in developmental agendas to promote these crops, which are still, in some instances, gendered and labelled as “*animal feed and poor farmers’ crops and food*” (2, p3). This continues to hinder the potential of NUS to contribute to reinstating food sovereignty, food and nutrition security and socio-economic improvements, especially in rural settings (2,8,41).

To date, genetic resources improvement, seed systems, and the broader value chain of NUS and the currently limited NUS products are marginal and managed, sustained and fuelled within rural communities by primarily women (10,41,57,68). This, because of gender dynamics and other socio-economic and cultural barriers, leads to an ongoing cycle of informalised seed systems and NUS crop value chains. This situation would be different with correct institutional support, properly aligned research priorities, improved genetic resources and ensuring that the seed systems of these crops are managed and conserved through formal seed production institutions (5,8,58,57).

iii. Biophysical barriers and natural attributes

Some NUS, because of their biophysical characteristics, have been widely reported to lack preferred consumer attributes. These attributes, for example, are reported to be high-yielding, easy to process, with shorter cooking times, a familiar/favourable taste, and requiring less water and minimal energy during processing (2,24,31). Neglect of these crops has translated to them not having improved high-yielding varieties, and they lack modernised processing techniques, inputs and necessary

promotion and have limited market access (10,24,56,57). Underutilised crops, in some cases, as cultural crops lack, but require innovations of culturally acceptable, feasible and nutrient-sensitive processing techniques to improve their adoption within different settings (31,57).

2.5 Discussion

Research on NUS has increased steadily over the past 23 years and more exponentially since 2015, highlighting a linkage between the increasing interest in NUS and the United Nations' Sustainable Development Goals (SDG) agenda. This review outlines various perspectives on the utilisation and potential of NUS to achieve sustainable, equitable, inclusive, resilient and diversified agri-food systems and reinforce food sovereignty within safe planetary boundaries under climate change in SSA. Publications on the use and potential of NUS are from multiple perspectives, ranging from sustainability and environmental research and climate change to food science and nutrition research. This highlights NUS's transformative and integrative potential to contribute to a broader sustainability agenda that cuts across systems and scales, particularly after the COVID-19 pandemic.

This review further highlights significant barriers to NUS adoption, often contributing to the underutilisation of these species at different levels. The review highlighted the lack of integrated knowledge and seed systems, ill-defined value chains at different scales, gendered restrictions, and natural or biophysical challenges as the main barriers to NUS production. Other challenges included socio-cultural and structural ideologies. All of these are major bottlenecks hindering the adoption of NUS and the better positioning of these crops in development agendas and adoption for utilisation, and are an outcome of their lack of inclusion and misaligned priorities between research, genetic improvements and policies (Table 2.3) (1,2,10,11,24,30).

Food security is defined as a situation where “*all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their food preferences and dietary needs for an active and healthy life*” (10, pp.5686). Climate change, reduced agricultural diversity, and biodiversity loss negatively affect food and nutrition security outcomes because access constraints to diverse food options and choices vector food- nutrition and health-related challenges. Further, reports highlight that climate change has evolved into a climate crisis, with devastating effects on food production and food security, including supply, availability, accessibility, and human livelihoods, especially in SSA (29,40,43,59,71). Most of the reviewed literature highlights and advocates for NUS as a solution to these challenges, especially in rural areas most vulnerable to climate crises and resulting production challenges, poverty, and food and nutrition insecurity challenges (11,16,30,34,54,60).

Table 2.3: Summary of drivers of adoption and adoption barriers of NUS. The drivers of adoption were conceptualised by the authors based on the reported barriers.

Potential drivers of adoption	Reported barriers to adoption
Improved seed systems and seed availability through, for example, local stakeholder-inclusive seed banks	- Ill-defined seed systems and value chains (production, consumption, processing, feasible markets and product development) around NUS (8,9,10,11,12). - Perceived poor competitiveness of NUS in mainstream markets.
Building local community capacity and understanding of NUS benefits for food security, climate resilience, and shock absorption in local livelihoods	- Insufficient genetic and traditional data on NUS production, storage and processing (2,24,70,75). - Ideological barriers and policies that are pro-mainstream crops pushing NUS to the risk of genetic erosion (11). Discouragement from incorporating such crops into farming systems due to institutional, socio-cultural and ideological barriers, such as labelling them as “poor men’s crops” and neglecting and forbidding them in seed systems because they are “unregistered crop varieties.” - Poor and underdeveloped seed systems (primarily farmer-driven) (12,14,40). - Long cooking time requires more resources such as wood and water (31).
Improving local agri-food systems, agrobiodiversity and dietary diversity in a sustainable and resilient way	- Most NUS are lower-yielding compared to major crops (14). - Consumer preferences and reported attributes of some NUS crops, such as bad/bitter taste hindering utilisation (42).

Their potential to reinstate food sovereignty	- Lack of relevant data and limited inclusion in developmental agendas as strategic crops. - Stereotypes and lack of information acknowledging the value of NUS (66). - Neglect in genetic improvement efforts. - Lack of production data and planting knowledge and materials. - Lack of processing techniques and diversification of products of most NUS for consumption (31). - Lack of processing information, some NUS can be poisonous if not well-prepared.
Genetics-assisted breeding to help improve crop cultivars to require less processing time	- Lack of relevant genetic and phenotypic data on NUS.

2.5.1 Policy and Practice: Challenges and a need for transformation

2.5.1.1 Governance & coordination

Global conversations and action plans on climate change adaptation options for developing countries, focusing on agri-food systems, need to prioritise benefits for human nutrition to bridge existing food and nutritional gaps (9). Future strategies, policies, and action plans must acknowledge the importance of intersectoral collaboration for environmental, food production, and nutrition strategies, as they bring co-benefits. Policy interventions also need to support the formalisation of systems to improve the knowledge base and availability of priority NUS. For example, effective seed systems management is crucial for agricultural improvements and climate change adaptation. Policies should also focus on funding and support from country-specific governing institutions, as well as ethical communication and promotion to destigmatise NUS. Previous strategies have proven short-sighted and have yet to be holistic, sustainable, and inclusive. They are limited in their account of environmental and cultural sensitivity, as well as of local populations' nutritional and health needs.

The main challenges underlying the shortcomings and failures of the current agri-food systems, food and nutrition insecurity, and health challenges in the region are well known within the policy space. However, the efforts to address them have stagnated. Existing key regional policies and strategies put in place, such as the SADC Regional Indicative Strategic Plan (RISDP) of 2003 (www.sadc.int. n.d.)), African Union Agenda 2063 (*Agenda 2063: The Africa We Want.* | *African Union*. n.d). Comprehensive Africa Agricultural Development Programme (CAADP) (African Union Development Agency-CAADP. n.d), Regional Agricultural Policy (RAP) (www.nepad.org. n.d), African Union Malabo Declaration on Accelerated Agricultural Growth acknowledge all challenges underlying food and nutrition insecurity in SSA and put agricultural development at the centre of addressing existing challenges (www.nepad.org. n.d). Supporting these are country-specific strategies for climate change adaptation, national development and disaster management plans, all calling for actions towards ending food and nutrition insecurity through the transformation of the current, outdated agri-food systems, which lack resilience and are translated to one of the underlying contributors to food and nutrition insecurity in the region (2,24,58).

However, there needs to be more explicit mention of the need for food- and nutrition-sensitive innovations and food sovereignty within existing agricultural development policies,

plans, and frameworks. While food and nutrition insecurity are mentioned in the policy documents as two challenges to be addressed, clear revisions to agri-food systems in the region's contextual settings are lacking. The implementation of interventions designed to address challenges related to food and nutrition insecurity also falls short due to a need for greater contextualisation to address area-specific challenges. For example, progress toward the Malabo Declaration for Agricultural Transformation in Africa is slow and insufficient in vital components of the declaration: ending hunger by 2025, Agricultural investments, and improving resilience to Climate change and variability in many countries in the region (www.nepad.org. nd.).

A need for policy revisions, interdisciplinarity, cross-sectoral collaboration, and coherence in the agri-food-nutrition-health systems is urgent, and the window for action is narrowing. The inclusion of NUS as a sustainable and resilient option for reinstating food sovereignty, transforming existing agri-food systems, and mitigating the impacts of climate change in the food and nutrition sectors needs to be prioritised as a strategy in the policy space. However, it should be an important and strategic component in transforming food systems from monopolised to inclusive spaces and in reinforcing food sovereignty for improved food and nutrition security, particularly within marginalised communities in SSA (Figure 2.8).

2.5.1.2 Research & innovation alignment

Most barriers to NUS adoption and improved utilisation can be addressed through realigning research and policy priorities. In SSA, for example, due to misaligned priorities and the lack of integration across policy, research, and adaptation strategies, the number of malnourished people has been increasing post-2014, and the hidden hunger index is worsening in the region faster than anywhere else in the world (2,24). The reintroduction and inclusion of NUS crops in local agri-food and seed systems to support sustainable and resilient production and productivity, and to improve agricultural biodiversity within farming systems, particularly marginalised farming systems within safe planetary boundaries, can also aid in addressing these barriers (18,68,71). Table 2.3 summarises drivers of adoption and reported barriers to NUS adoption.

The potential for NUS to address existing challenges is widely researched and documented. However, their inclusion is hindered by a lack of structures and policies to support

their adoption and implementation of processes that could enable their inclusion (28,32,33,55). Policy biases, for example, within current agricultural and seed systems, expose the lack of alignment to address existing and projected challenges related to food and nutrition insecurity, and to policy inequality and inequity across SSA. In this way, current policies undermine local food sovereignty and an opportunity to bridge existing food and nutrition-related challenges (28,32). Existing policies have supported smallholder agriculture and farmers, for example, by subsidising inputs. However, these efforts continue to support and reinforce the acceptability and adoption of outdated and failing agri-food systems instead of accommodating and supporting transformation towards feasible, context-specific, inclusive, resilient and sustainable systems. This is evident in the existing gaps and biases in policy.

2.5.1.3 Financial & market inclusion

While the need for financial support and services is well documented, an urgent need within existing policies and plans is to strengthen non-financial assets and services to avoid the ill-implementation of interventions at different scales. In a region like SSA, where financial poverty prevails, agricultural and development policies should integrate financial policy considerations (28,32). This should underly an environment that aims to bridge financial gaps within the agricultural value chains by being comprehensive, equitable and inclusive enough to accommodate the poor farmers and current NUS conservators and grant them access to financial services to support their efforts.

Underutilised crops have served as safety nets for rural communities, providing nutrition, food security, and food sovereignty for centuries under diverse, adverse climatic conditions (23,40). However, cultivation of NUS has been declining over the years as more farmers abandon these species for highly promoted, policy-supported commercial crop species and changing eating habits (1,14). One of the main focuses of agri-food systems policies should be to reinforce food stability and ensure the availability, accessibility, and affordability of healthy, nutritious food, as well as to improve local food sovereignty at different scales. Underutilised crops offer an opportunity to realise this.

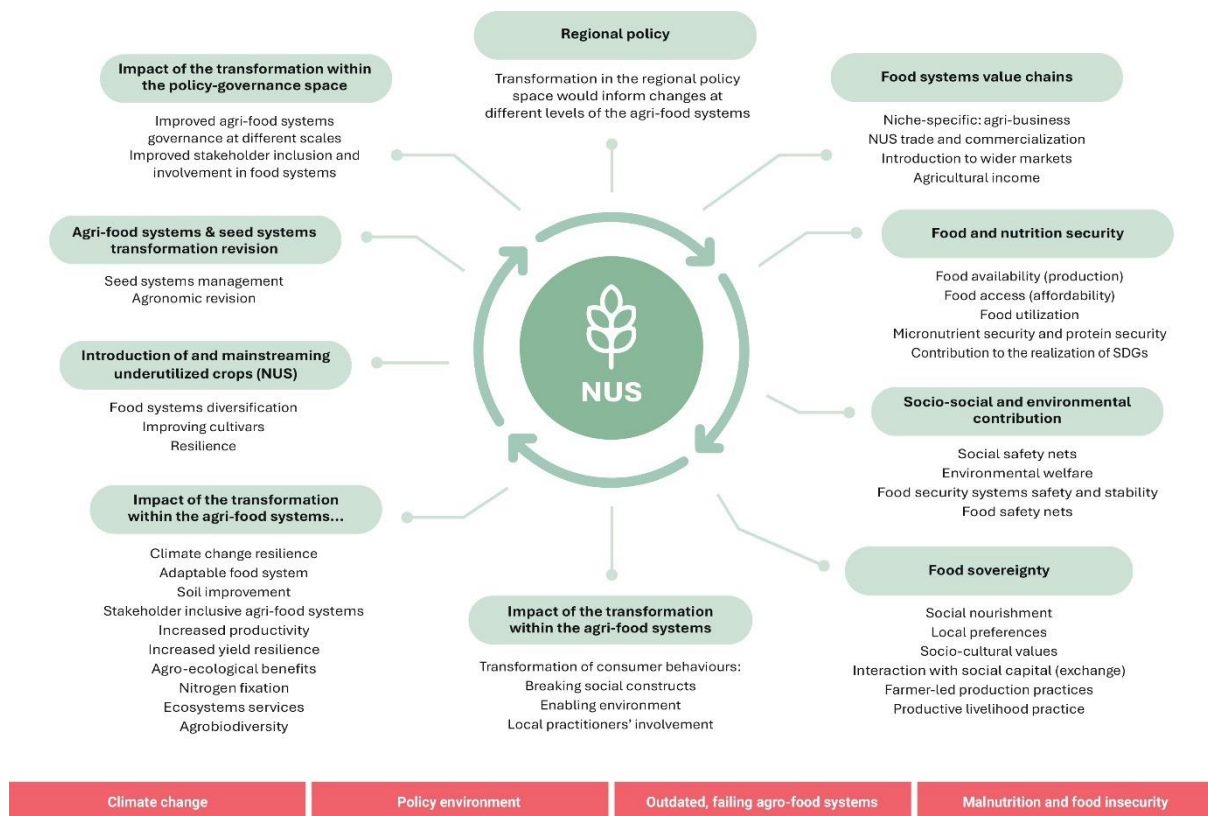


Figure 2.8: A conceptual framework for NUS-sensitive policy transformation to enable agri-food systems transformation to improve the state of malnutrition and food insecurity in SSA within safe planetary boundaries. The framework also highlights a gap: different stakeholders at different governance levels, including NGOs, development partners, and similar, can serve as role players in NUS-focused agri-food systems transformation. The framework was conceptualised by the authors.

2.6 Theoretical Framework: Enabling agri-food systems transformation by incorporating NUS

Current agri-food systems have contributed to multiple environmental and socio-economic challenges in SSA. Transforming these agri-food systems through incorporating alternative and contextualised systems that are sustainable, inclusive and serve within safe planetary boundaries will have multiple benefits for the environment and different aspects of human life, particularly food and nutrition security. There is growing evidence that NUS have substantial potential to address the existing socio-economic challenges in the region and contribute to climate change mitigation, adaptation and resilience of the region's agri-food

systems. However, there is a gap in actualising this potential and successfully mainstreaming NUS into agrifood systems.

The framework presented in Figure 2.9 conceptualises regional challenges, a need for transformation and the benefits of incorporating NUS into agri-food systems to assist in solving existing regional food, nutrition, environmental and socio-economic challenges and contribute towards achieving the five pillars of the SDG agenda and specific sustainable development goals, particularly SDGs 1, 2, 3, and 15. The framework integrates the potential benefits of including NUS in agri-food systems into positive food, water, energy, environmental, socio-economic, and cultural systems, and human health outcomes. We connect these co-benefits to aiding the realisation of SDGs and addressing food-nutrition-environmental challenges in the region. A need for transformation, especially within the policy and governance environment, to enable necessary changes in the agri-food systems is also highlighted in the framework.

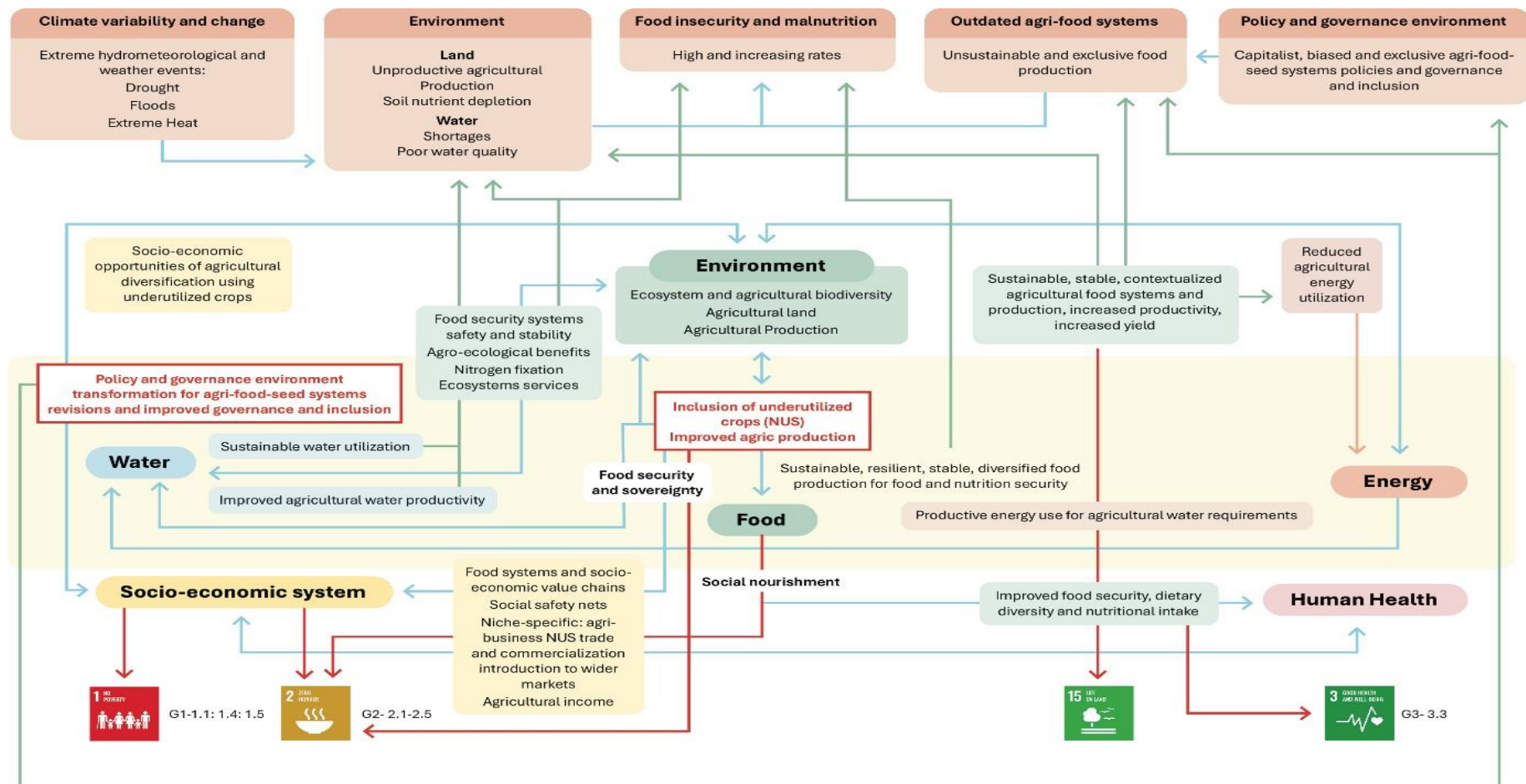


Figure 2.9: Synthesis of linkages between existing challenges in SSA and the potential of NUS to address these challenges, which fall under SDG priority areas, particularly SDGS 1, 2, 3, and 15. Source: The framework was conceptualised by the authors based on the authors based on the review findings.

2.7 Limitations

The synthesis was limited to research published between 2000 and June 2023. The study's inclusion criteria were strict, and the search terms were very specific; this may have inadvertently excluded some publications that would have been useful but were disqualified during the screening phases. However, synonyms were used to avoid bias. The methodological quality of the studies included in the synthesis was not evaluated. The authors opted not to include grey literature publications due to a lack of verifiable, comprehensive information and publication language barriers, among other challenges. Access to appropriate grey literature would have broadened the scope of the synthesis on applying NUS. However, the authors chose to follow the quality-over-quantity approach to the literature included. This study does not include a comparative analysis of NUS and major crops. Rather, it focuses on identifying pathways to mainstreaming NUS into the agri-food system and identifying the positive spinoffs from doing so. The authors collectively believe that the publications selected are a good representation of literature documented across different disciplines on the subject.

2.8 Conclusions and Recommendations

In this review, we integrated existing research on the use and potential of underutilised crops to contribute towards solving recurring challenges in SSA. There has been a growing body of knowledge on NUS species over the past 23 years, particularly after 2015; however, their adoption is still constrained by structural, institutional, socio-cultural, and ideological barriers, and there has been little effort to infiltrate them. Overlapping themes reported possible outcomes of NUS incorporation in agri-food systems, including health and well-being, as well as environmental and socio-cultural outcomes. NUS have the potential to support food sovereignty and food and nutrition security by promoting culturally sensitive, inclusive, diverse farmer-driven agri-food systems and value chains where farmers, particularly women farmers, are not excluded from fundamental agri-food systems value chains. Bambara groundnut was the most researched and promoted NUS species due to its potential to contribute to various components of food and nutrition security in an environmentally safe way.

With a comprehensive review of 75 publications, we investigated the utilisation of these crops, barriers hindering their utilisation and an opportunity for their strategic positioning to inform the transformation of existing agri-food systems into sustainable, resilient, inclusive and diversified agri-food systems within safe planetary boundaries. What is common across the literature reviewed is that the current agri-food systems are

outdated and unsustainable, competing with local populations and the environment for scarce resources such as water in SSA, while failing to meet essential requirements, particularly under the climate crisis.

The current mainstream agri-food systems are further among SSA's prominent underlying causes of food and nutrition insecurity and poverty. NUS are promoted by research as a solution to transforming these agri-food systems. However, despite supporting these crops, the policies and agricultural development initiatives currently in place suppress NUS crops and are monopolised, reinforcing dependence on mainstream crops, being exclusive, lacking contextualisation, and failing to focus on interventions sensitive to the environment and food and nutrition security. Transformation in the existing agri-food systems and supporting policies is necessary and urgent to address existing food, nutrition, environmental and socio-economic challenges and progress towards achieving Sustainable Development Goals, particularly SDGs 1 (no poverty), 2 (zero hunger), 3 (good health and well-being), 5 (gender equity), 13 (climate action) and 15 (life on land) by 2030 in Sub-Saharan Africa. The evidence gathered in this review highlights the need for transformation across multiple sectors to address institutional barriers as a foundation for initiatives aimed at addressing existing challenges. There is a need to incentivise local private-sector engagement. There is also a need to integrate NUS into development frameworks and policies; formalise NUS seed systems; provide financial support to current custodians of NUS; and establish capacity-building initiatives that strengthen indigenous knowledge systems. Based on the evidence gathered in this review, the following recommendations apply for SSA (Figure 2.10).

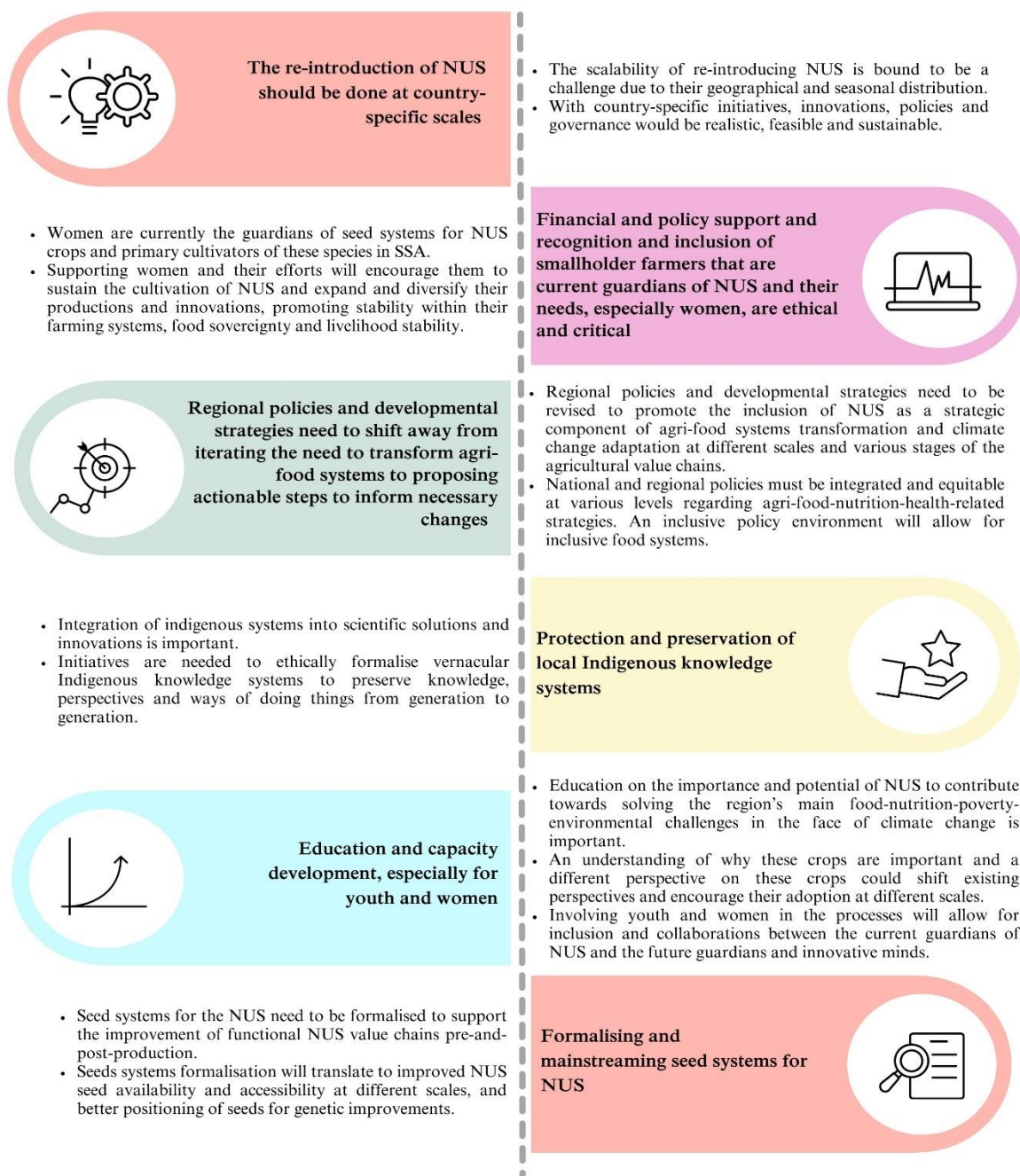


Figure 2.10: Study recommendations (presented in coloured sections) and their explanations (in white sections). These are the author's recommendations based on the study's findings. They highlight the need to integrate NUS into development frameworks and policies, formalise NUS seed systems, provide financial support for the current guardians of NUS, and establish NUS capacity-building and indigenous knowledge systems.

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Supplementary material:

- a. <https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2024.1498402/full#supplementary-material> (Access: 2026/03/10)

CHAPTER 3: UNDERSTANDING CLIMATE RISKS FOR WATER AND AGRI-FOOD SYSTEMS: IMPLICATIONS FOR SMALLHOLDER FARMERS

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3.1. Abstract

South Africa (SA) is projected to become warmer and drier, with increasing frequency and intensity of extreme climatological and hydrometeorological events. The changing climate affects the agri-food systems, compounds water insecurity, and impacts socio-economic and environmental systems. This study analyses climate risks on water and agri-food systems in three provinces, representing three Hydro-Climatic Zones (HCZs) of SA. The study used the Climate Moisture Index (CMI) to assess water stress and the Thermal Heat Index (THI) to identify heat stress across different HCZs and time periods. Projected rainfall and air temperatures for the present (1960-1990), near future (2015-2044), and distant future (2070-2099) time horizons were used to compute the CMI and THI. More severe changes in the CMI and THI, indicative of drier, hotter climates, are observed in HCZ 1. The results indicate a heterogeneous decrease in rainfall across the study sites alongside distinct increases in temperatures. These conditions indicate an increasing likelihood of water and heat stress, which will exceed the optimal thresholds for crops. Understanding the severity of climate risks is critical to mitigating their impact on socio-ecological and agri-food systems. The study's results highlight the need for context-specific, transformative adaptive strategies. Simplifying crop stress indices and prioritising the adoption of crops with high thresholds to water and heat stress will support sustainable natural resource management and strengthen the resilience of agri-food systems, particularly in marginalised environments.

Keywords: adaptation, vulnerability, natural resource management, heat stress, water stress, resilience

3.2. Introduction

Climate change exacerbates extreme events, affects agri-food systems, and compounds water risks across Sub-Saharan Africa (SSA), a region identified as a hotspot for climate-related vulnerabilities and risks (Edokpayi et al., 2020; Nhemachena et al., 2020; Engelbrecht et al., 2024). Climate change manifests as pronounced rainfall variability, rising temperatures, and other extreme weather events, a combination of the most limiting factors for food and water security, socio-economic and environmental systems in the region at large (Engelbrecht et al., 2015; Nhemachena et al., 2020; Edokpayi et al., 2020; Ayanlade et al., 2022; McBride et al., 2022; Nhamo et al., 2024; Nyoni et al., 2024; Touch et al., 2024). SSA's vulnerability is further exacerbated by widespread poverty, limited adaptive capacity, and an extensive reliance on rainfed farming systems, particularly among marginalised smallholder farmers, exposing them to pronounced disruptions (Davis-Reddy & Vincent, 2017; Ogundeji, 2022; Sikhwari *et al.*, 2022; Ncoyini *et al.*, 2022; Okolie *et al.*, 2023; Zenda, 2024; Johnston *et al.*, 2024).

Recent research indicates that between 2014 and 2023, climatological and hydrometeorological extremes, including record-breaking global temperatures, intensified storms, floods, droughts, and heatwaves, have become more frequent, worsening environmental and livelihood crises in the region (Davis-Reddy and Vincent, 2017; Ayanlade et al., 2022; Gosset et al., 2023; Franchi et al., 2024; Rouault et al., 2024; NOAA, 2024; WMO, 2024). Despite agriculture and water sectors being central to food security, livelihood, and economic stability in SSA, underdevelopment and climate-related stressors have weakened their performance, impacting over 33 million smallholder farmers who provide 70% of the region's food supply (Mabhaudhi et al., 2018; Bjornlund et al., 2020; Ringler et al., 2022; Kapari et al., 2023; Maguire, 2024). Given that 95% of agriculture in the region is rainfed, sustainable natural resource management and climate-resilient strategies are essential for reducing risks and safeguarding the well-being of both humans and the natural environment (Biazin et al., 2012; Nhemachena et al., 2020; Nyoni et al., 2024).

Alongside the pronounced susceptibility to high potential evapotranspiration, South Africa (SA) is characterised by spatial rainfall variability and faces unprecedented hydrometeorological and climatological extremes with significant impacts (Edokpayi et al., 2020; Du Preez and Van Huyssteen, 2020; Scholes and Engelbrecht, 2021; McBride et al., 2022; Engelbrecht et al., 2024; Nhamo et al., 2025). The country is classified as semi-arid to arid, with common occurrences of dry spells and droughts that are often reinforced by the El Niño, primarily in the western parts (Rouault et al., 2019; Botai et al., 2021; Chikoore and Jury, 2021; de Perez et al., 2024; Letswamotse et al., 2024; Opiyo et al., 2025). While these occurrences can be linked to specific weather and climatic phenomena, they are increasing in frequency and intensity (Letswamotse et al., 2024; Opiyo et al., 2025). Drought and dry spells have immeasurable consequences for

water resources, water quality and availability, and, in turn, agricultural production and productivity, as well as socio-economic and environmental sectors in the country (Scholes and Engelbrecht, 2021; DWS, 2024; Opiyo et al., 2025).

SA is also prone to localised flooding due to the increasing frequency of extreme rainfall events (McBride et al., 2022; de Perez et al., 2024; DWS, 2024). The eastern side of the country, along the Indian Ocean, frequently experiences flash flooding and extreme rainfall events (Mashao et al., 2023; Moses et al., 2023; Eloff, 2024; Stoddard, 2025), especially in the recent decade. These typically occur in late summer-early autumn and are often associated with rain-bearing pressure systems such as the cut-off low and La Niña (Rouault et al., 2019; Mashao et al., 2023; Moses et al., 2023; de Perez et al., 2024; Stoddard, 2025). Extreme rainfall events are further projected to increase in frequency and intensity in some localities in South Africa (McBride et al., 2022).

On the other hand, parts of the country are projected to become warmer and drier in the future (Scholes and Engelbrecht, 2021; Engelbrecht et al., 2024). However, there is less agreement over the eastern escarpment areas of SA, where some models project increases in total rainfall (Lee et al., 2021). Increases in atmospheric temperatures are linked to the intensification and frequency of both drought and floods (Scholes and Engelbrecht, 2021; McBride et al., 2022; Pizzorni et al., 2024). The frequency and intensity of extreme temperature events, such as heatwaves, are projected to increase in South Africa due to anthropogenic climate change (Scholes and Engelbrecht, 2021; Engelbrecht et al., 2024). On the contrary, cold spells are expected to occur less frequently (Scholes and Engelbrecht, 2021). The increasing warming and aridity in the country will negatively impact people, livestock and crop production, which rely on sensitive temperature thresholds for wellbeing, production, and productivity (Scholes and Engelbrecht, 2021; Engelbrecht et al., 2024).

Extreme weather events pose a significant risk to people and livelihoods by adversely affecting water resources, agri-food systems, environmental sustainability, and socio-economic systems. Together, they compound climate risks for resource-constrained smallholder farmers in marginal and underperforming agri-food systems, and, as a result, poverty and hunger (Harvey *et al.*, 2014; Engelbrecht et al., 2015; Archer et al., 2018; Williams *et al.*, 2018; Giller, 2020; Bjornlund *et al.*, 2020; Scholes and Engelbrecht, 2021; Bjornlund *et al.*, 2022; Engelbrecht et al., 2024; Johnston *et al.*, 2024). Hydrometeorological and climatological extreme events are projected to intensify in SA, which makes addressing these risks a critical developmental and climate action requirement.

Although widespread literature exists on climate risks and their impacts on water and agriculture in SA (Archer et al., 2018; Nhemachena et al., 2020; Meza et al., 2021; Engelbrecht et al., 2024; Johnston *et al.*, 2024; Zenda et al., 2024; Nhamo et al., 2025), most of these studies are conducted at a regional and national level. However, climate risks manifest disproportionately due to varying geographical, social, and

economic vulnerabilities, posing significant risks to local communities, particularly smallholder farmers. This study examines climate risks and their effects on water and agri-food systems among smallholder farmers in selected Hydro-Climatic Zones (HCZs) of South Africa (HCZs 5, 2, and 1, represented by the Eastern Cape, KwaZulu-Natal, and Limpopo provinces). This is achieved by examining projected climate risks and impacts on water and agriculture using the Climate Moisture Index (CMI) and the Thermal Heat Index (THI). The study also explores ways to enhance climate action and adaptation planning to improve water and food security. The study provides insights to inform climate action in the water and agricultural sectors, as well as adaptation planning at appropriate scales.

3.3. Methods

3.3.1 Description of study areas

The study focuses on three HCZS represented by three provinces in SA: HCZs 1, 2 and 5, as detailed in the Department of Water and Sanitation, South Africa (DWSSA, 2022). HCZs are spatial units defined by a combination of factors, including current water-related climate features, such as seasonality, interannual variability, and the magnitude of variables such as rainfall and PET (DWSSA, 2024). They also incorporate projected climate change signals and administrative boundaries (WMAs/municipalities) for water resources planning (DWSSA, 2024). The study reports on Limpopo as HCZ 1, KwaZulu-Natal as HCZ 2 and the Eastern Cape as HCZ 5 (Figure 3.1). The three HCZs exhibit distinct geographical characteristics that contribute to their unique climate and weather patterns, thereby delineating specific climate regions, as noted by Kruger (2004). Their differing characteristics indicate that the HCZs will face distinct, context-specific climate change risks and impacts, requiring tailored mitigation and adaptation measures. Hydrological, meteorological and climatological disasters are becoming a prominent risk to local agri-food systems, food and water security and the environment across the three provinces (Ndlovu *et al.*, 2021; Thoithi *et al.*, 2022; Sikhwari *et al.*, 2022; Mudefi, 2023). Since climate change impacts are multifaceted, they require context-specific solutions that strengthen localised coping and adaptation strategies (Braunschweiger and Ingold, 2023).

All HCZs experience specific wet, warm, dry, and cooler periods, corresponding to the summer and winter seasons. The Eastern Cape (HCZ 5) is a coastal province located in the southern bound of the KwaZulu-Natal province, on the eastern south-central side of SA. The province encompasses all seven ecological zones, highlighting the province's extensive climatic and vegetative diversity. The province receives between 300 and 550 mm of rainfall annually, bi-modally (summer and winter). It has daily

maximum air temperatures of up to 40°C in summer and a mean annual temperature of 17.6°C (Botai et al., 2021). KwaZulu-Natal (HCZ 2) is a coastal province occupying the southeastern side of SA along the Indian Ocean shoreline. The province receives approximately 650 mm of annual rainfall in the eastern Grasslands and 900 mm in the central Bushveld, while the Coastal Bushveld receives approximately 1400 mm (Ndlovu et al., 2021). During the austral summer months, from October to March, most rainfall occurs in the province (Rouault et al., 2013; Ndlovu et al., 2021). Limpopo, representing HCZ 1, is located in the northeastern part of SA, bordering Mozambique, Zimbabwe and Botswana. The province is characterised by warm air temperatures throughout the summer season, averaging 27°C but reaching 40°C to 50°C in some localities. The rainfall season in Limpopo begins in early or mid-summer, around mid-December, and lasts an average of four months, with an annual average of 500 mm (Cai et al., 2017; FAO, 2024). The province's annual evaporation ranges from 1600 mm to 2600 mm/year, depending on local temperatures (FAO, 2024).

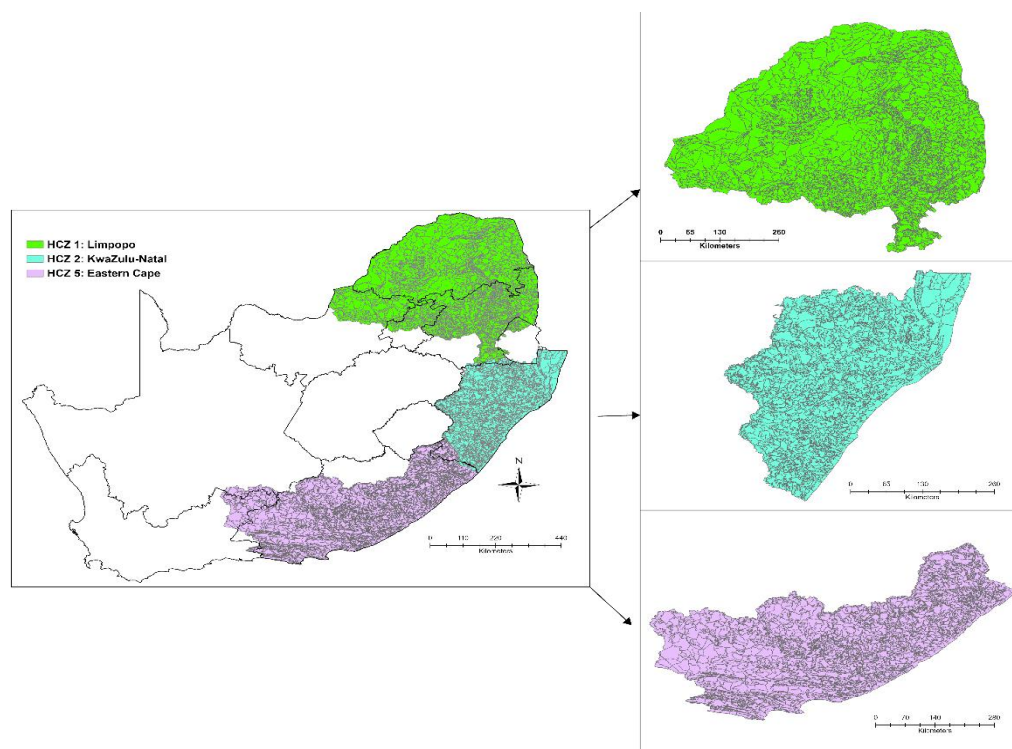


Figure 3.1: Map of the study areas showing Limpopo for HCZ 1, KwaZulu-Natal for HCZ 2 and the Eastern Cape for HCZ 5.

3.3.2. Data acquisition

Climate projections were carried out as part of the Water Research Commission's National Assessment of Potential Climate Change Impacts on the Hydrological Yield of Different Hydro-Climatic

Zones 9 (HCZs) of South Africa (Schütte et al, 2023). The rainfall and air temperature change projections are presented for three periods: the present (1960-1990), near future (2015-2044), and distant future (2070-2099). These changes are projected using an ensemble of six different computational Global Climate Models (GCMs): the ACC, CCS, CNR, GDF and MPI (table 3.1), at quaternary catchment resolution. The projections were forced by the low mitigation scenario (RCP 8.5), and downscaled using the regional climate model, the Conformal Cubic Atmospheric Model (CCAM) from CSIRO. The CCAM has locally calibrated physics options for SA and is a flexible and unified downscaling system. The chosen pathway, the RCP 8.5, remains the most feasible and realistic pathway for producing results that reflect the sensitivity of different systems beyond the mid-century. The projections were bias-corrected against historical observed data from 1961 to 1999 following the Quantile Delta Mapping method (Cannon *et al.*, 2015; Schulze *et al.*, 2023).

Table 3.1: Details on the six GCMs used in this study.

Abbreviation	GCM details
ACC	Australian Community Climate and Earth System Simulator (ACCESS1-0)
CCS	Community Climate System Model (CCSM4)
CNR	National Centre for Meteorological Research Coupled GCM v5 (CNRM- CM5)
GFD	Geophysical Fluid Dynamics Laboratory Coupled Model (GFDL-CM3)
MPI	Max Planck Institute Coupled Earth System Model (MPI-ESM-LR)
NOR	Norwegian Earth System Model (NorESM1-M)

3.3.3. Indices

Areas with more sensitivity to heat and water stress were identified through an assessment done using the THI and CMI. The two indices were better suited as proxies of moisture and heat stress in long-term projections for this study.

3.3.3.1. Climate Moisture Index (CMI)

The study uses the Climate Moisture Index (CMI) to assess moisture conditions, a key indicator of aridity (water stress and degree of aridity or wetness), across the study areas over different time periods. The index, as highlighted in Vörösmarty et al. (2005), Nhamo et al. (2019 and Nhemachena et al. (2020), assesses the ratio of annual precipitation (P) to annual Potential Evapotranspiration (PET).

$$CMI = 1 - \left(\frac{PET}{P}\right)$$

when there is more precipitation than PET or P=PET

while

$$CMI = \left(\frac{P}{PET} \right) - 1$$

when there is more PET compared to precipitation

PET was substituted for Actual Pan Evaporation (APAN) in this study, making our equations:

$$CMI = 1 - \left(\frac{APAN}{P} \right)$$

when there is more precipitation than APAN or P=APAN

while

$$CMI = \left(\frac{P}{APAN} \right) - 1$$

when there is more APAN compared to precipitation

CMI values range from -1 to +1. Positive values of the CMI suggest that the study site has a wetter climate with sufficient precipitation for healthy vegetation (Vörösmarty et al., 2005). Negative CMI values, on the other hand, indicate drier conditions and are often seen in arid/semi-arid environments (Vörösmarty et al., 2005). The CMI for each HCZ was calculated using data from a WRC study (Schütte et al., 2023). The results were interpolated in ArcGIS Pro 3.0.0 to create visual representations of the CMI results. The CMI results for three time periods are presented as: the present (1960- 1990), near future (2015- 2044), and distant future (2070- 2099).

3.3.3.2. Thermal Heat Index (THI)

The study used the Thermal Heat Index (THI) to assess potential heat stress in agricultural crop production across the study sites using the following equation:

$$THI = 0.8 * T + RH * (T - 14.4) + 46.4$$

Where T is the maximum temperature (in °C), and RH is the relative humidity. RH is expressed as a decimal (e.g., 75% humidity is 0.75). Temperature data used for the computation of the THI were generated from an ensemble of six GCMs: ACC, CCS, CNR, GDF and MPI for three time periods: the present (1960- 1990), near future (2015- 2044), and distant future (2070- 2099). The results were interpolated in ArcGIS

Pro 3.0.0 to create visual representations of the THI outputs. Du Preez et al. (1990), Nesamvuni et al. (2012) and Mpandeli et al. (2019) define the different categories of heat stress as (Table 3.2):

Table 3.2: Categories of the THI classes.

THI	Classification
<72	No heat stress
72-78	Mild heat stress
78-89	Severe heat stress
89-98	Extreme heat stress
>98	Death

3.3.3.3. Analysis of data

The mean annual precipitation results are presented in two forms: relative (%) change and absolute (mm) change approaches, as defined by Baker and Huang (2012). The changes in precipitation and air temperature were projected as an ensemble of six different GCMs. They were forced by a low mitigation scenario (RCP 8.5) across 5838 sub-catchments in South Africa. Changes in rainfall and air temperature were projected for the present (1961-1990) to the near future (2015-2044) and from the present (1961-1990) to the distant future (2070-2099) at a Quaternary Catchment resolution scale.

3.4. Results

3.4.1. Overview of projected changes in annual precipitation across the three HCZs at a quaternary catchment resolution

3.4.1.1. Limpopo - Hydro-Climatic Zone 1

Projected absolute changes (mm) in mean annual precipitation show subtle changes in Hydro-Climatic Zone 1, represented by Limpopo, across two time periods: present to near future and present to distant future. Variations between <20 mm absolute change and 100-200 mm reduction are observed across Limpopo in the present-to-near-future simulations, while variations ranging from >20 to 50-100 mm increase are observed in the present-to-distant-future simulations (Figure 3.2). Relative changes (%) predominantly show reductions of 5-10% and 10-20%, except in some areas where changes of more than 5% are expected over

the present-to-near-future timelines. Similar results are observed across the present-to-distant-future timelines, except in some areas on the northeastern side of the province, where a 10-20% increase is observed at a quaternary catchment resolution.

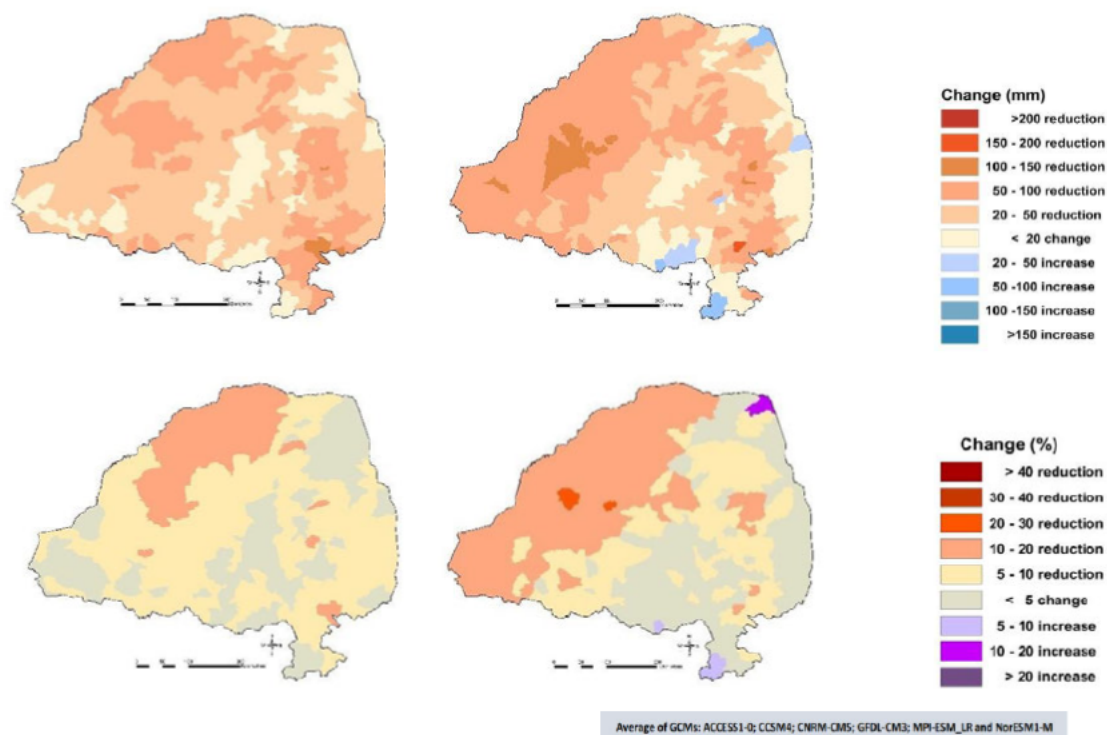


Figure 3.2: Projected changes in absolute (mm) and relative (%) changes in mean annual precipitation for Hydro-Climatic Zone 1 (Limpopo) from the present to the near future [left] and the present to the distant future [right] at a Quaternary Catchment resolution (Schütte et., 2023).

3.4.1.2. KwaZulu-Natal: Hydro-Climatic Zone 2

Projections of absolute (mm) and relative (%) changes in mean annual precipitation for HCZ 2, represented by KwaZulu-Natal, for the present to near future and present to distant future at quaternary catchment resolution are presented below. Projections of absolute changes show predominantly 20-50 mm reduction in much of the province, followed by <20 mm changes and exceptions of a combination of 50-100 mm reductions along the coast and some 20-50, 50-100 mm and 100-150 mm increases inland in the present to near future simulation. Similar results are seen in the present to distant future timelines with an expansion of areas where 20-50, 50-100 mm, and 100-150 mm increases are seen both inland and in the south coast area. Projections for the same time frame show a >150 mm increase in mean annual precipitation across the

Drakensberg region near the border. Projections of relative changes show predominantly <5% change and 5-10% reduction across both timelines. An exception of a 5-10% increase is observed inland towards the Drakensberg areas in the present-to-near-future timelines. Reductions of 10-20% are seen in some areas in the southern inland of the province, while increases of 5-10%, 10-20% and >20% are seen in parts of the Midlands extending towards and in the Drakensberg region (Figure 3.3).

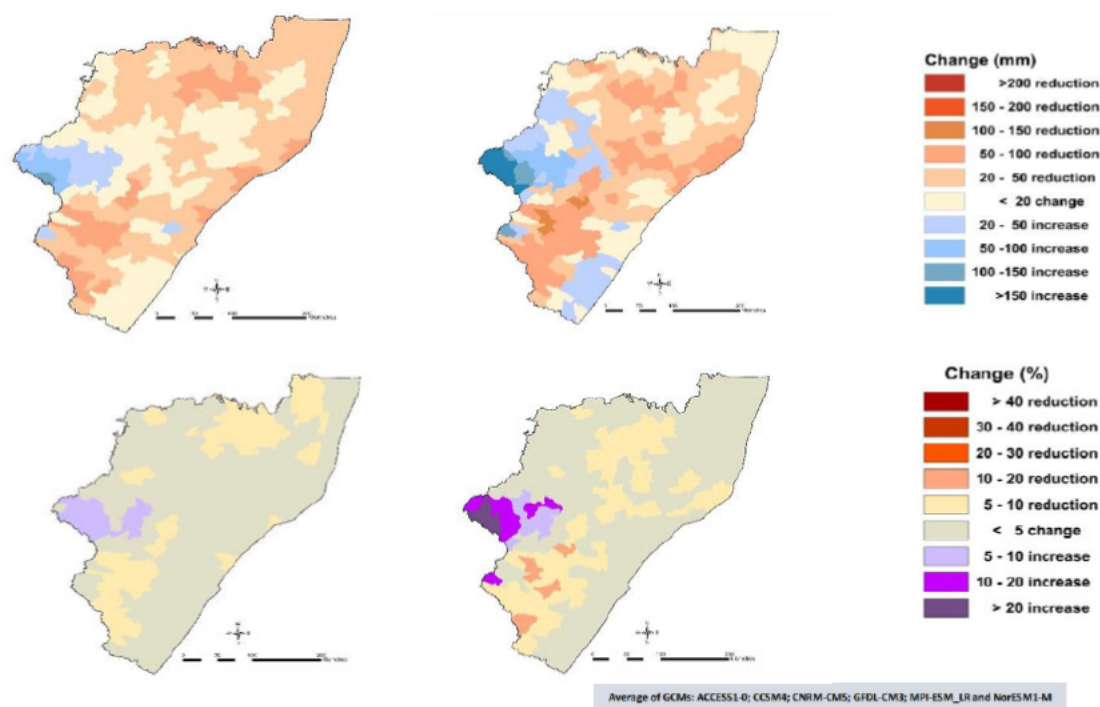


Figure 3.3: Projected absolute (mm) and relative (%) changes in mean annual precipitation for Hydro-Climatic Zone 2 (KZN) from the present to the near future [left] and the present to the distant future [right] at a Quaternary Catchment resolution (Schütte et al., 2023)

3.4.1.3. Eastern Cape: Hydro-Climatic Zone 5

The Eastern Cape (EC) represents HCZ 5. Projected changes (mm) in mean annual precipitation over the present to near-future timeline show <20 mm change in much of the province, with some exceptions: inland areas show a 20-50 mm reduction, while areas near the Lesotho border show a 20-50 mm increase. Increases of 20-50, 50-100 and 100-150 mm inland towards the border are also observed in the present to the distant-future timeline, while <20 mm change, 20-50 and 50-100 mm reductions are seen in much of the province, both inland and coastal areas. An exception is seen along the northern coast of the province towards

the KZN border, where projections show increases of 20-50 and 50-100 mm from the present to the distant-future timelines. Similar patterns are shown in the relative (%) change projection for both timelines. Increases of predominantly 5-10% are seen towards the Lesotho border, while a <5% change is seen in most of the province, with some exceptions of 5-10% reductions in some inland areas in the present to near future timeline. In the present to distant future timeline, <5% changes are predominantly observed across the province, with 5-10% and 10-20% reductions also observed inland. Some cases of 5-10% and 10-20% increases are observed along the Lesotho border, and some exceptions of 5-10% increase are seen in the province's northern coast (Figure 3.4).

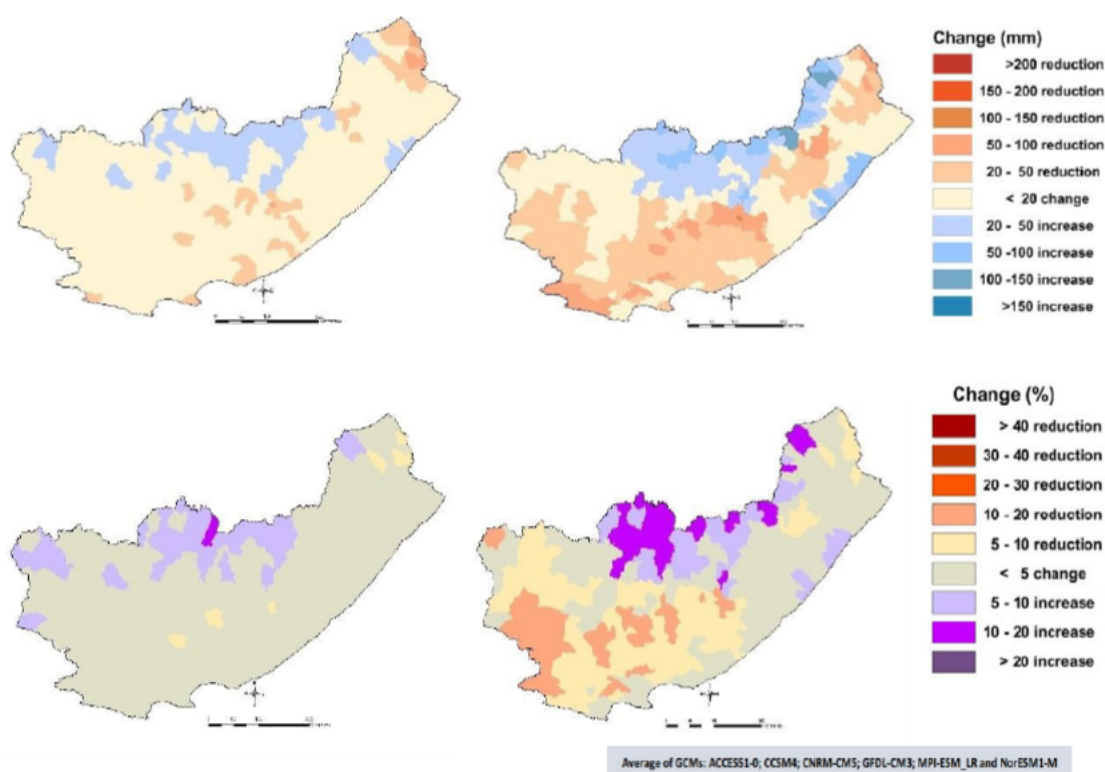


Figure 3.4: Projected changes in absolute (mm) and relative (%) changes in mean annual precipitation for Hydro-Climatic Zone 5(Eastern Cape) from the present to the near future [left] and the present to the distant future [right] at a Quaternary Catchment resolution (Schütte et. al., 2023)

3.4.2. Projected changes in air temperature (Daily Minimum and Daily Maximum) in the three Hydro-Climatic Zones at a Quaternary Catchment Resolution

3.4.2.1. Means of daily minimum air temperatures (Tmin)

Projected changes in the annual means of daily minimum air temperatures (°C) for the present-to near-future timelines were similar across all HCZs, showing increases of 1-2°C (Figure 3.5). For the present-to the distant-future, projected changes in annual means of daily Tmin varied across the HCZs. HCZ 1, across Limpopo, showed increases of 3-4°C and 5-6°C in some localised areas, while increases of 4-5°C were seen predominantly across the climatic zone (Figure 3.5). HCZs 2 (across KZN) and 5 (across EC) presented similar projections of a combination of 4-5°C and 3-4°C increases for the present to distant future timelines. In both HCZ 2 and 5, the more extreme changes (4-5°C) in air temperature are seen in the inland areas, while increases of 3-4°C dominate along the coastline.

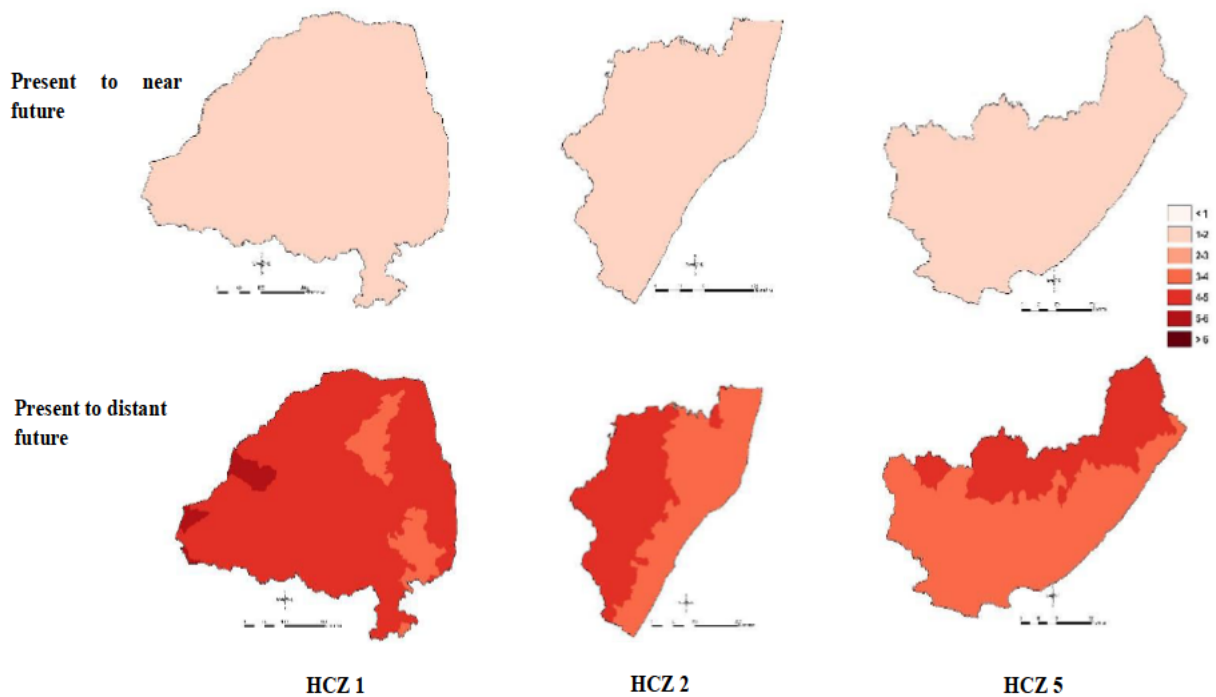


Figure 3.5: Projected changes in annual means of daily Tmin (°C) from the present to near future (top) and the present to distant future (bottom) for three Hydro-Climatic Zones existing in the three study sites presented at a Quaternary Catchment resolution.

3.4.2.2. Means of daily maximum air temperatures (Tmax)

Hydro-Climatic Zone 1, across Limpopo, showed more severe changes in both timelines compared to HCZs 2 and 5, where KwaZulu-Natal and the Eastern Cape, are located, respectively. HCZ 1 showed varied results in both timelines, with daily Tmax increases ranging from 1-2 °C to 2-3 °C in the present-to-near-

future timeline, and more severe changes ranging from 4-5 °C to >6 °C in the present-to-distant-future projections. Subtle changes are seen in HCZ 2 in the present to near-future timeline, while more severe changes ranging from 4-5°C to 5-6°C are seen in inland areas, and changes of 3-4°C are seen along the coastline in the present to distant-future timeline. Similar to HCZ 2, changes of 1-2°C are observed in HCZ 5 over the present-to-near-future timeline. Present to distant future projections in HCZ 5; however, show mixed results indicating moderate changes of 2-3°C and 3-4°C along the coastal areas and more severe changes ranging between 4-5°C and 5-6°C inland, with more severe changes towards the Lesotho border along the Drakensberg region (Figure 3.6).

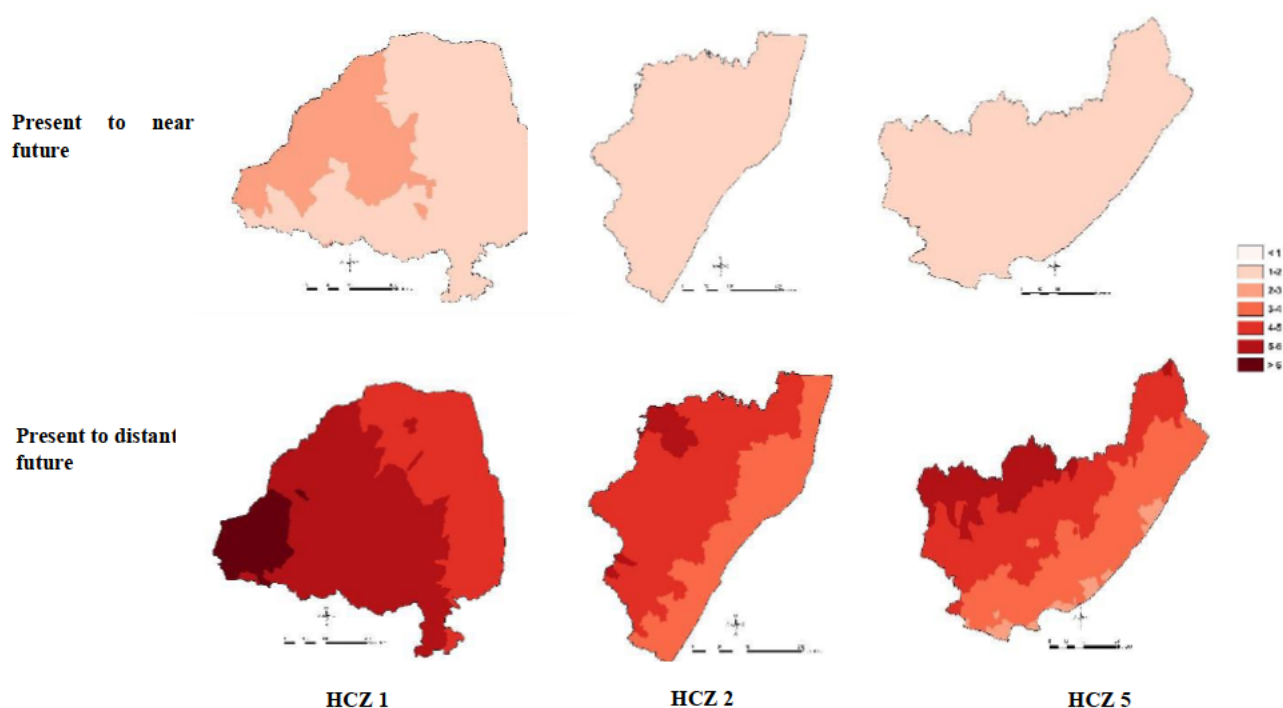


Figure 3.6: Projected changes in annual means of daily Tmax (°C) from the present to near future (top) and the present to distant future (bottom) for three Hydro-Climatic Zones existing in the three study sites presented at a Quaternary Catchment resolution.

3.4.3. Climate risks: CMI and THI

The CMI and THI were computed to assess the degree of aridity, moisture availability and heat stress across the HCZs (Du Preez et al., 1990; Vörösmarty et al., 2005; Nhamo et al., 2019). We present the CMI and THI results across three timelines: the present (1960- 1990), near-future (2015- 2044), and distant-future (2070- 2099). The CMI results are presented as relative changes (mm) and absolute changes (mm). Results

for the CMI and THI are projected using an ensemble of 6 GCMs, forced by a low mitigation scenario (RCP 8.5). The positioning of all the HCZs in different geographical locations and climatic regions contributes to their susceptibility and vulnerability to specific spatio-temporal climate risks. CMI values range from -1 to +1, with aridity indicated by negative CMI values and moisture availability indicated by positive CMI values in specific climates (Vörösmarty et al., 2005).

3.4.3.1. Climate Moisture Index (CMI):

The selected study sites were primarily associated with negative CMI values in the present timeline. The CMI values averaged -0,62, -0,66 and -0,69 mm, respectively, across the present-, near- and distant-future across the study sites, indicating that the sites are generally dry. HCZ 5 showed outliers, with both the highest (CMI Max) and lowest (CMI Min) CMI values within a single hydro climatic zone. CMI max values across the study sites were +0.168, +0.103, and -0,008, respectively, across the timelines, and were found in inland HCZ 5 (positive values) and HCZ 2 (negative values) Sub-Catchments 4573 and 4840 (Figure 3.6). CMI min values, also found within the same zone, ranged from -0,929; -0,932 to -0,949 mm from the present-, near- and distant-future, progressively increasing towards the 21st century (Figure 3.7). The distribution and variability of the CMI within and across the HCZs are distinct. However, the degree of moisture availability progressed negatively (CMI -) in all HCZs, with the present period exhibiting higher moisture availability.

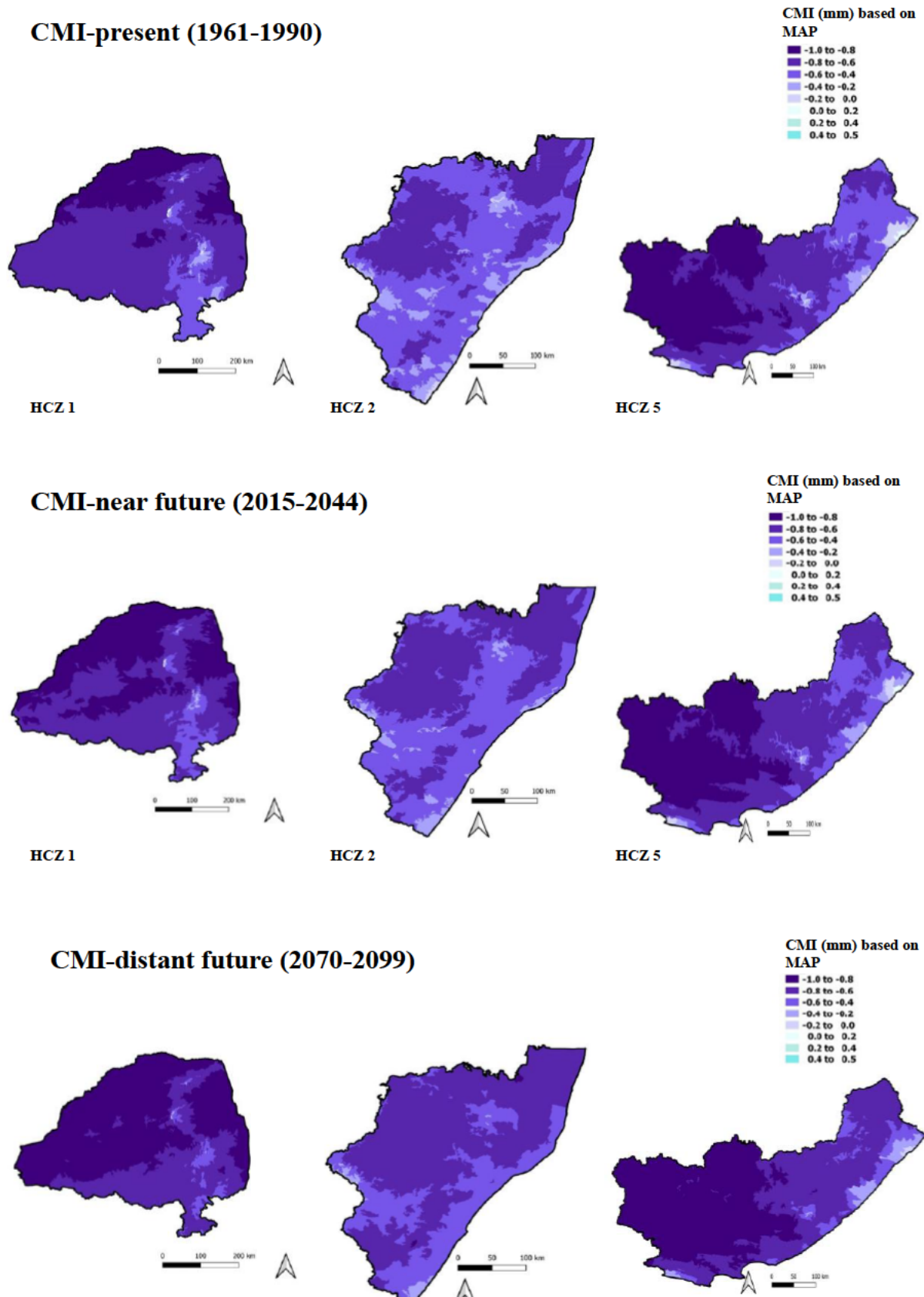


Figure 3.7: Projected change in Climate Moisture Index (CMI) across the present, near future and distant future timelines in HCZs 1,2 and 5.

a. Projected absolute change in CMI

Projected absolute changes in CMI follow a similar trajectory to those of projected relative changes across the present-to-near-future and present-to-distant-future timelines. Moisture availability is projected to decrease drastically within and across the HCZs. The CMI values averaged -0.0357 in the present-to-near-future projection and -0.0764 in the present-to-distant-future timelines, exhibiting a -0,0407 change towards more aridity. CMI max values were higher in HCZ 5 (0,0148; SubCat 3635) in the present-to-distant-future projections and in HCZ 2 (SubCat 4840) in the present-to-distant-future projections (0,0429). CMI min values, found in HCZ 1 (SubCats 5427 and 5767), ranged from -0,1299 in the present-to-future projection to -0,2606 in the present-to-distant-future projection, indicating increasing aridity with increasing CMI values (Figure 3.8).

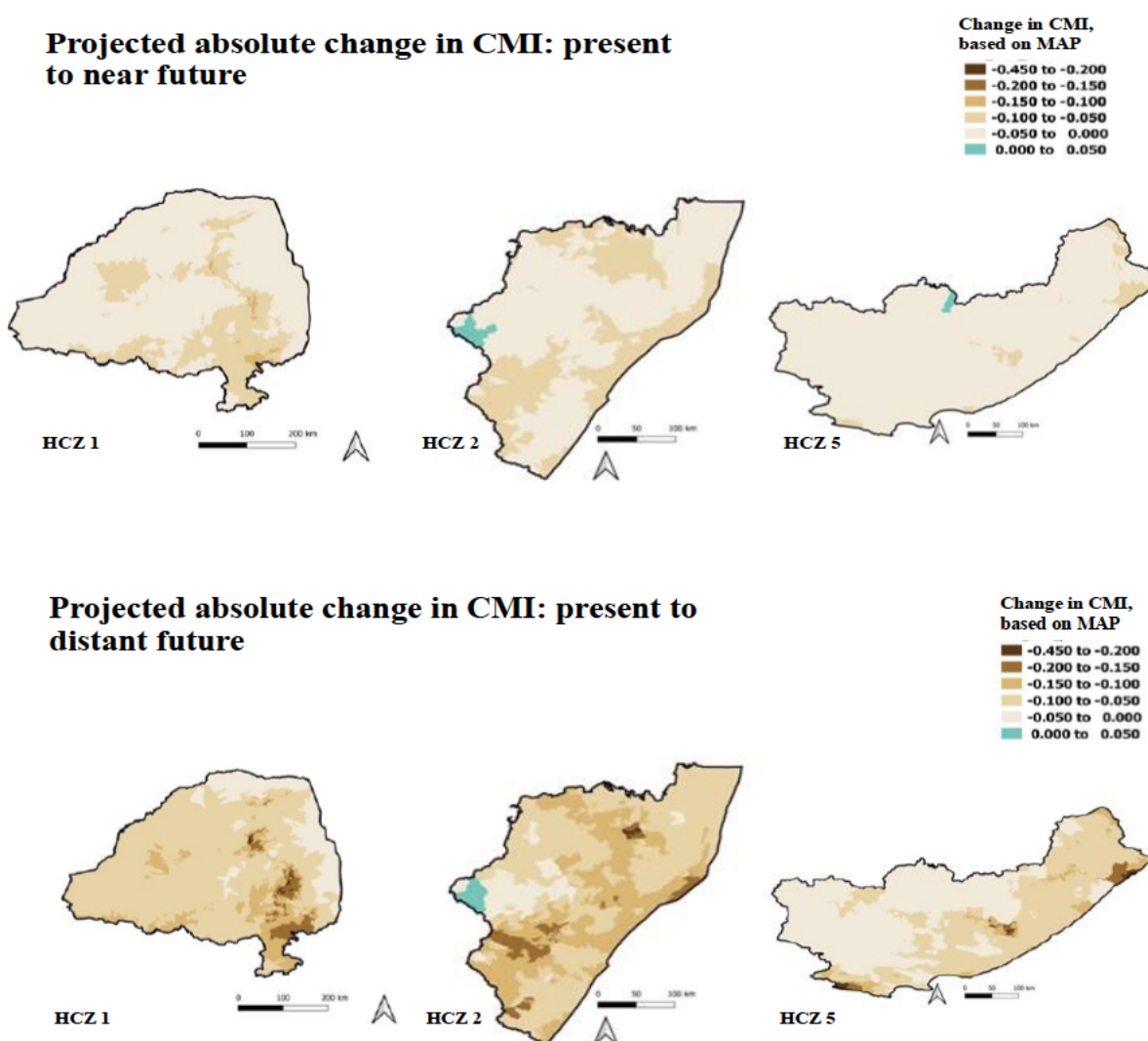


Figure 3.8: Projected absolute changes in the CMI in the present to near future and present to distant future timelines across HCZs 1,2 and 5.

3.4.3.2. Thermal Heat Index (THI)

b. Present timeline (1961-1990)

Projections of heat stress under present climate conditions (1961-1990) indicate varying and uneven heat stress across the study sites. Mild and severe heat stress (mean THI: 71,62 and max THI: 79,73) was prominent in HCZ 1 under present climate conditions. Under the same conditions, the projections indicated largely mild to no heat stress in HCZ 2, with exceptions of very localised severe heat stress (THI max: 78,68) in northern KwaZulu-Natal (KZN) towards the borders with Eswatini and Mpumalanga. Projections for HCZ 5 indicated primarily no heat stress in the area under present climate conditions, with a mean THI of 70,90 and THI max of 76,22, indicating some mild heat stress in primarily inland areas in the region, with some exceptions along the coastline (Figure 3.9).

THI- present (1961-1990)

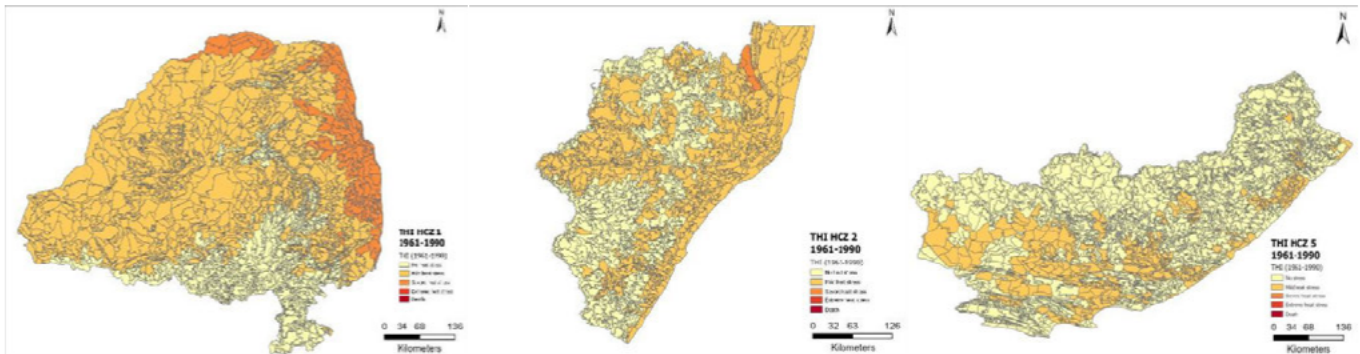


Figure 3.9: Projected THI in the present timeline.

c. Near future timeline (2015-2044)

In the near-future timeline, projections indicate varying increases in heat stress across the HCZs. Mild to severe heat stress is projected in HCZ 1, with a THI max value of 81,61 and an increased mean THI of 75,61, an increase of 3,99 (5.57%) relative to the present timeline mean. In the same timeline, projections indicate that predominant mild heat stress will be experienced in HCZ 2, peaking at THI max 79,90, with an

average THI of 73,20. More severe heat stress also exists in the northern parts of KZN, bordering Eswatini, Mpumalanga, and Mozambique, as well as in some isolated coastal areas. Primarily, mild heat stress is indicated by projections for HCZ 5, both inland and along the coast. The THI max for the near-future timeline in this HCZ is 77,55, while the average is 71,58, indicating the lowest THI among all HCZs studied (Figure 3.10).

THI-near future (2015-2044)

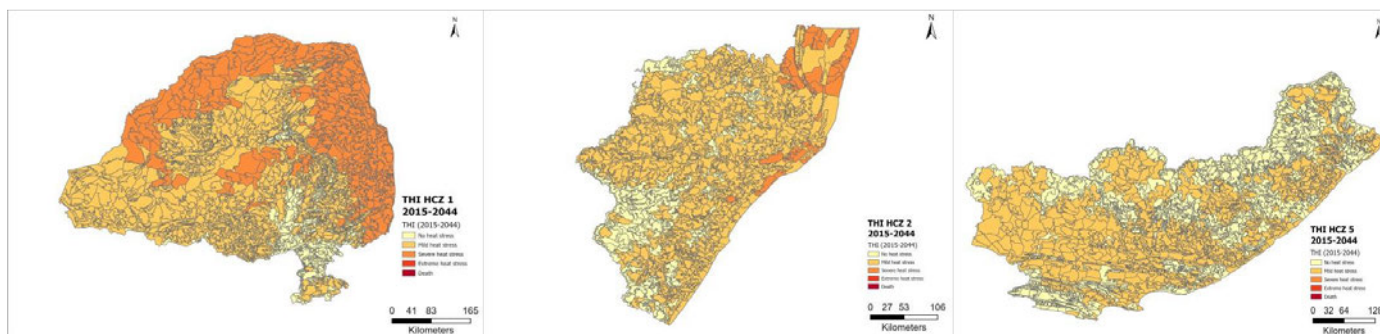


Figure 3.10: Projected THI in the near future timeline.

d. Distant future timeline (2070-2099)

The distant-future projections indicate increasing heat stress across all study areas. Severe heat stress is indicated prominently across HCZ 1. The THI max in this area under this timeline peaks at 83,25, and the average THI across the region is 78,91. HCZ 2 projections also signal increasing mild and severe heat stress in the region. The mean THI in HCZ 2 under this timeline is projected at 76,68, while THI values peak at 82,12. Projections for HCZ 5 also indicate increasing mild heat stress across the region. The mean THI in the region under the distant future timeline is 74,41, while the maximum THI is 79,93, indicating severe heat stress in specific isolated localities within the same HCZ (Figure 3.11).

THI-distant future (2070-2099)

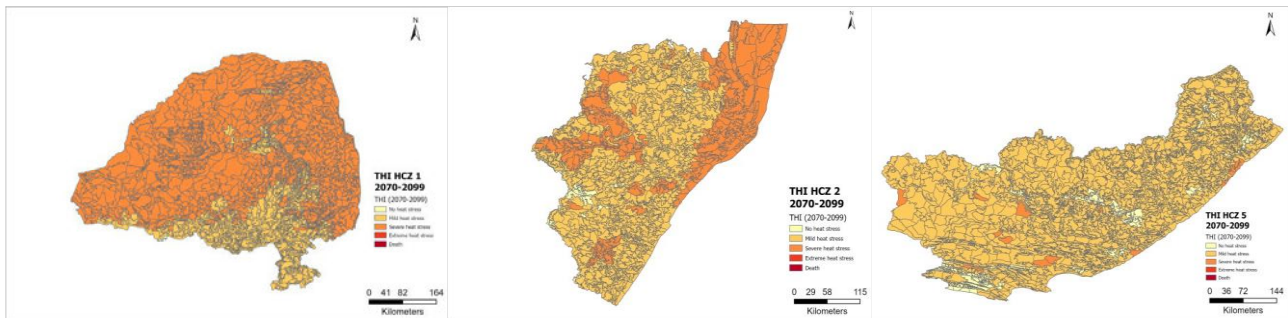


Figure 3.11: Projected THI in the distant future timeline.

3.5. Discussion

Water and crop production challenges are among the major outlets through which climate change impacts will manifest, particularly in water-scarce environments such as SA. However, the degree of climate-driven impact will differ. Recent evidence, such as that by Rouault et al. (2024) and Engelbrecht et al. (2024), highlights variations in the degree of changes in rainfall and air temperature regimes across SA. Rouault et al. (2024) further highlight the increasing influence of localised pressure systems and natural climate patterns, such as the ENSO phenomenon, on interannual variability and the onset and demise of the rainfall season. Over the past decade, the country has been subject to increasing extreme weather events, changes in rainfall distribution and variation and altered air temperatures (Ndlovu et al., 2021; McBride et al., 2022). All these changes have presented and exacerbated challenges within agri-food systems, including risks related to heat, water, and food and nutrition, particularly in smallholder farming systems (Du Preez and Van Huyssteen, 2020; Mirzabaev et al., 2023).

3.5.1. Rainfall and air temperature

Limpopo(HCZ 1) is among the driest provinces in the country (Phophi *et al.*, 2020; Maposa *et al.*, 2021; Matimolane et al., 2024; Nhamo et al., 2025) with a high risk of dry spells and droughts (Phophi *et al.*, 2020; Maposa *et al.*, 2021; Matimolane et al., 2024; Nhamo et al., 2025). Projected reductions in rainfall in Limpopo (Figure 3.2) indicate that intensifying dry spells and droughts will likely undermine water availability and crop productivity. In the absence of appropriate coping and adaptation strategies, this will negatively impact smallholder farmers' livelihoods and food and nutrition security outcomes. Changes in mean annual precipitation in HCZ 2 across KZN (Figure 3.3) are consistent with findings by Engelbrecht et

al. (2024), highlighting that rainfall increases are projected in some parts of the province. A study by Ndlovu *et al.* (2021) also projected a decrease in annual rainfall days along the KZN coastline, while an increase in rainy days was seen in parts of central KZN. This aligns with the study's results, which highlight the degree of variability in the rainfall regime across the KZN climatic zones. Under HCZ 5, projections for the Eastern Cape also showed mixed rainfall trends, indicating a combination of rainfall reduction and increases across the two timelines, with unclear changes and increasing rainfall reduction primarily in the inland parts of the province (Figure 3.4)

Projected means of minimum (Tmin) and maximum (Tmax) daily air temperatures systematically increase across all HCZs, indicating a clear warming trend in future climates. More extreme changes in Tmax from the present to near-future and present to distant-future timelines were observed in HCZ 1 (Limpopo), followed by HCZ 5 (Eastern Cape) (Figures 3.5 and 3.6). Limpopo is already at a heightened risk of heat waves and heat stress (Phophi *et al.*, 2020; Maposa *et al.*, 2021). The projected changes indicate a potential increase in both the intensity and frequency of heat-related disasters in this region. However, the overall study's objective of focusing only on mean annual precipitation and mean Tmin and Tmax is limited and risks overlooking the dynamics of extreme weather events across all HCZs. Both in their increasing frequency and intensity (Engelbrecht *et al.*, 2024; Jubase and New, 2025; Nhamo *et al.*, 2025), extreme rainfall and temperature events drive some heat and water stress in agricultural production and risks to socio-ecological systems.

3.5.2. Water and heat stress indicators: Climate Moisture Index (CMI) and Thermal Heat Index

South Africa is a water-scarce country with a semi-arid climate and is characterised by high potential evapotranspiration, which poses a great threat to agricultural productivity and production under rainfed conditions (Du Preez and Van Huyssteen, 2020; Bonetti *et al.*, 2022). The CMI and THI were computed to examine heat and water stress in agriculture across 1961-1990, 2015-2044, and 2070-2090 time periods in three HCZs. The application of the CMI and THI indices in the context of agricultural crop production ensures a multi-perspective link of agro-climatology indicators under climate change to improve food production and agri-food systems productivity in SA.

3.5.2.1. Degree of moisture availability and aridity: Climate Moisture Index (CMI)

The mean annual CMI for the chosen study sites ranges between -0,623 in the present timeline, -0,659 in the near-future and -0,700 in the distant-future timelines. The minimum CMI values across the study

sites range from -0,929 in the present timeline to -0,932 and -0,949 in the near and distant-future timelines, respectively (Figures 3.6 & 3.7). The CMI values vary spatially and temporally across the three HCZs. However, they are primarily negative across the HCZs across all timelines, indicating moisture scarcity at the selected study sites. However, water scarcity and availability vary due to intra-annual rainfall variability, which means moisture availability also varies within and across the study sites. Despite this, Vörösmarty et al. (2005) classify CMI values into five distinct categories: $CMI < -0.6$ is considered arid; $-0.6 < CMI < 0$ signifies semi-arid; $0 > CMI < 0.25$ is classified as sub-humid, and $CMI > 0.25$ denotes humid. In this context, the results suggest that our study sites are characterised by increasingly arid to semi-arid climates (Nhamo et al., 2019).

Decreasing CMI values may trigger natural feedback, such as soil degradation, reduced vegetation cover, changes in crop suitability, and challenges to the long-term productivity of agri-food systems across the study sites (Nhemachena et al., 2020; Furtak and Wolińska, 2023). The spatial heterogeneity in CMI trends across the study sites underscores a growing need for context-specific interventions in natural resource use and management. For example, decreasing CMI values, particularly in inland HCZ 5 in the Eastern Cape, which is projected to be at increased risk of day-zero-type droughts (Archer et al., 2022; Engelbrecht et al., 2024), indicate increasing aridity in the region and a need for water-adaptation plans. Similarly, the decreasing CMI values across the three timelines in HCZ 1, under which Limpopo falls, as expected, indicate increasing widespread aridity in the region under future climates and emphasise a need for context-specific adaptation plans, particularly since Limpopo is among the driest and drought-prone provinces in SA (Matimolane et al., 2024; Nhamo et al., 2025). In areas as arid as the chosen study sites, agri-food systems, which are primarily rainfed, need progressive interventions to sustain agricultural production under increasing aridity (Mpandeli et al., 2019; Nhemachena et al., 2020).

3.5.2.2. Degree of Heat Stress

The THI results indicate increasing heat stress spatially and temporally across the study sites (Table 3.3/Figures 3.9-3.11). Heat stress severity is primarily observed in HCZ 1 across the study sites, while the least heat stress is observed in HCZ 5. This corresponds with previous studies such as Archer et al (2021) and Jubase and New (2025), which highlighted that Limpopo is among the region's most vulnerable to temperature extremes and heat stress in SA. Heat stress in KwaZulu-Natal is predominantly mild, with increasing severity from the present- to the distant-future. The increasing heat stress alongside rainfall reduction in Limpopo (HCZ 1) suggests compounding climate stress in the region, which will have a negative impact on socio-ecological and agri-food systems, and natural resource availability, underscoring a need for

intentional climate risk assessments and water and heat adaptation strategies (Engelbrecht et al.,2024; Jubase and New., 2025). An urgent need for adaptation planning also applies to HCZs 2 and 5, although projected changes do not exhibit the same extremes as those in HCZ 1. Ensemble and scenario uncertainties could oversimplify the projected spatial variabilities in the regions, and the study overlooked the probability of extreme weather events within the given timelines.

Table 3.3: Summary of THI Max in the HCZs across three timelines.

Risk Category	Timeline	HCZ 1	HCZ 2	HCZ 5
Heat stress: THI	1961-1990	79,73	78,61	76,22
	2015-2044	81,01	79,9	77,55
	2070-2099	83,75	82,12	79,85

3.5.2.3. The application of the THI in agricultural crop production

The THI index combines air temperatures and relative humidity to quantify heat stress. However, linking the THI to agricultural crop production is unconventional. The index is often linked to livestock production (Du Preez et al., 1990; Nesamvuni et al., 2012; Mpandeli et al, 2019). However, crops also have temperature thresholds and can experience both heat and water stress (Mugiyo et al., 2021; Nzimande et al., 2025); therefore, the index can be applied in crop production. Both heat and water stress affect crop phenology and yield, thereby influencing the productivity, particularly under rainfed conditions (Hatfield and Prueger, 2015; Nzimande et al., 2025).

Thermal indices, such as the THI, can play a crucial role in agricultural crop production by providing accurate, simplified forecasts throughout crop development. This can safeguard crop production under short-term weather and long-term climate scenarios and serve as a decision-support tool, strengthening coping and adaptation strategies and building resilience. Indices such as the THI can be adapted to crop-specific physiological thresholds for anticipating potential heat stress and related losses, and crop-calibrated THI thresholds can indicate heat stress across different seasons. For example, integrating crop-calibrated THI with remote sensing and real-time weather feeds offers an easy platform for real-time stress management in water-scarce environments.

Although THI is a straightforward index, due to crop-specific heat and water thresholds and additional requirements (Nzimande et al., 2025), it may lack sufficient sensitivity. However, these crop-specific thresholds can be developed and identified on platforms such as AquaCrop ([FAO|AcquaCrop](#)) to define the onset and tipping points of heat-stress risk in warming environments. This can also improve the model’s sensitivity to predicting the impact of extreme heat on crop production. Following the identification of crop

thresholds, crop-sensitive THI classifications can be utilised, enabling the accurate application of THI to crop production as a straightforward, cost-effective method for measuring temperature stress.

3.5.2.4. Implications for crop production

Due to climate change, air temperatures are increasingly likely to exceed optimal thresholds for crop growth (Hatfield and Prueger, 2015), directly impacting crop productivity and, by extension, human and environmental health. The study projected increasing THI values and moisture scarcity, indicating potential heat and water stress, which will pose undeniable challenges for crop production across the study areas. Studies such as those by Chapman et al. (2020) and Chemura et al. (2022) have highlighted that coupled water and heat stress lead to ecological shifts that enforce changes in crop species distribution and suitability.

Mainstream crops, specifically, are becoming increasingly unsuitable under these changing environments across broader Sub-Saharan Africa, including SA (Chapman et al. 2020). However, neglected and underutilised crops (NUS) have proven to be heat- and water-stress-adapted and to have higher temperature and water-stress thresholds than mainstream crops (Mabhaudhi et al., 2017; Nzimande et al., 2025). Under environments marked by increasing aridity and temperature stress, such as those in this study, NUS gain competitive advantage and offer a sustainable solution to building resilient agri-food systems through improving diversity and derisking rainfed agri-food systems (Mabhaudhi et al., 2017; Mugiyo et al., 2021, Ndlovu et al., 2024). However, realising the full potential of NUS requires overcoming significant socio-economic and institutional barriers (Ndlovu et al., 2024). To leverage NUS strategically as a resilience strategy, it is crucial to integrate climate risk research with agri-food systems and crop production, as well as breeding and agronomy research, policy, market support, and extension services, to position them as a plausible adaptation strategy within local agri-food systems under current and projected climatic conditions.

3.6. Study recommendations: improving adaptation planning for improved water and food security

The findings of the study underscore the importance of context-specific adaptation planning informed by climate risk assessments. The authors recommend the following:

- **Integration of climate-risk assessments and social-vulnerability research to identify and prioritise areas that are vulnerable to food and nutrition insecurity:** In areas vulnerable to water stress and food insecurity, there is an urgent need to develop localised climate-risk overlay maps that incorporate

projected CMI and THI outputs with high-resolution food insecurity data. The maps would enable visual identification and prioritisation of the most vulnerable food insecurity hotspots requiring immediate transformative adaptation.

- **Development of crop-calibrated THI thresholds:** The application of the THI to crop production could be a straightforward and economical tool to measure crop temperature stress. However, to get to that point, future research is needed to develop crop-calibrated THI thresholds using crop-specific physiological data for priority crops, which could help address the food insecurity pandemic in the country and beyond. This action would transform the THI into a practical and sensitive tool for risk detection and management in crop production.

- **Transformative adaptation:** Adaptive planning and policies at national and provincial levels need to promote climate-informed transformative adaptation frameworks and strategies to climate action and adaptive planning instead of reinforcing incremental adaptation measures. This entails, for example, adopting locally adapted risk-detection tools and water-efficient crop species in local agri-food systems to sustainably improve natural resource management and enhance food and nutrition security outcomes.

- **Integrated basin management (IBM) and water storage:** The results of the study indicate that climates across the study sites will become drier and hotter. This necessitates urgent conjunctive ground- and surface-water management to sustain farmers' productivity during dry spells and droughts.

- **Coordination and collaboration:** Coordination and collaboration among key stakeholders when initiating climate action and adaptation initiatives ensure that they are feasible and contextually relevant. Such stakeholders can include government officials, researchers, policymakers, extension services, and farmers. This collaboration could ensure alignment in adaptation planning, policy and development, water management, climate risk research, and local agriculture towards context-specific, sustainable, and resilient adaptation frameworks and pathways.

3.7. Conclusions

This study examined climate risks and their effects on water and agri-food systems using the Climate Moisture Index (CMI) and the Thermal Heat Index (THI) across three Hydro-Climatic Zones in South Africa. Understanding the spatio-temporal severity of climate-related risks is critical to managing their impacts on resource availability and the broader socio-ecological and agri-food systems. The decreasing CMI alongside increasing THI in the chosen study sites indicate a general, progressive increase in moisture and heat stress from the present to the future climate. Consequently, there is a pressing need to develop sustainable, context-specific frameworks and pathways for adaptation to heat and water stress, particularly within smallholder

farming systems. These could include nature-based solutions that strengthen natural systems while derisking agri-food systems, and prioritising the adoption of strategic, nutrient-dense crops with high water and heat stress thresholds.

3.8. References

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CHAPTER 4 PATHWAYS TO RESILIENCE: COPING STRATEGIES TO CLIMATE RISKS: AND FOOD SECURITY OUTCOMES AMONG SMALLHOLDER FARMERS IN RURAL SOUTH AFRICA

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4.1 Abstract

The increasing frequency and intensity of climate risks have complex implications for agri-food systems, livelihoods, and food and nutrition security within rural households. We assess smallholder farmers' coping strategies to climate risks, and their impact on food and nutrition security of rural households in the Eastern Cape (EC), KwaZulu-Natal (KZN), and Limpopo Provinces, South Africa, using secondary data collected from 16,971 households. Coping strategies and their impact on food and nutrition security outcomes are measured through the instrumental variable regression model, Household Food Insecurity Access Scale (HFIAS) and Household Dietary Diversity Score (HDDS). Households across study sites primarily relied on their savings, help from friends/relatives, and changing dietary patterns as main strategies to cope with environmental shocks to their food and nutrition security. The EC (14,10%) and Limpopo (7,80%) provinces had the most households without any coping strategies. Food and nutrition security estimates indicated regionally differentiated challenges. Food insecurity was high, estimated at 73,4% in the EC, 70,40% in KZN and lower in Limpopo at 58,8%. The HDDS scores highlighted EC as the province with the least dietary diversity (78,00%), while Limpopo (81,60%) and KZN (81,50%) had the highest dietary diversity. Household size, age of the household head, number of household members under 18 years and household income were among the major factors that significantly affected food and nutrition security outcomes. Households that adopted coping strategies were associated with improved food and nutrition outcomes. The findings of the study underscore the complexity of addressing climate change impacts at local and household levels and highlight the need for agro-climatology-informed integrated approaches that simultaneously enhance climate resilience and ensure food security.

Keywords: environmental stressors, sustainable food systems, climate change adaptation, resilient communities

4.2 Introduction

Sub-Saharan Africa (SSA), including South Africa (SA), is a climate hotspot, with a high prevalence of food and nutrition insecurity, which is increasing faster than anywhere else in the world (Wudil *et al.*, 2022; Ouko and Odiwuor, 2023; Engelbrecht *et al.*, 2024). The prevalence of poverty and inherently low coping and adaptive capacity in the region further makes smallholder farming households particularly vulnerable to climate risks (Ogundeji, 2022; Sikhwari *et al.*, 2022; Ncoyini *et al.*, 2022; Okolie *et al.*, 2023; Zenda, 2024; Johnston *et al.*, 2024). The vulnerability of these households stems from their heavy reliance on on-farm activities for their income, food security and general livelihoods (Rurinda *et al.*, 2014; Williams *et al.*, 2018; Mutea *et al.*, 2019; Pawlak and Kołodziejczak, 2020; Cammarano *et al.*, 2020; Ogundeji, 2022) with often limited possibilities for income diversification beyond the farms. Consequently, rural smallholder farming households face increasing constraints to production, translating to a decline in agriculture's contribution to food and nutrition security and increasing poverty (Harvey *et al.*, 2014; Williams *et al.*, 2018; Giller, 2020; Bjornlund *et al.*, 2020; Bjornlund *et al.*, 2022; Johnston *et al.*, 2024).

The ability of smallholder agricultural systems to adapt to climate change is closely linked to a household's coping strategies (short-term reactive strategies) (Harvey *et al.*, 2014; Ogundeji, 2022; Kandel *et al.*, 2024). Therefore, locally appropriate coping and adaptation strategies are central to improving the sustainability and resilience of smallholder agricultural systems, livelihoods and food and nutrition security outcomes under climate change (Mabhaudhi *et al.*, 2018; Makungo and Nkuna, 2023). Historically, African rural smallholder agricultural systems capitalised on production diversity as a coping and adaptation strategy to sustain food production, food security, and nutrition security (Mabhaudhi *et al.*, 2018). However, colonialism and its associated policies and systems contributed to a shift from diverse agri-food systems that historically embraced locally adapted crops (indigenous crops) towards an over-reliance on a limited number of climate-sensitive major crops and yield-centric monocultural approaches (Mabhaudhi *et al.*, 2017; Agulanna, 2020).

While coping and adaptation strategies in smallholder agri-food systems are vital in mitigating food and nutrition insecurity, there remains a significant gap in understanding their contextual relevance, long-term efficacy, and relationship to food and nutrition security outcomes under varying climatic scenarios and risks. This often translates from the limited integration between agricultural development studies and climatology research that should inform coping and adaptation pathways (Mabhaudhi *et al.*, 2025). The existing research has either focused primarily on climate risk projections (Engelbrecht *et al.*, 2015; Davis *et al.*, 2017; Archer *et al.*, 2021) or on coping and adaptation strategies in isolation (Thinda *et al.*, 2020; Ojo *et al.*, 2021), with limited empirical linkage to food and nutrition security outcomes. Some studies, for example,

Mkhawani et al. (2016), Ngumbela et al. (2020) and Cheteni et al. (2020) highlight the prevalence of food insecurity, but do not associate it with specific coping strategies or their effectiveness. These gaps are critical to consider when developing context-specific, targeted, evidence-based adaptation strategies for smallholder farmers. The current study aims to assess the relationship between the coping strategies of smallholder farming households and food and nutrition security outcomes using the Household Food Insecurity Access Scale (HFIAS) and Household Dietary Diversity Score (HDDS). By evaluating smallholder farmers' coping strategies to climate risks and their association with food and nutrition security outcomes, we aim to develop targeted, locally relevant recommendations to enhance smallholder farming resilience and safeguard food, nutrition and livelihood security under climate change.

4.3 Materials and Methods

4.3.1 Description of Study Sites

The three poorest rural provinces in South Africa, the Eastern Cape, KwaZulu-Natal and Limpopo, were selected for this study (Figure 4.1). These provinces were selected because of their exposure and vulnerability to climate risks, having the highest number of rural households dependent on agriculture as their main livelihood strategy and their high prevalence of poverty (STATISTA, 2022¹; Stats-SA, 2019). The Eastern Cape (EC-Sample-6104) is the second largest and 3rd most populous province in South Africa, located just south of KwaZulu-Natal on the country's Eastern Coast. The province comprises six district municipalities and covers about 170,000 square kilometres of landscape (ecprov.gov.za, n.d.). The KwaZulu-Natal province (KZN-Sample-8824) is on the East Coast of South Africa. It is the second most populous and the 3rd smallest province in the country, covering about 94 361 km² of subtropical savanna and mountainous landscapes (municipalities.co.za, n.d.). Limpopo (Sample-2043) is in the northernmost part of the country, bordering three other countries (Zimbabwe, Botswana and Mozambique). Limpopo is the 5th largest province (in size and population) in South Africa, covering an area of 125 754 km² of natural forests, bushveld, wilderness and farmlands (municipalities.co.za, n.d.). The provinces are in different Hydro-Climatic Zones and have differing climatic characteristics, climate risks, ecological and typological zones, demography, main economic activities, and involvement in agricultural activities.

¹ [South Africa: agricultural households, by province| Statista](#)

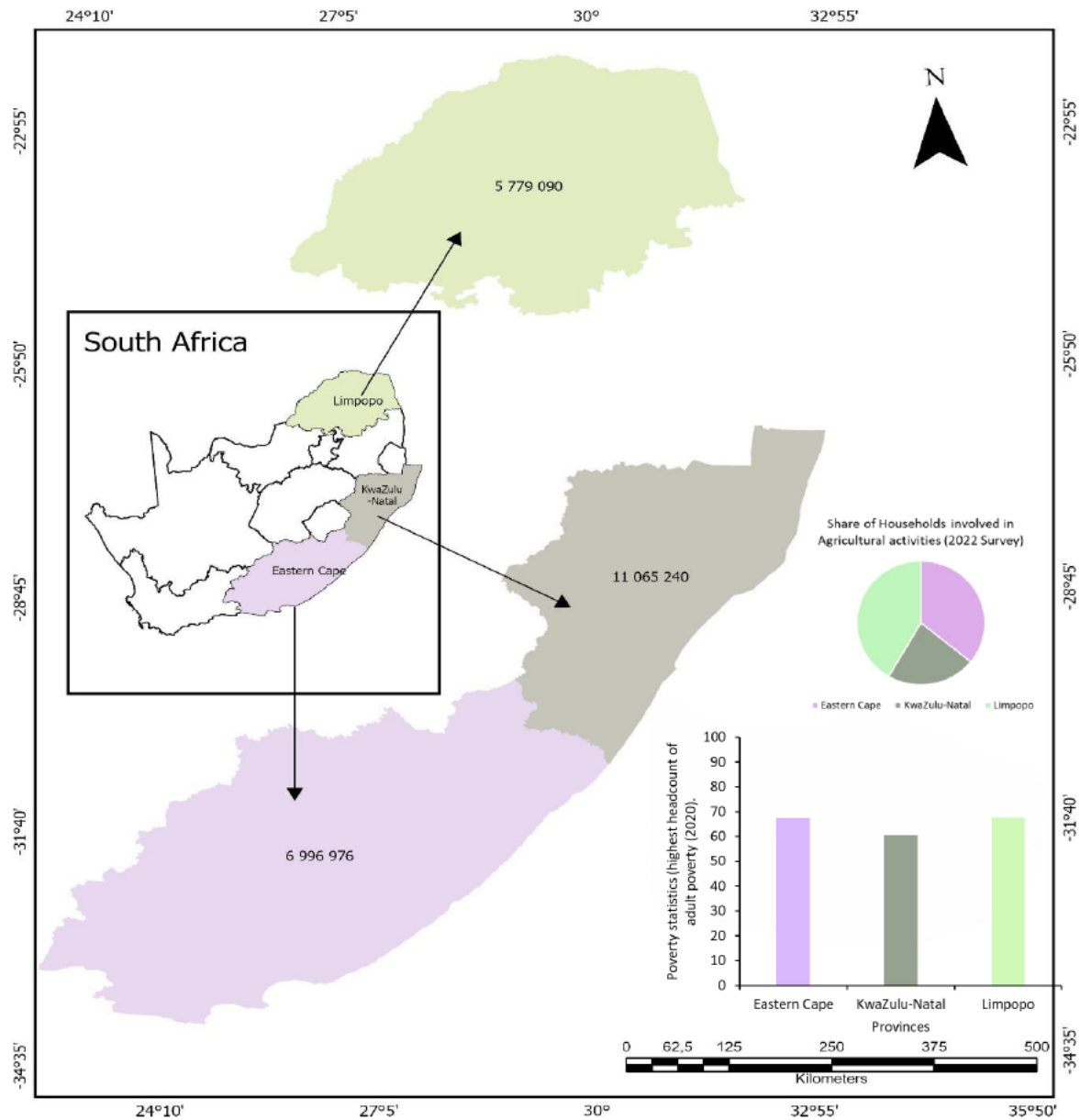


Figure 4.1: Map of the study sites showing the population and supporting inserts showing poverty statistics and the share of household involvement in agricultural activities across the study sites.

4.3.2 Conceptual framework

Figure 4.2 presents a conceptual framework for this study. We hypothesise that vulnerability and exposure to climate risks in the absence of appropriate coping and adaptive capacity contribute to negative outcomes for food and nutrition security. The impact will be unevenly distributed across the study sites, depending on factors that determine the vulnerability and exposure of local agricultural and food systems. We connect climate change to climate risk in vulnerable and exposed contexts, the existence of coping strategies (or the lack of), and specific food and nutrition security indicators as defined in van den Berg and Walsh (2023). We highlight how coping pathways for climate change mitigation could help reduce the impact of climate risks on vulnerable communities and strengthen food and nutrition security outcomes at the household level, and how, if well-designed, they could lead to long-term adaptation and resilience.

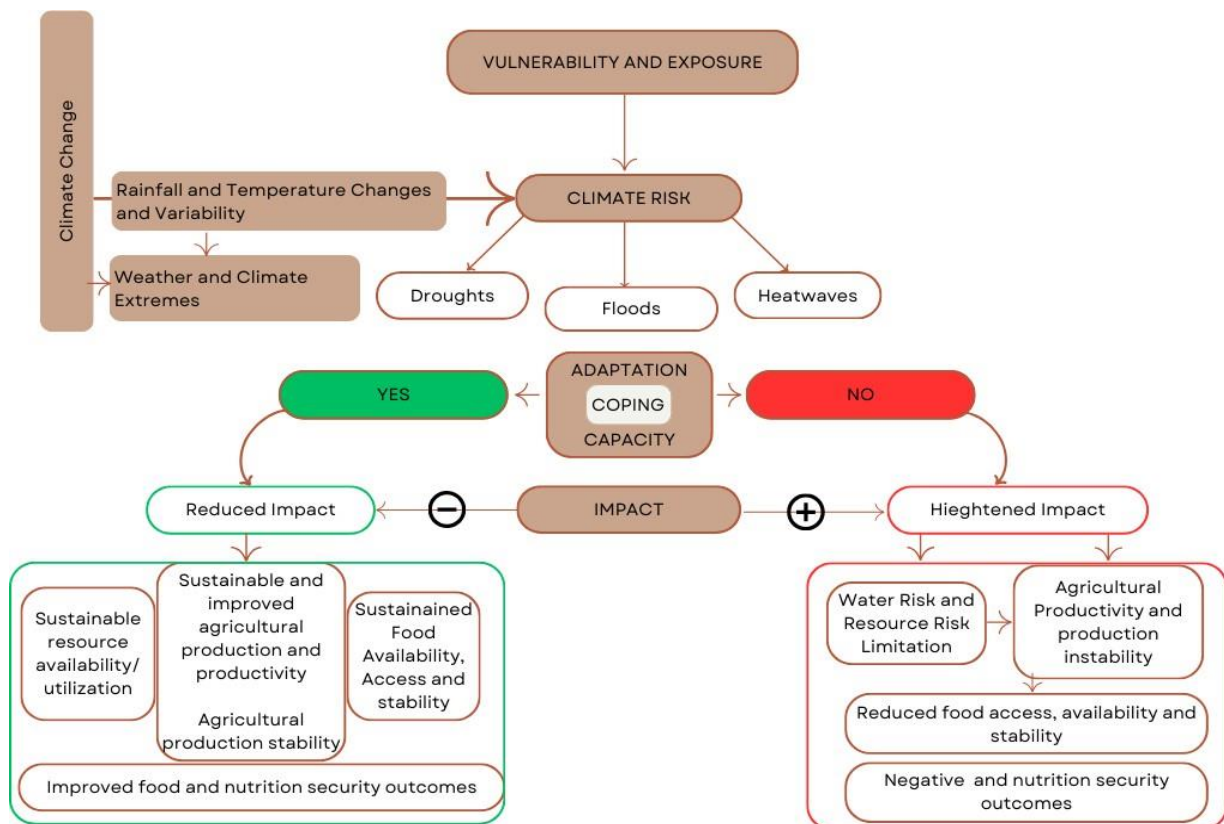


Figure 4.2: Conceptual framework for linking vulnerability and exposure to climate risks in the presence or absence of appropriate coping and adaptive capacity to contribute to food and nutrition security outcomes.

4.3.3 Sources of data

The study made use of secondary data collected through the National Food and Nutrition Security Survey conducted in 2021–2022 by the Human Sciences Research Council (HSRC), commissioned by the Department of Agriculture, Land Reform and Rural Development (DALRRD (Simelane et al., 2023). For this survey, the HSRC employed a multi-stage stratified random sampling technique (Simelane et al., 2023). Populations within the different provinces were first divided into strata based on common cross-cutting characteristics. After stratification, sampling fractions were allocated to ensure that diverse groups within each province's landscape were adequately represented (Simelane et al., 2023). Using this method, the survey gathered quantitative data from 6,104 household heads in the Eastern Cape, 8,824 in KwaZulu-Natal, and 2,043 in Limpopo, resulting in a total sample size of 16,971 respondents.

4.3.4 Data analysis

The data collected from the study sites were loaded into the Statistical Software for Social Sciences (SPSS) version 29, cleaned by the researcher, and then used as input to the instrumental variable regression model. Data analysis began with descriptive statistics to understand and compare the socio-economic environment across the different study sites. Subsequently, we employed an instrumental variable treatment regression model to determine the influence of adopting coping strategies on HFIAS and HDDS.

The Household Food Insecurity Access Scale (HFIAS) was employed to assess food insecurity among rural households. The HFIAS is a self-reported instrument designed to classify households according to their level of food security or insecurity (D’Haese et al., 2013; Maziya et al., 2017). Its efficacy and accuracy have been evaluated and validated by authors such as Knueppel et al. (2009) and Becquey et al. (2010). The HFIAS includes nine questions on how often households experience specific conditions related to food insecurity. The questions address three core themes: concerns and uncertainty about food access, inadequate food quality (including diet variety and nutritional sufficiency), and insufficient food intake and related physical effects (such as hunger) (Coates et al., 2007). The total HFIAS score reflects the extent of food insecurity experienced over the past 30 days, with scores calculated by summing the responses to each question. Each item is scored on a scale from 0 to 3, giving a total possible range from 0 (most food secure) to 27 (most food insecure) (Coates et al., 2007).

The Household Dietary Diversity Score (HDDS) reflects the variety and range of foods available to a household. It is calculated from data collected through 24-hour recalls, in which households report the food

groups they consumed the previous day before the interview. Cereals; fish and seafood; meat; roots and tubers; poultry and eggs; vegetables; fruits; sugar or honey; oils and fats; pulses, legumes, or nuts; milk and dairy products; and a miscellaneous category (including spices, sauces, salt, and other condiments) were identified as a standard set of 12 food groups by Swindale and Bilinsky (2006). In this study, the HDDS served as a dependent variable to assess household nutritional diversity.

4.3.5 Descriptive statistics of model variables

The study used an instrumental variable regression model to examine the influence of adopting coping strategies on the Household Food Insecurity Access Scale (HFIAS) and the Household Dietary Diversity Score (HDDS). This model is most suited for count-dependent variables, such as the number of coping strategies employed, which are non-negative integers. A household adopts a coping strategy if it uses at least one of the strategies listed above. These practices are commonly used in climate-resilient agriculture to cope with the negative impacts of weather extremes and improve food security. The efficacy of such measures in enhancing household resilience has been documented in various studies, including those conducted by Waha et al. (2018).

The instrumental variable model is used to estimate the parameters of a Poisson regression when some regressors are endogenous (Ward and Rosenberg, 2020). In this approach, instrumental variables that are correlated with the endogenous regressors but are uncorrelated with the error term are employed to obtain consistent estimates. The model can be specified using either additive or multiplicative error terms, as shown in Equations (1) and (2) (Onyeneke, 2021).

$$Y_i = \beta_1 A_i + \beta_2 X_i + \varepsilon_1 \quad \text{Equation 4.1}$$

$$A_i = P_i \delta_1 + \delta_2 X_i + \varepsilon_2 \quad \text{Equation 4.2}$$

where Y_i = outcome/dependent variable of the i th farmer; A_i = number of coping strategies of the i th farmer with parameter estimate, β_1 ; X_i = vector of household-level control variables of the i th farmer with parameter vectors, β_2 ; P_i = instrument variable with parameter estimates, δ_1 ; ε_1 and ε_2 = error terms with zero means and nonzero correlations.

The coping strategies, HFIAS and HDDS of rural farmers are influenced by several unobserved variables, making them endogenous variables, and the inability to account for this endogeneity might lead to biased and inconsistent findings. These factors complicate the interpretation of the differences in household

food insecurity and dietary diversity, specifically regarding the impact of adopting coping strategies in response to environmental shocks. The challenge necessitates a fitting econometric technique, such as instrumental variable regression, to overcome this endogeneity. The technique requires a suitable instrument which must be correlated with the endogenous variable (i.e. coping) but not directly related to the outcome variables (i.e. HFIAS and HDDS) (Onyeneke *et al.*, 2020). The analysis was taken a step further to account for endogeneity and provide unbiased estimates of the effect of climate risk coping response on HFIAS and HDDS. The endogenous treatment effect model, which accounts for unobservable variables that may affect the treatment and outcome (Wudil *et al.*, 2023), was used to estimate the impact of adopting climate risk coping strategies on the overall population (ATE), treated population group (ATET) and untreated group (ATENT). This was done to quantify the possible benefits to households of adopting climate risk coping strategies. The model is represented as follows:

$$ATE(x_i) = E(y_{i1} - y_{i0} \mid x_i, D_i) \quad \text{Equation 4.3}$$

$$ATET(x_i) = E(y_{i1} - y_{i0} \mid x_i, T_i = 1, D_i) \quad \text{Equation 4.4}$$

$$ATENT(x_i) = E(y_{i1} - y_{i0} \mid x_i, T_i = 0, D_i) \quad \text{Equation 4.5}$$

where E is the mean operator; T_i treatment taking only two values, 1 and 0, taking a value of 1 for households using a higher number (X or more) of climate risk strategies and 0 for households using a lower number of climate risk coping strategies (X or less); D_i representing the instrumental variable (i.e. household visits); x_i representing the independent variables; y_{i1} representing the dependent variables of households using a higher number of (X or more) climate risk coping strategies and y_{i0} representing the dependent variables of households using a lower number of (X or less) climate risk coping strategies.

4.4 Results and discussion

4.4.1 Demography and socio-economic characteristics of the study population

The population had predominantly female participants, 53,50%, 54,70%, and 53,80%, respectively, in the Eastern Cape, KwaZulu-Natal and Limpopo, presenting as household heads (Table 4.1). The high percentage of female-headed households is indicative of greater vulnerability, as females are more vulnerable to shocks than male-headed households (Misselhorn and Hendriks, 2017; Flatø *et al.*, 2017; Santos *et al.*, 2022; Salman *et al.*, 2023; Megbowon *et al.*, 2024). This stems from systemic gender inequalities that reinforce exclusion in access to land, financial services and structural barriers that undermine their ability to absorb and recover from different shocks. Most of the population surveyed was single in the Eastern Cape (31,00%) and KwaZulu-Natal (41,10%), while the majority of the population (29,80%) was married in Limpopo. Single adults typically rely on a single income stream, a condition that can constrain their financial resilience due to limited income diversification, reduced access to informal support networks, and greater vulnerability to economic shocks (Stats SA, 2017; SALDRU, 2018). However, this generalization overlooks critical variations in age, education, and the existence of informal support networks that can either amplify or buffer vulnerability to climate-related shocks. Therefore, framing coping pathways for climate risk mitigation as universally “critical” across the three provinces demands a contextualised understanding of institutional and social capital structures that shape coping and adaptive capacity.

High unemployment rates are prevalent throughout the three study sites, with 73,60% not receiving salaries or wages in the Eastern Cape, 68,80% in KwaZulu Natal and 60,00% in Limpopo. This aligns with several reports indicating high unemployment in the country, alongside a high reliance on social security grants (Patel *et al.*, 2023). Only 0,30% of the surveyed population received income from small-scale farming in the Eastern Cape, and 0,90% in KwaZulu-Natal. At the same time, no records were found for households receiving income from small-scale farming in Limpopo. The high unemployment rates and over-reliance on social grants translate to poverty, low coping and adaptive capacity, which translates to high levels of vulnerability. This calls into question the long-term sustainability of existing social assistance initiatives for eradicating poverty, addressing food and nutrition insecurity, and building resilience in these communities. The lack of contribution of small-scale farming to household incomes highlights systemic barriers to agrarian livelihoods, which need to be examined and addressed across the study sites to tackle the lack of coping and adaptive capacity and vulnerability. Support for smallholder farming households must address structural constraints and be embedded in inclusion and contextualised participatory governance frameworks that co-

design climate-smart innovations with local communities to enhance their coping and adaptive capacity and productivity (Ogundeji, 2022; Jellason *et al.*, 2022; Kandel *et al.*, 2024).

Table 4.1: Demography and socio-economic characteristics of the study population.

Variable	Variable Description	Eastern Cape		KwaZulu Natal		Limpopo	
		Freq. (n)	%	Freq. (n)	%	Freq. (n)	%
Gender	Male	2840	46.5	3994	45.3	944	46.2
	Female	3264	53.5	4830	54.7	1099	53.8
Marital Status	Legally married (include customary, traditional, religious)	1880	30.8	2567	29.1	608	29.8
	Living together like husband and wife	264	4.3	572	6.5	102	5.0
	Divorced	228	3.7	99	1.1	28	1.4
	Separated but still legally married	75	1.2	35	0.4	10	0.5
	Widowed	1316	21.6	1459	16.5	334	16.3
	Single, but have lived together with someone as husband/wife	417	6.8	421	4.8	71	3.5
	Single and have never been married/never lived together as	1890	31	3624	41.1	446	21.8
Employment Status	Yes	1558	26	2713	30.7	372	18.2
	No	4495	73.6	6067	68.8	1226	60
Income from small-scale farming	Yes	20	0.3	79	0.9	-	-
	No	6065	99.4	8696	98.5	490	24
	Don't know	8	0.1	13	0.1	-	-
	Missing System	-	-	-	-	1553	76

4.4.2 Application of coping strategy responses

Households experiencing climatic shocks adopt various strategies to cope with these challenges. Understanding the specific coping strategies employed by households in response to both current and projected climatic risks provides a valuable foundation for identifying localised vulnerabilities. This, in turn, supports the development of targeted adaptation strategies, which are crucial for building resilience in agri-food systems and related livelihoods. In this study, households were asked to indicate how they responded to climatic risks. This subsection presents the coping strategies adopted by households in response to climatic shocks. The findings show that many households primarily relied on their savings, sought assistance from

relatives or friends, and adjusted their eating patterns (Table 4.2). These findings are consistent with studies showing that, in the absence of formal support systems, rural households in South Africa often depend on informal networks and consumption-binging practices, such as reducing food intake or drawing down savings, to manage shocks (Tambo & Abdoulaye, 2012; Le Roux et al., 2017; Garber et al., 2023). Some households reported not being able to take action in response to climatic shocks. These unstructured, asset-depleting social coping strategies expose gaps in appropriate formal social protection initiatives and reflect inequalities in resource access, particularly for women, who constitute the majority of participants across the study sites. This undermines long-term resilience, forcing households to rely on unsustainable coping mechanisms or rendering them unable to respond at all, thereby weakening their capacity to absorb and recover from subsequent shocks, perpetuating cycles of vulnerability and deepening livelihood insecurity. The existence of households that were unable to take action, for example, 14,10% in the Eastern Cape, 7,80% in Limpopo, and 3,20% in KwaZulu-Natal, signals the presence of more systemic, structural, and institutional barriers to adaptation across our study sites. This aligns with previous research indicating the existence of social, physical and structural barriers that disproportionately affect marginalised groups and perpetuate vulnerability (Vincent & Cull, 2012; Ziervogel et al., 2014). While the relevance of coping strategies varied across study sites, reflecting the context-specific nature of vulnerability, they were found to be applicable across sites. This underlines the need for contextualised, locally inclusive adaptation pathways that consider both spatial disparities in institutional capacity and household- and community-based socio-economic characteristics.

Table 4.2: Coping strategies adopted by households across the study sites.

	KwaZulu-Natal		Eastern Cape		Limpopo	
	Yes %	No %	Yes%	No %	Yes %	No %
Relied on own savings	39,70	60,30	31,60	68,40	16,40	83,60
Received help from relatives/friends	34,80	65,20	46,00	54,00	13,00	87,00
Received help from the government	4,60	95,40	3,00	97,00	4,30	95,70
Received help from NGO/Religious Inst.	1,10	98,90	0,60	99,40	0,20	99,80
Changed eating patterns	33,90	66,10	23,50	76,50	11,30	88,70
Employed HH members took on more employment	0,30	99,70	0,20	99,80	0,60	99,40
Adult HH members who were not working had to find a job	0,60	99,40	0,40	99,60	0,80	99,20
HH members migrated	0,30	99,70	0,01	99,90	0,70	99,30
Reduced expenditure on health and/or education	1,10	98,90	2,80	97,20	0,80	99,20
Obtained credit	4,90	95,10	11,10	88,90	5,80	94,20
Sold agricultural assets	0,20	99,80	0,10	99,90	0,30	99,70
Sold durable assets	0,20	99,80	0,10	99,90	0,20	99,80
Sold land/building	0,10	99,90	0,00	100,0	0,10	99,90
Sold crop stocks	0,40	99,60	0,20	99,80	0,50	99,50
Sold livestock	0,80	99,20	0,60	99,40	0,60	99,40
Intensify fishing	0,10	99,90	0,10	99,90	Missing	Missing
Sent children to live elsewhere	0,30	99,70	0,10	99,90	0,30	99,70
Engaged in spiritual effort	0,70	99,30	0,20	99,80	1,00	99,00
Intensify gardening	0,70	99,30	1,90	98,10	1,30	98,70
Did not do anything	3,20	96,80	14,10	85,90	7,80	92,20
Other (Specify)	15,50	84,50	0,10	99,90	1,70	98,30
Did Not Experience (NA)	6,30	93,70	10,40	89,60	0,70	99,30

4.4.3 Food and nutrition (in) security statuses among households in the study sites

Food insecurity was widespread across the study sites. The results revealed that 73,40%, 70,40%, and 58,80% of households in the Eastern Cape, KwaZulu-Natal (KZN), and Limpopo, respectively, were found to be food insecure. The categorised results of food security showed that 26,60% of the households were food secure in the Eastern Cape, while 29,60% and 41,20% were food secure in KZN and Limpopo, respectively. Results on mild food insecurity indicated that KZN had the highest proportion of mildly food-insecure people (24,00%) compared to the Eastern Cape (22,20%) and Limpopo, which had the lowest proportion (19,30%). Regarding moderate food insecurity, more participants reported it in the Eastern Cape (31,00%) compared to KZN (29,30%) and Limpopo (29,00%). Further, the Eastern Cape also had more severely food-insecure households (20,20%) compared to the KZN (17,10%) and Limpopo (10,50%) (Figure 4.3). These results align with those of Statistics South Africa (2020) and van den Berg and Walsh (2023), which indicate a high prevalence of mild to severe food insecurity across different provinces of South Africa. The results, however, further underscore the need to investigate the underlying drivers shaping provincial differences.

The results indicating a high prevalence of food insecurity (73.40%) in the Eastern Cape align with several studies focusing on the province. De Cock et al. (2013) highlighted that the Eastern Cape consistently ranks among the most food-insecure provinces, with rural households particularly vulnerable due to limited agricultural opportunities and high unemployment. Mudombi (2020) also supports these findings, documenting that 76,00% of households in selected Eastern Cape communities experienced some form of food insecurity, closely matching our overall food insecurity result for the province (73,40%). The significant levels of moderate (31,00%) and severe (20,20%) food insecurity observed reflect structural and institutional barriers. For example, Hendriks et al. (2016) highlighted that food insecurity in the Eastern Cape is exacerbated by high poverty rates, limited access to agricultural resources, and environmental challenges, including drought. Some studies suggest more heterogeneous patterns within the Eastern Cape. Chakona and Shackleton (2018), for example, reported lower levels of food insecurity in certain municipalities (+_64,00%), suggesting potential intraprovincial variations not fully captured in our aggregated provincial data. This highlights the importance of sub-provincial analysis in future research. Our findings for KwaZulu-Natal (70,40% overall food insecurity) are consistent with Mkhawani et al. (2016), who documented comparable food insecurity levels (68,00-72,00%) in rural KZN communities, particularly noting economic barriers to food access. The notable proportion of mild food insecurity (24.00%) in our KZN sample aligns

with observations by Hendriks (2014), who noted that food insecurity in KZN is characterised by significant rural-urban disparities, with certain rural districts experiencing up to 75.00% food insecurity rates. D'Haese et al. (2013), however, reported slightly lower overall food insecurity in selected KZN communities (+_63,00%), which differs from our finding for this province. However, this could be a result of methodological differences, temporal changes, or geographic sampling variations. Additionally, Ngidi and Hendriks (2014) found more pronounced seasonal variations of food security in KZN than our data suggests, with food insecurity peaking at 78% during certain months. This indicates that data collection timing may influence provincial outputs.

Limpopo demonstrated the lowest food insecurity (58,80%) among the three provinces, which is supported by previous research. De Cock et al. (2013) reported similar patterns, indicating that, despite significant challenges, Limpopo achieved better food security outcomes than the Eastern Cape and KZN. Oni et al. (2012) documented food insecurity at approximately 56% in rural Limpopo, closely matching our result (58,80%). Limpopo's low food insecurity can be attributed to its more intentional involvement in subsistence agriculture, as noted by Masekoameng and Maliwichi (2014). In contradiction, Modirwa and Oladele (2017) reported higher food insecurity levels of up to 67,00% in certain districts of Limpopo, indicating significant intra-household and provincial variations not captured in our provincial average.

The provincial patterns observed in our study reflect broader, existing national trends. In the Statistics South Africa 2019 report (StatsSA, 2019), the national pattern of food insecurity shows similar provincial rankings to our results. The Eastern Cape is consistently among the most food-insecure provinces, and Limpopo performs better. Ngema et al. (2018) also confirmed that the Eastern Cape and KZN consistently rank among provinces with the highest food insecurity levels nationally, attributing this to historical underdevelopment, climate vulnerability, and limited economic opportunities. Drimie and McLachlan (2013) documented persistent geographic disparities in food security across South African provinces, with patterns consistent with our findings showing the Eastern Cape among the most vulnerable. These consistent patterns point to structural barriers that go beyond household-level vulnerabilities. One key reason behind the persistence of these geographic disparities is that national food and social policies are often formulated at a central level and implemented broadly, without sufficient spatial differentiation. Drimie and McLachlan (2013) note that this approach limits the responsiveness and effectiveness of interventions at local levels. This challenge is further compounded by implementation strategies that are often standardised and poorly aligned with the specific socio-economic and ecological realities of different provinces. Our findings contribute to this body of knowledge by reinforcing the need for spatially targeted policies and investments that address province-specific challenges, particularly in historically marginalised regions such as the Eastern Cape.

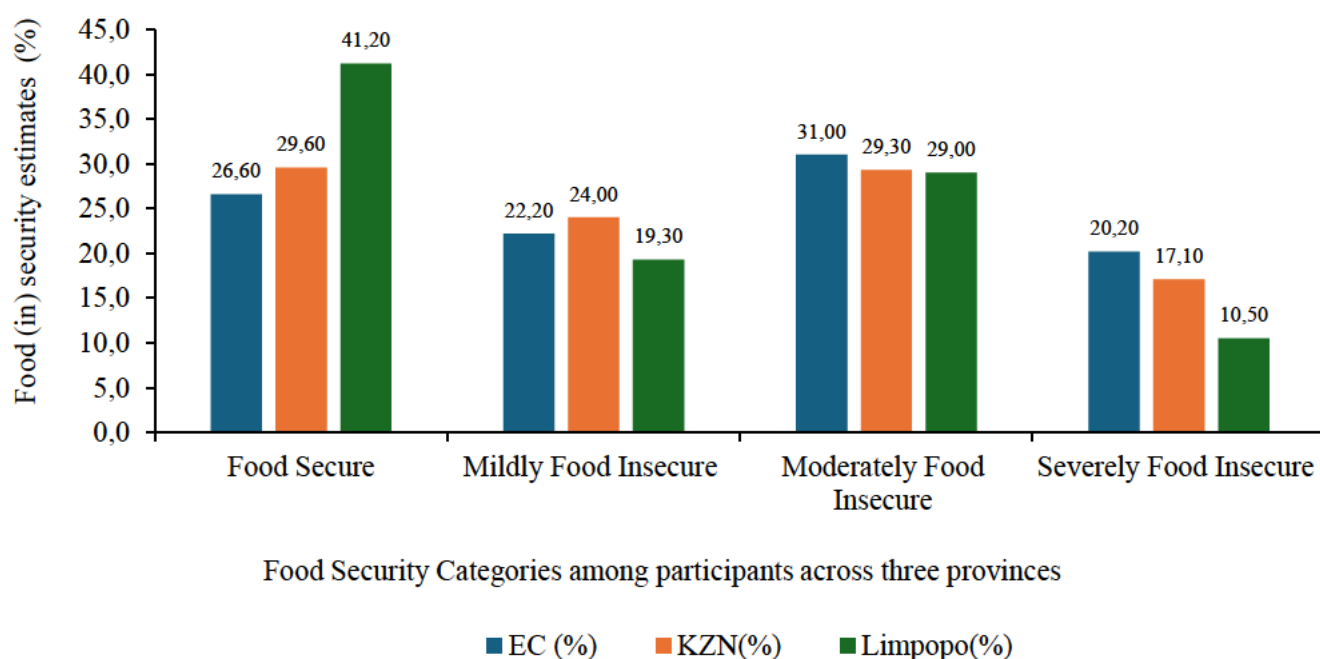


Figure 4.3: Household Food (in) security categorises and estimates across the study sites.

4.4.4 Household dietary diversity

Access to diverse food groups enables individuals to obtain macro- and micronutrients essential to their well-being (Cámara *et al.*, 2021). At the household level, dietary diversity could be linked to household income, with higher income associated with better food access and greater dietary diversity. However, our findings reveal a more complex reality. Despite high unemployment and minimal income from small-scale farming (as shown in the previous section), dietary diversity scores across provinces were relatively high, particularly in Limpopo and KwaZulu-Natal, and moderately high in the Eastern Cape. This suggests that food access and dietary diversity are also shaped by non-income factors (Faber *et al.*, 2017; Pereira *et al.*, 2014). The highest household dietary diversity scores (≥ 6 food groups) were in Limpopo (81,60%), KwaZulu-Natal (81,50%) and the Eastern Cape (78%), respectively (Figure 4.4). Estimates of medium dietary diversity scores (4 and 5 food groups) were higher in KwaZulu-Natal (15,60%), the Eastern Cape (15,50%) and Limpopo (14,90%), respectively. The highest estimates of lowest dietary diversity scores (≤ 3 food groups) were in the Eastern Cape (6,50%), Limpopo (3,50%) and KwaZulu-Natal (2,90%), respectively.

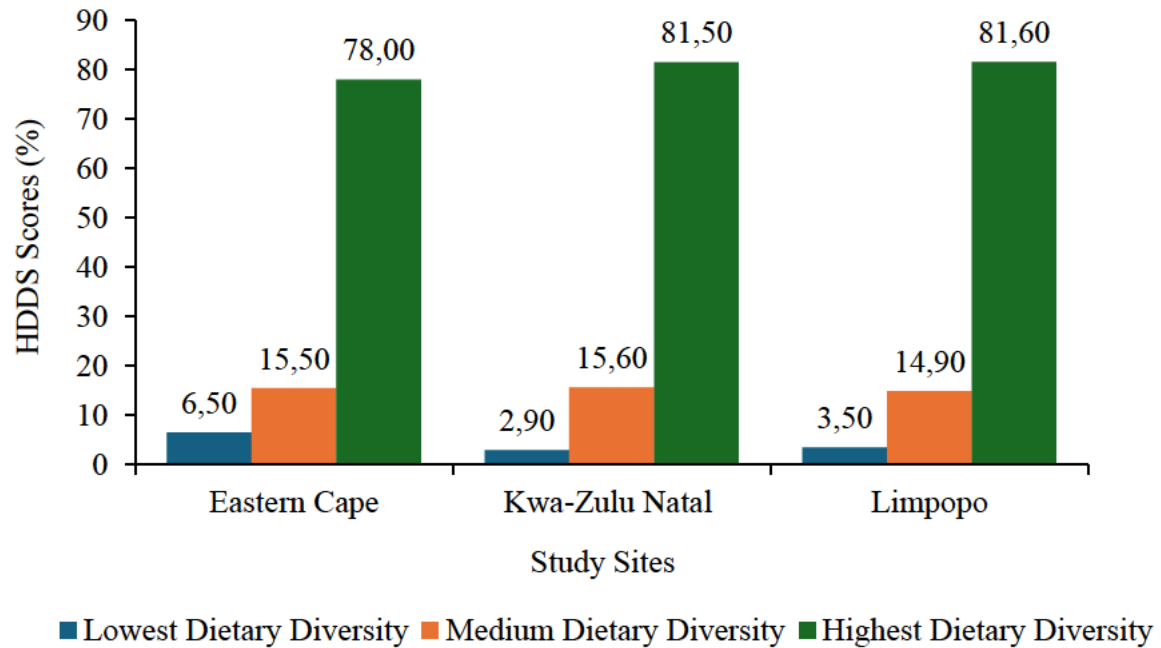


Figure 4.4: Household dietary diversity score estimates across the study sites.

The provincial patterns in dietary diversity align with findings by Chakona and Shackleton (2017), who observed higher dietary diversity in Limpopo compared to the Eastern Cape. Their study of three South African towns found that Limpopo households consumed about 6.2 food groups on average, while Eastern Cape households averaged 5.9 food groups. Similarly, Masekoameng and Maliwichi (2014) documented relatively high dietary diversity in Limpopo's Sekhukhune District, where 78.00% of households consumed six or more food groups, closely matching our study finding for Limpopo.

The relatively high dietary diversity in KwaZulu-Natal (81,50% consuming ≥ 6 food groups) corresponds with research by Faber et al. (2017), who found that 79,00% of rural KZN households consumed at least six food groups, despite significant food insecurity challenges. This suggests that food-insecure households in KZN may still maintain relatively diverse diets through various coping strategies. However, in contradiction, Napier et al. (2018) reported notably lower dietary diversity in certain KZN townships, with only 65% of households consuming from six or more food groups. Although 78,00% of households in the Eastern Cape consumed about six food groups, about 6,50% had the lowest dietary diversity, highlighting the coexistence of moderate dietary access alongside deeper household-level vulnerabilities and intra-provincial heterogeneity. The study results of higher dietary diversity in the Eastern Cape (78,00%) are higher than previously reported in the literature. Roos et al. (2013), for example, documented considerably lower dietary diversity in rural Eastern Cape communities, with only 62% of households consuming from six or

more food groups. This discrepancy may reflect methodological differences, temporal improvements in dietary diversity, or geographic heterogeneity and sampling variations. Hendriks et al. (2016) also found that the Eastern Cape consistently demonstrated the lowest dietary diversity among South Africa's provinces, with particularly limited consumption of vitamin A-rich fruits and vegetables and animal proteins, supporting our finding that the Eastern Cape had the highest percentage (6,50%) of households with low dietary diversity scores. The observed pattern of Eastern Cape having the highest proportion of households with low dietary diversity (≤ 3 food groups) is also consistent with Pereira et al. (2014), who found that food access challenges were most severe in Eastern Cape compared to other provinces, with limited availability of diverse food groups in rural areas. Contrary to our findings, however, Steyn et al. (2016) documented smaller provincial differences in low dietary diversity, with the Eastern Cape only 2,10% points higher than Limpopo, compared to our observed difference of 3,00% points.

4.4.5 Factors affecting food (HFIAS) and nutrition (HDDS) security across the study sites

The next section analyses factors affecting HFIAS and HDDS. Table 4.3 presents the results for the factors affecting the HFIAS and HDDS of households participating in the study. The results show a positive and significant association ($p < 0.003$) between the household head's age and food insecurity. This implies that as the household head ages, their food insecurity increases. While this is unusual, it aligns with studies that show that as the age of the household head increases, the severity of food insecurity also increases, particularly if the head is female (Santos *et al.*, 2022; Akalu and Wang, 2023; Megbowon *et al.*, 2024). This association may reflect cumulative vulnerabilities of ageing, for example, diminishing physical capacity, potentially confounded by household dependency ratios and the gendered inequalities and caregiving roles in our study sites. However, other studies have found the opposite, reporting that older household heads were more likely to be food secure due to their experience and established livelihoods (Obeng et al., 2021; Tessema, 2024). Together, these results underscore the need for longitudinal studies to examine the direct ageing effects from broader structural drivers and socio-demographic heterogeneities. The number of household members significantly positively affected HFIAS, increasing the incidence of food insecurity at the household level. This is consistent with previous studies, which have confirmed that household size is associated with food insecurity (Sekhampu, 2017; Sisha, 2020; Salman *et al.*, 2023).

Based on our results, household income negatively affects HFIAS, indicating that as income increases, household food security improves. This is in line with previous studies that have highlighted that access to income improves food security (Sisha, 2020; Purwaningsih *et al.*, 2022; Kori *et al.*, 2023). Therefore, income

diversification is important to fight food insecurity at the household level (Sisha, 2020). Salaries and Wages of household heads, salaries and wages from an additional member within a household, and Net Profit from other activities (on-farm and off-farm) were positive and significant, indicating that having a salary and wages and Net profit from other activities did not improve the food security situation. This is in line with previous research. For example, St-Germain and Tarasuk (2018) found that despite increased income, households in Canada did not experience a significant reduction in food insecurity, suggesting that factors such as debt and lack of access to credit may offset the benefits of increased income. Further, a study by Furbush et al. (2024) concluded that livelihood diversification did not significantly reduce food insecurity during the COVID-19 pandemic, indicating that income diversification may not always lead to positive outcomes for food security.

The study results also indicate that all the independent variables had a statistically significant impact on HDDS (Table 4.3). With that, the gender of the household head was a critical determinant, with female-headed households exhibiting lower dietary diversity. Our finding aligns with the widely held view that female-headed households are more vulnerable to food and nutrition insecurity compared to their male-headed counterparts (Misselhorn & Hendriks, 2017; Flatø et al., 2017; Santos et al., 2022; Akalu & Wang, 2023; Salman et al., 2023; Megbowon et al., 2024). Additionally, Omonona and Agoi (2019) observed that women-headed households, particularly in rural areas, are likely to experience lower dietary diversity due to limited access to land and income-generating opportunities. Furbush et al. (2024) also noted that during the recent COVID-19 pandemic, female-headed households across sub-Saharan Africa faced higher food insecurity as a result of reduced livelihood options and weakened support networks. However, our findings contrast with some recent studies that report a positive trend in dietary diversity among female-headed households. For instance, Egah et al. (2023) found that in parts of West Africa, female-headed households exhibited higher dietary diversity due to improved food planning and resource management. Further, Kassie et al. (2022) documented that in some rural areas in Ethiopia, women-headed households benefited from increased access to diverse food groups through participation in agricultural cooperatives and extension services.

The results further show that the household head's age and household size negatively affected HDDS. This means that as household age and size increase, households experience lower dietary diversity. Household head age can be linked to the availability pillar of food security, while household size is linked to food accessibility (Purwaningsih *et al.*, 2022). The interaction between household head age and HDDS can indicate two scenarios: one in which the household head is young and inexperienced, and the other in which the household head is older and more vulnerable, with sole dependence on maladapted, monotonous agricultural practices for their entire livelihoods and food and nutrition security. On the other hand, household size influences HDDS by limiting food access, particularly under climate change, which reduces farm-level

food production and increases food prices (Purwaningsih *et al.*, 2022; Kori *et al.*, 2023; and Salman *et al.*, 2023). On the contrary, Ngoma *et al.* (2023) found that larger households were associated with greater dietary diversity due to resource pooling and shared responsibilities. Further, Bandyopadhyay *et al.* (2021) observed a positive correlation between household size and dietary diversity, suggesting that larger families may consume more diverse foods due to varied preferences and food acquisition practices. These findings highlight the complexity of household dynamics and their relationship with food and nutrition security.

The number of household members under the age of 18 positively affected HDDS outcomes. In South Africa, children under the age of 18 are entitled to child support grants, which, in many low-income households such as in the selected study sites, is an important source of income that supports food and nutrition security outcomes. Household income in different forms also significantly positively affected HDDS. Income is one of the key components to ensuring food availability and accessibility, particularly in unstable food production environments; therefore, it affects food and nutrition security outcomes at household levels (Purwaningsih *et al.*, 2022; Akalu and Wang, 2023; Salman *et al.*, 2023; Begashaw *et al.*, 2024). Agricultural livelihoods are increasingly vulnerable under climate change due to the resulting food production insecurities (Kori *et al.*, 2023). In the context of our study sites, variables with implications for HDDS must be considered when adopting coping strategies because HDDS is significantly positively affected by adopted coping practices as also seen in Ayalew *et al.* (2025). However, HDDS as a proxy for nutrition security can overlook seasonal diet fluctuations, food quality and intra-household allocations, which underlines its limitations and suggests that complementary indicators need to be considered, particularly in contexts of climate change adaptation.

Table 4.3: Results of the factors affecting the HFIAS and HDDS of households across the study sites.

	HFIAS			HDDS		
	Coefficient	Std. err.	P-value	Coefficient	Std. err.	P-value
Household Head Gender	0.156	0.169	0.358	0.118	0.059	0.043**
Household Head Age	0.019	0.006	0.003***	-0.005	0.002	0.022**
No of Household Members	0.844	0.047	0.000***	-0.141	0.016	0.0***
Number of Household Members Under 18	-0.133	0.124	0.284	0.103	0.043	0.018***
Household Income	-2.535	0.111	0.000***	0.470	0.039	0.000***
Salaries and Wages	0.817	0.226	0.000***	-0.125	0.078	0.109
Net Profit from Business or Professional Practice Activities or Commercial Farming	0.682	0.362	0.060*	0.203	0.124	0.102
Income from Small-Scale Farming	-0.400***	0.754	0.596	0.350	0.256	0.172
Income From Social Welfare Grants (Including Old Age Grants)	0.288	0.209	0.170	0.092	0.072	0.204
Regular Allowances / Remittances Received from Non-Household Members	0.508	0.542	0.349	0.450	0.185	0.015***
Salaries And Wages Person 2	0.480	0.216	0.026**	-0.179	0.074	0.016***
Total production	-0.000	0.000	0.214	-0.000	0.000	0.372
Total income	0.000	0.000	0.663	0.000	0.000	0.562
_cons	0.191	1.109	0.863	3.944	0.821	0.000***

Notes: *** indicates significance at 1%, ** indicates significance at 5%, and * indicates significance at 10%. [*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$]

4.4.6 Adoption of climate risk coping strategies on HFIAS and HDDS

Table 4.4 presents the results of the treatment effects (ATE, ATET, and ATENT) for the average treatment effect of adopting climate change coping strategies on household food insecurity (HFIAS) and nutrition security (HDDS) across the study areas. An instrumental variable treatment regression model was fitted and used to estimate the impact of adopting coping strategies on the overall population (ATE), the treated population group (ATET), and the untreated group (ATENT), thereby quantifying the possible benefits to farmers of adopting coping strategies.

The results of the HFIAS indicate that food insecurity was negatively affected by the adoption of coping measures to mitigate climate change across the study sites. These coping strategies are put in place to alleviate the impact of climate change on food security, therefore negatively affecting food insecurity, suggesting that they contribute to climate risk mitigation and improving food security across the study sites. However, misaligned strategies can inadvertently exacerbate the situation when scarce resources are allocated to climate risk mitigation instead of immediate food. The study findings underscore a need for context-specific multidimensional efforts to simultaneously prioritise food security and climate resilience for sustainable and equitable development.

The results suggest that adopting climate change coping strategies significantly positively affects HDDS outcomes for all population groups. Previous studies, such as Purwaningsih *et al.* (2022), Kori *et al.* (2023), and Begashaw *et al.* (2024), support this finding and highlight the importance of adopting coping strategies to improve food and nutrition outcomes. The results also suggest that households that adopted climate change coping measures (ATET) improved their nutrition security outcomes more than those of the untreated (ATENT) population. As indicated in these results, HDDS is positively affected by the adoption of coping measures. Overall, households that adopted coping measures were associated with improved food and nutrition outcomes, as in research conducted by Mekonnen *et al.* (2021), Ogundeji (2022), and Ayalew *et al.* (2025). Therefore, coping strategies are central to achieving sustained food and nutrition security at a household level under projected climate change. The statistical gaps (Table 4.4) between those who adopted coping strategies and those who did not are important to understand for policy recommendations.

Table 4.4: Average treatment effect of adoption of climate change coping strategies on HFIAS and HDDS.

Outcome variables	Treatment type	Sample Size	Mean	Standard error
HFIAS	ATE	7553	-3.253***	0.009
	ATET	4118	-2.321***	0.006
	ATENT	3847	-2.671***	0.005
HDDS	ATE	7714	4.127 ***	0.024
	ATET	4255	2.332***	0.004
	ATENT	3863	4.036***	0.002

Notes: *** indicates significance at 1%, ** indicates significance at 5%, and * indicates significance at 10%. [*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$]

4.5 Conclusions and recommendations

Household food and nutrition security outcomes are affected by vulnerability and the effectiveness of coping systems in responding to climate change and related risks. We examined the impact of climate risk coping strategies on food and nutrition security outcomes using HFIAS and HDDS indicators in three provinces of South Africa. Our findings revealed that 14.10% of households in the Eastern Cape reported not having been able to adopt any coping strategies. The reality was the same for 7,80% and 3,20% of households in Limpopo and KwaZulu-Natal, respectively. Food insecurity was high across the study sites, with 73,40%, 70,40% and 58,80% of households reporting food insecurity in the EC, KZN and Limpopo, respectively. Of all the provinces, Limpopo had the highest value of food-secure households (41,20%). Specific variables such as household income and the number of household members under the age of 18 had a positive impact on HDDS and a negative impact on HFIAS, indicating that they play a positive role in countering food insecurity and promoting nutrition security among households. The overall results of the HFIAS suggest that food insecurity was negatively affected by the adoption of coping measures, and adopting climate change coping strategies significantly positively affect HDDS outcomes across the study site. The heavy reliance on social grants, limited savings and informal support networks highlights how systemic constraints shape coping strategies that lack agency. The positive association between household income and the adoption of coping strategies reveal the critical role of economic capacity and resilience in adaptation planning. The findings of the study underscore the complexity of addressing climate change impacts at local and household levels and highlight the need for integrated, transformative approaches that simultaneously enhance climate resilience, ensure food security, and build agency.

Initiatives to improve food and nutrition security in South Africa should, therefore, include improving climate change awareness, increasing access to climate information, and capacity building for climate change resilience, particularly within the country's rural development agendas. Systemic approaches are needed to dismantle structural barriers and embed climate-smart innovations within inclusive, and participatory governance frameworks, that are co-designed with local communities to ensure equitable, sustainable development and positive food and nutrition outcomes under climate change. Interventions must be regionally differentiated to better reflect local biophysical and socio-economic vulnerabilities and align with provincial and municipal development agendas. For example, provincial and district development plans and strategies need to include budgets for the adoption of NUS that perform well in their biophysical contexts and could be leveraged to address pressing socio-economic challenges. Provincial and district development plans also need to account for flexible funding structures to support capacity building, piloting NUS production, designing a monitoring and acceptability framework, and scaling up NUS production. Futuristic planning of local livelihood systems to deliver sustainable and resilient co-benefits for food and nutrition security and biophysical outcomes should form the foundation for such coping and adaptation measures and strategies. Supporting household coping strategies and improving their adaptive capacity is central to forming a solid foundation for the future of food, nutrition and livelihood security, particularly in rural areas. In the academic space, future research should explore the correlation between food security metrics and indigenous farming practices to determine how NUS contribute to food security and food system resilience. Future research examining how gender shapes the adoption of coping and adaptation strategies, and why, with what success, can be suggested.

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CHAPTER 5: NUTRITIONAL YIELD AND NUTRITIONAL WATER PRODUCTIVITY OF UNDERUTILISED CROPS FOR CLIMATE- RESILIENT AGRI-FOOD SYSTEMS

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5.1 Abstract

South Africa is a water risk hotspot characterised by a semi-arid climate and highly variable rainfall patterns. Under this situation, sustainable water resource management is a prerequisite for resilient, nutrition-sensitive agri-food systems under climate change. We assessed Water Use Efficiency (WUE), Nutritional Yield (NY), and Nutritional Water Productivity (NWP) of four mainstream (Groundnut, sorghum, potato, and soybean) and four neglected and underutilised crop species (NUS) (Bambara, maize, taro, and amaranth) under rainfed conditions in South Africa. The AquaCrop Model was run for three time periods: the present (1961-1990), the near future (2015-2044), and the distant future (2070-2099), using climate data from an ensemble of six GCMs forced by RCP 8.5 for 5838 relatively homogeneous response zones in South Africa. NY and NWP were calculated using model outputs as an average of the 6 GCMs. Mainstream crops, such as potatoes and maize, had higher WUE across the 5838 sub-catchments. NUS, on the other hand, had specific, narrow suitability zones that overlapped with rural areas in the Eastern Cape, KwaZulu-Natal, and Limpopo. NUS presented higher NY and NWP for Vitamin A, Iron and Zinc, which are typically deficient in rural populations. The variations in WUE, NY, and NWP of NUS and mainstream crops in similar and across different geographic zones highlight the importance of regionally differentiated adaptation strategies. Targeted deployment of NUS in rural areas could help transform local agri-food systems into more sustainable, resilient, and nutrient-sensitive systems under climate change.

Keywords: Crop Diversity, Dietary Diversity, Opportunity Crops, Sustainable Agriculture.

5.2 Introductions

South Africa (SA) is among the driest countries in the world, and climate projections forecast drier and hotter conditions for Sub-Saharan Africa (SSA) (Du Preez and Van Huyssteen, 2020; Engelbrecht et al., 2024; Rouault et al., 2024). Under these different scenarios, the country is further subject to highly variable rainfall patterns, increasing frequency and intensity of extreme weather events and high potential evapotranspiration (Du Preez and Van Huyssteen, 2020; Ndlovu et al., 2021; McBride et al., 2022). However, in the same environments, agricultural activities underpin food, nutrition and livelihood security for many rural households (Pawlak and Kołodziejczak, 2020; van den Berg and Walsh, 2023; Kapari et al., 2023). The country is also subject to a growing population on dwindling natural resources that are crucial for agricultural production and productivity, particularly in smallholder settings (Du Preez and Van Huyssteen, 2020; Tantoh and McKay, 2023).

About 80% of the country's total land area is utilised for agricultural purposes, accounting primarily for mainstream agriculture (Johnston et al., 2024). Furthermore, agriculture constitutes one of the largest consumers of freshwater and soil resources in South Africa, with approximately 60% of the country's available freshwater allocated to irrigation, predominantly in commercial farming contexts. In contrast, smallholder farmers, who are often poorly resourced and primarily situated in marginalised areas, engage in rainfed agriculture (Crookes et al., 2018; Du Preez and Van Huyssteen, 2020; Nhamo et al., 2020). In this context, weather and climatic variability pose extended risks to different sectors linked to water, agriculture and the environment (Calzadilla et al., 2014; Ziervogel et al., 2014; DeFries et al., 2016; Meza et al., 2021; Bonetti et al., 2022; Feng et al., 2023). Water productivity in agriculture is crucial and extends beyond the management of natural resources and nutrient management; it forms a critical component of achieving food security and environmental sustainability (Calzadilla et al., 2014; Crookes et al., 2018; Gerten and Kummu, 2021; Duncan et al., 2022; Bonetti et al., 2022; Feng et al., 2023; Liao et al., 2023).

While SA is considered food secure at the national scale, persistent food and nutrition insecurity persists at the household level. However, food insecurity levels differ in severity across provinces and socioeconomic groups, and their underlying drivers and regional dynamics remain poorly understood (Govender et al., 2021; van den Berg and Walsh, 2023; Human Sciences Research Council (HSRC), 2024). However, paradoxically, areas with high production potential still exhibit rising rates of hunger and malnutrition, suggesting critical gaps in our knowledge of why existing agri-food systems fail to translate productivity into improved and equitable nutrition outcomes (Hart et al., 2022; Human Sciences Research Council, 2023; van den Berg and Walsh, 2023). There is limited evidence on how current agri-food systems can be diversified and adapted to climate variability and change while delivering diversified, nutrition-

sensitive food options for local people in an environmentally sustainable manner (Dwivedi et al., 2017; Mabhaudhi et al., 2017; Gerten and Kummu, 2021; Duncan et al., 2022; Liao et al., 2023; Rötter et al., 2024).

The agri-food systems, dominated by a few major crops, are threatened by climate variability and change in the country. These agri-food systems are unsustainable and exceed planetary boundaries through competing with natural biophysical systems, unsustainable natural resource use, and contributing to greenhouse gas emissions (DeFries et al., 2016; Gerten and Kummu, 2021; Liao et al., 2023). In comparison to certain neglected and underutilised crop species (NUS), mainstream crops frequently exhibit deficiencies in essential micronutrients, including minerals such as iron and calcium, as well as other vitamins critical for maintaining optimal health (Mabhaudhi et al., 2017; Li et al., 2020). Most NUS are locally viable, adaptable and nutrient-dense and have the potential to strengthen local food systems and livelihoods under climate change, especially in marginalised communities (Mabhaudhi et al., 2017; Agulanna, 2020). They could contribute to sustainable intensification and diversification of agri-food systems and to the reinstatement of food sovereignty in resource-constrained settings (Shilomboleni, 2017; Mabhaudhi et al., 2017; Agulanna, 2020). However, previous studies have evaluated crop water productivity and crop nutritional composition in isolation. This translates to a lack of comprehensive understanding of how water productivity and micronutrient yields interact. This study integrates biophysical modelling and micronutrient-yield metrics to assess spatio-temporal trade-offs between micronutrient yields and water productivity between mainstream and underutilized crops across different timelines under climate change. The study presents a comparative analysis of Nutritional Yield (NY) and Nutritional Water Productivity (NWP), specifically focusing on Iron, Zinc, vitamin A, Energy, and Protein, which are still deficient in people's diets in SA (Govender et al., 2017), between mainstream crops and underutilised crops. By comparing the two, we aim to develop water- and nutrition-sensitive recommendations to inform climate change adaptation strategies in resource-constrained, food-insecure settings.

5.3 Materials and Methods

5.3.1 Location Description

SA is a water-scarce country and is divided into 24 climatic regions based on the climatic properties of each landscape, as well as several hierarchical levels of catchments specific to water resource management (Kruger, 2004). SA has 5838 quinary catchments within 1946 quaternary catchments (Maherry et al., 2013). Food and nutrition insecurity remains a significant challenge in SA, affecting a large portion of the population at household scales across the country, primarily in marginalised environments (HSRC, 2023). The country

also faces a complex interplay of factors, including poverty, unemployment, and inequality and inequity in agri-food systems, which contribute to poor food and nutrition security outcomes (May and Losch, 2022). These challenges are exacerbated by climate change and variability.

5.3.2 Crop selection, calibration and validation information of selected crops

Four mainstream crops and four NUS were included in this research (Table 5.1). The selection of these crops was guided by their extensive presence in literature, particularly in studies that focus on and advocate for NUS inclusion in SA agri-food systems.

Table 5.1: Crops included in this study

Mainstream Crops	Neglected and Underutilized Crops (NUS)
Groundnut	Bambara
Maize	Sorghum
Potato	Taro
Soybean	Amaranth

5.3.2.1 Nutrient content of selected crops

For this research, I used crop nutrient content data from West Africa (Figure 5.2) because data for South Africa were unavailable.

Table 5.2: Nutrient contents used for calculations in this chapter.

Crop	Energy (kcal)	Iron (mg)	Protein (g)	Vitamin A (mcg)	Zinc (mg)
Amaranth	40	7	4	225	1
Bambara	320.78	4.07	20.3	N/A	2.36
Groundnut	568.22	3.17	22.09	2	2.75
Maize	323.54	2.88	8.4	4.75	1.88
Potato	79	0.97	1.5	0	0.37
Sorghum	344.33	7.17	10.57	0.67	1.98
Soya Bean	293.5	5.03	25.91	0	3.579
Taro	83	2	3	76	1

Source: [FAO, 2019: FAO/INFOODS Food Composition Table for Western Africa \(2019\)](#).

5.3.3 GCM selection

Global climate models (GCMs) are computational tools designed to simulate and project natural earth-atmospheric and oceanic systems (Raju and Kumar, 2020). A multi-model ensemble approach was used to assess the Nutritional Yield and Nutritional Water Productivity of selected NUS crops relative to Mainstream crops in this study. Six GCMs from the CMIP5 repository (Table 5.3), as detailed in the Intergovernmental Panel on Climate Change's Fifth Assessment Report (2014), were selected and utilised (IPCC, 2014; Kunz et al., 2024). The climate projections for the six GCMs were dynamically downscaled with the regional climate model by the Council for Scientific and Industrial Research (CSIR), then bias-corrected against historical observed data from 1961-1999 following the Quantile Delta Mapping method (Cannon et al., 2015). Only one Representative Concentration Pathway (RCP 8.5) was considered in this study.

Table 5.3: Details on the six GCMs chosen for this study.

Abbreviation	GCM details
ACC	Australian Community Climate and Earth System Simulator (ACCESS1-0)
CCS	Community Climate System Model (CCSM4)
CNR	National Centre for Meteorological Research Coupled GCM v5 (CNRM-CM5)
GFD	Geophysical Fluid Dynamics Laboratory Coupled Model (GFDL-CM3)
MPI	Max Planck Institute Coupled Earth System Model (MPI-ESM-LR)
NOR	Norwegian Earth System Model (NorESM1-M)

5.3.4 Model Description

The AquaCrop model (Steduo et al., 2009) is a water-driven crop model that requires specific input files detailing soil properties, climate and management conditions to simulate yield responses to water under different management practices (Steduo et al., 2009; Mabhaudhi et al., 2014; Mthembu et al., 2025). The model was selected to estimate attainable yields and water-use efficiency for all selected crops (Kunz et al., 2024). The AquaCrop model was run using 50 years of observed data (1950-1999), yielding 49 seasons of crop data (Kunz et al., 2024). In the study, locally calibrated and validated files were used. Table 5.4 summarizes the sources of these files. All crops were simulated under rainfed conditions during the main summer rainfall season (September-March), which represents the primary production window for smallholder systems in South Africa. In addition, the model was run with future projections covering the years 1961 to 2100 from 6 GCMs forced by RCP 8.5. The projections were not continuous; they were divided into 30-year data periods: the present climate (1961-1990), the near future (2015-2044) and the distant future

(2070-2099), providing 29 seasons of crop data, under dryland conditions per timeline (Kunz et al., 2024). Planting dates for the selected crops were as follows: 15 September for Amaranth, 15 October for Bambara groundnut and Sorghum, and 15 November for Taro. The AquaCrop model outputs were used to calculate NY and NWP.

Table5. 4: Sources of Calibration and Validation for the files used.

Crop	Cultivar/landrace	Source calibration	Source validation
Amaranth	<i>Amaranthus cruentus</i>	Nyathi et al. (2018)	Nyathi et al. (2018)
Bambara nut	<i>Red landrace</i>	Mabhaudhi et al. (2014a)	Mabhaudhi et al. (2014a)
Groundnut	<i>Arachis hypogaea L.</i>	Chibarabada et al. (2020a)	Chibarabada et al. (2020a)
Maize		Mbangiwa NC (2018)	Mbangiwa NC (2018)
Potato	<i>AquaCrop Default File</i>	Raes et al., 2018	Raes et al., 2018
Sorghum	<i>Macia Ujiba Pan8816</i>	Hadebe et al. (2017)	Hadebe et al. (2017)
Soybean	<i>Soybean Glycine max (L.) Merrill cultivar (PAN 666R)</i>	Mbangiwa, et al., 2019	Mbangiwa, et al., 2019
Taro	<i>Dumbe dumbe L.</i>	Mthembu et al. (2025)	Mthembu et al. (2025)

5.3.5 Concepts

Nutritional yield (NY): A measure of the nutritional value of the harvested yield (t ha^{-1}). In this chapter, NY is calculated for energy (kcal ha^{-1}), Iron (mg ha^{-1}), protein (g ha^{-1}), vitamin A (mcg ha^{-1}) and Zinc (mg ha^{-1}). The micronutrient content harvested over the three time periods was calculated from the yield (t ha^{-1}) multiplied by the crop nutrient concentration (NC).

$$NY = Yield \times NC \times 10000$$

Equation 5.1

where: **NY** – nutritional yield

Y – Yield (t ha^{-1})

NC – Nutrient content, measured as *kcal/100 g of crop, mg/100 g of crop, g/100 g of crop, or mcg/100 g of crop*. The Nutrient Content data used was sourced from the FAO data repository for West Africa due to limited data availability for South Africa.

Nutritional Water Productivity (NWP; g m^{-3}) : Emphasises the importance of the nutritional quality of yield in relation to water requirements during production (Drastig et al., 2023). The concept shifts the focus from mass production to focusing on the nutritional outputs of cropping systems, particularly in resource-poor environments such as South Africa, a water-scarce country (Drastig et al., 2023; Engelbrecht et al., 2024).

$$NWP = WUE \times NC \times 10$$

Equation 5.2

where: **NWP** – Nutritional Water Productivity (g m^{-3})

WUE – Water Use Efficiency

NC – Nutrient content

Water Use Efficiency WUE Describes the relationship between yield output per unit of water (kg m^{-3} or kg mm^{-1}).

5.3.6 Data Analysis

The model simulation outputs provided data on the Yield and WUE. NY and NWP were calculated in Excel from an average ensemble of Yields and WP per period at a quinary catchment resolution, using the equations in section 5.3.5. Outputs for NY and NWP were mapped using ArcGIS Pro 3.4 (ESRI, 2024).

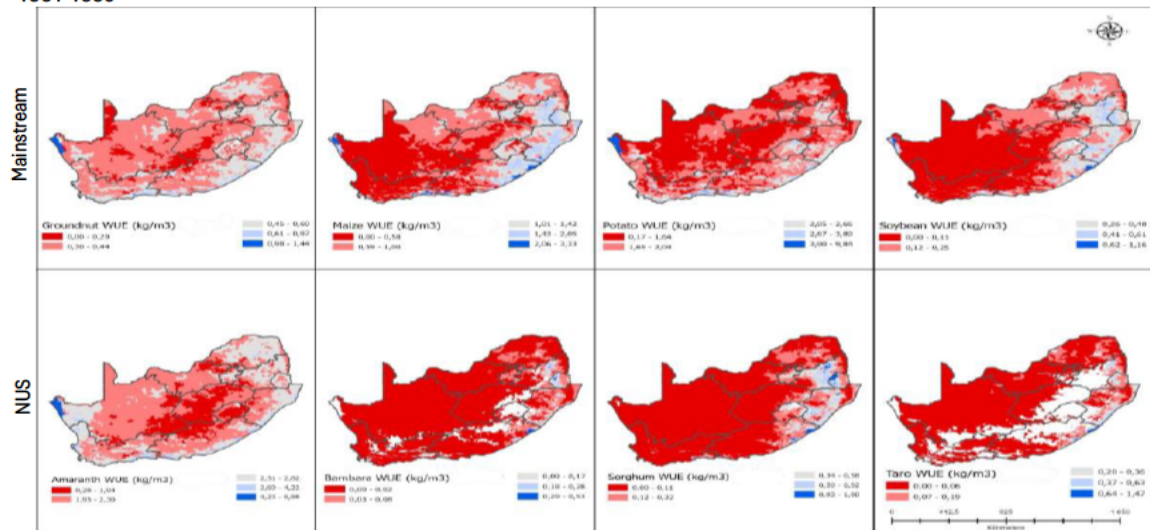
5.4 Results

5.4.1 Water Use Efficiency of Mainstream and Underutilised Crops

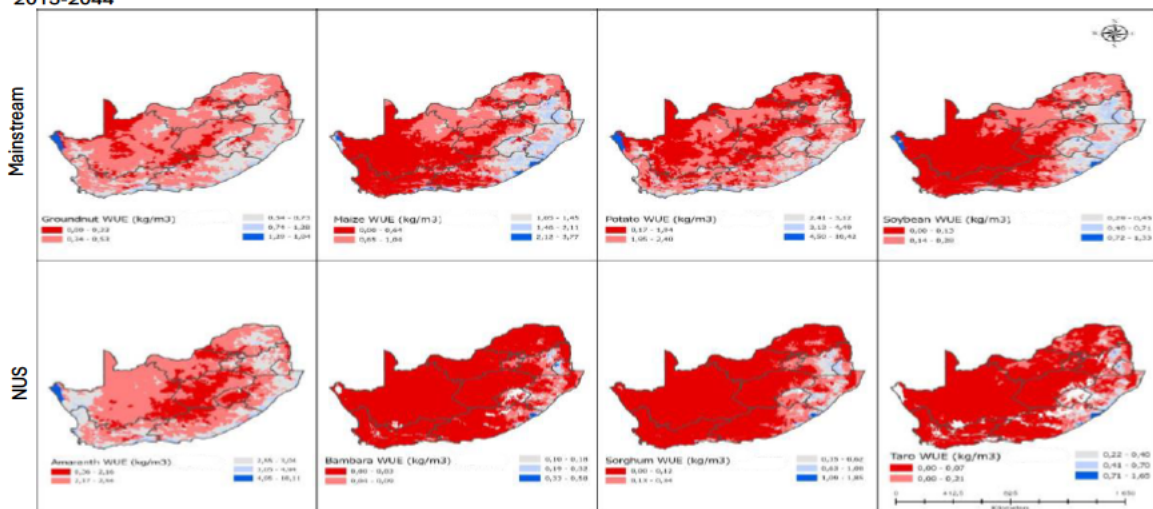
Water Use Efficiency (WUE) of Mainstream and NUS crops over the 1961-1990 period indicates that potatoes had the highest WUE values among the Mainstream crops, which ranged from 0.17-1.64 kg m⁻³ (lowest) to 3.90-9.84 kg m⁻³ (highest) in some localities across the northern west side of Northern Cape and the Western and Eastern Cape provinces. Maize also had the highest WUE among Mainstream crops, particularly along coastlines in the Western and Eastern Cape provinces, KwaZulu-Natal, Mpumalanga, and the Northern Cape (Figure 5.1). Amaranth had the highest WUE among the NUS, particularly along the South African coastline, extending from the Northern Cape along the coast to the KwaZulu-Natal coast. Amaranth further presented higher values of WUE across the country among all the selected crops in this timeline, presenting the lowest values of 0.28-1.94 kg m⁻³, dominant values of 1.95-2.31 kg m⁻³ across most of the country and higher values of 2.83-4.22 and 4.23-8.88 kg m⁻³ along the coastal areas (Figure 5.1). Taro and Sorghum also presented notable WUE, particularly across the Eastern Cape and KwaZulu-Natal Coastlines.

WUE of the potato improved generally across the country, peaking at 5.59-12.44 kg m⁻³ in some localities in the Northern, Western and Eastern Cape provinces in the 2015-2044 and 2070-2099 timelines. There was also an improvement in the WUE of Groundnut, Maize and Soybean from the near and distant future timelines (Figure 5.1). Looking at NUS, Amaranth presented the highest and improving WUE across the 2015-2044 and 2070-2099 timelines nationwide. The WUE of Amaranth were higher, particularly along the South African coast, peaking at 3.36-5.10 and 5.11-10.87 kg m⁻³ in the 2070-2099 timeline and inland localities, peaking at 2.46-2.86 and 2.87-3.35 kg m⁻³ in the Northern, Western and Eastern Cape provinces, KwaZulu-Natal and Mpumalanga. Sorghum and Taro also showed improved WUE, particularly in the Eastern Cape, KwaZulu-Natal, and Mpumalanga regions, from the 2015-2044 to the 2070-2099 timelines. Bambara groundnut presented the least improvement in WUE across all timelines.

1961-1990



2015-2044



2070-2099

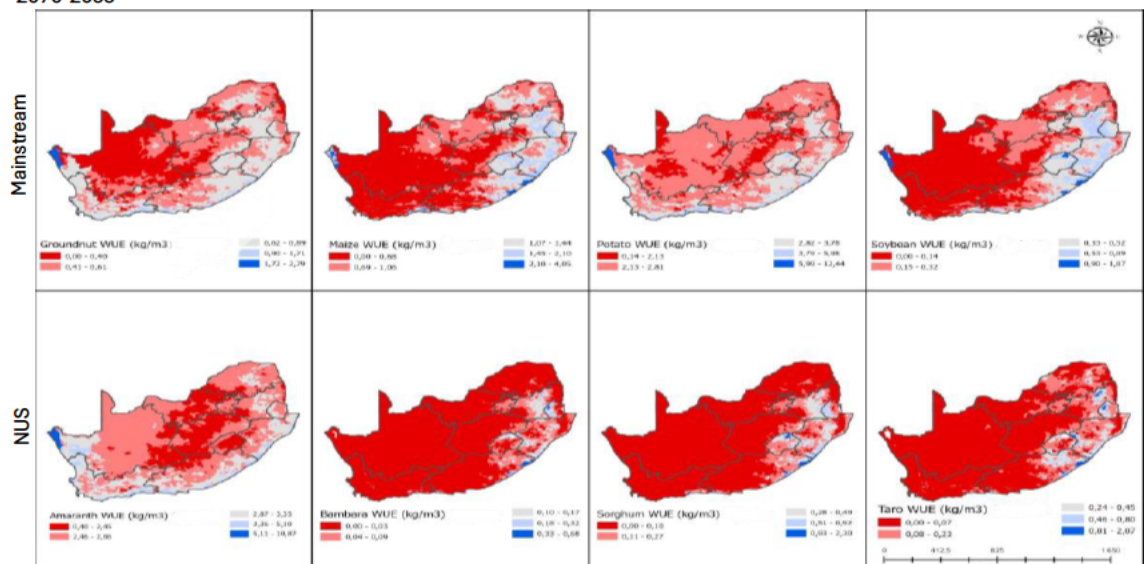


Figure 5.1 : Water Use Efficiency of Mainstream and Underutilised Crop across three timelines 1961 - 1990; 2015 - 2044; 2070 – 2099.

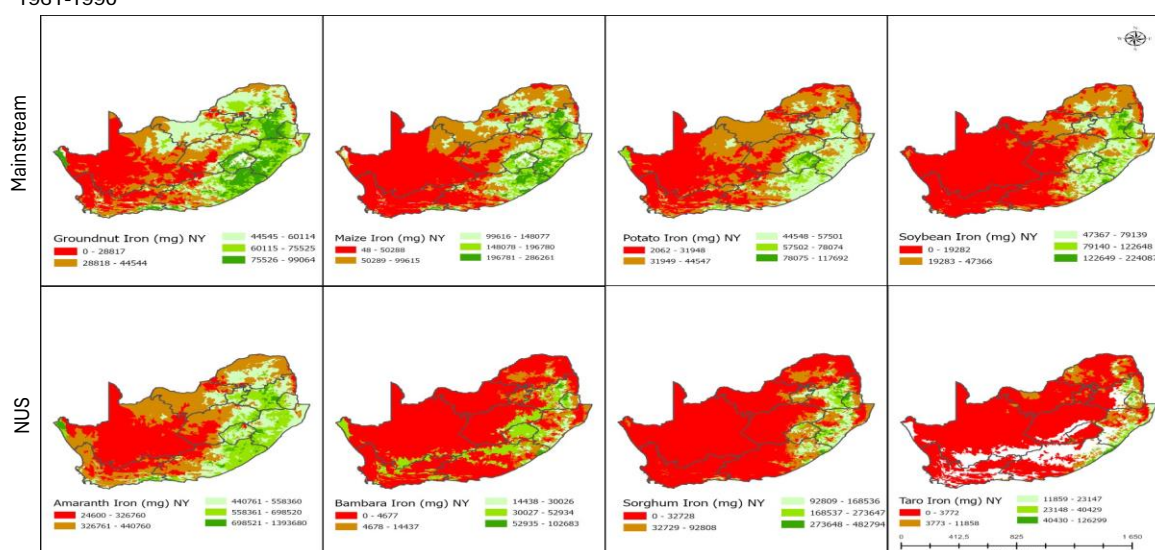
5.4.2 Identifying differences in Nutritional Yields (NY) between selected Underutilised and Mainstream crops

This section provides a comparative analysis of NY between Mainstream and Underutilised (NUS) crops.

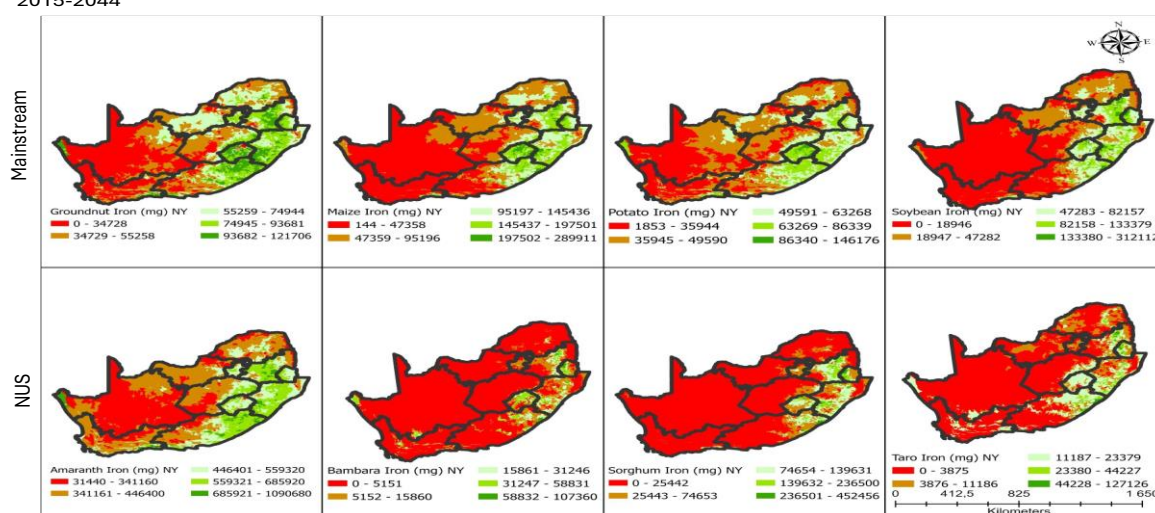
a. Iron

Nutritional Yields (NY) of Iron (mg ha^{-1}) in Mainstream crops were primarily lower than those of NUS crops across the three time periods (1961-1990, 2015-2044, and 2070-2099). Despite being underutilised and marginalised in research and crop improvement, NUS crops, such as Amaranth and Sorghum, presented the highest nutritional yields of Iron among all crops across the three time periods. Sorghum presented a higher NY of Iron compared to Maize, which is a Mainstream crop. However, Maize had a wider distribution pattern across the country compared to Sorghum, which secures its dominant status despite its lower nutritional value. Potatoes showed slightly higher NY and suitability across the three timelines in South Africa compared to an underutilised tuber crop, Taro (Figure 5.2). Bambara groundnut presented lower NY and distribution zones compared to the Groundnut, predominantly in the 2015-2044 to 2070-2099 time periods. Nutritional Yields of Iron in Soybean increased steadily from 1961-1990 to 2070-2099 alongside a similar distribution pattern across the country.

1961-1990



2015-2044



2070-2099

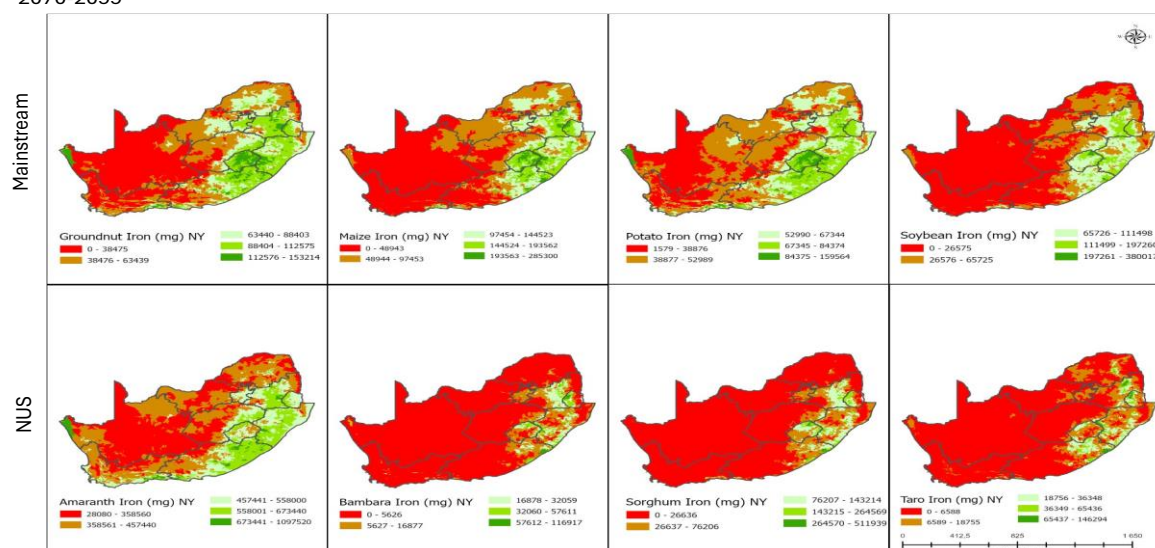
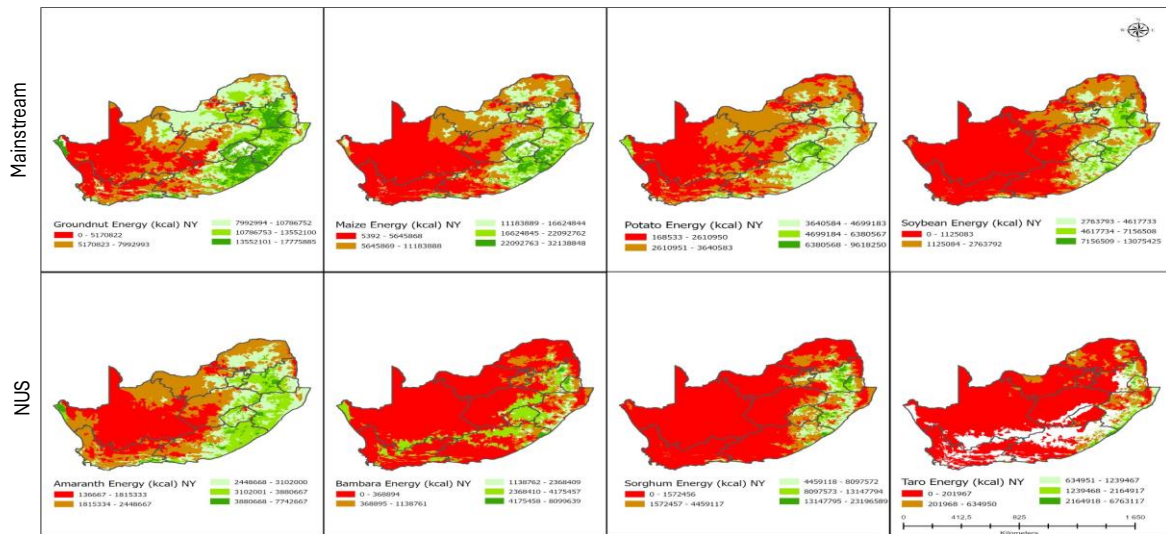


Figure 5.2: Nutritional Yields (NY) of Iron among Mainstream and Underutilised Crops across three timelines: 1961-1990; 2015-2044; 2070-2099.

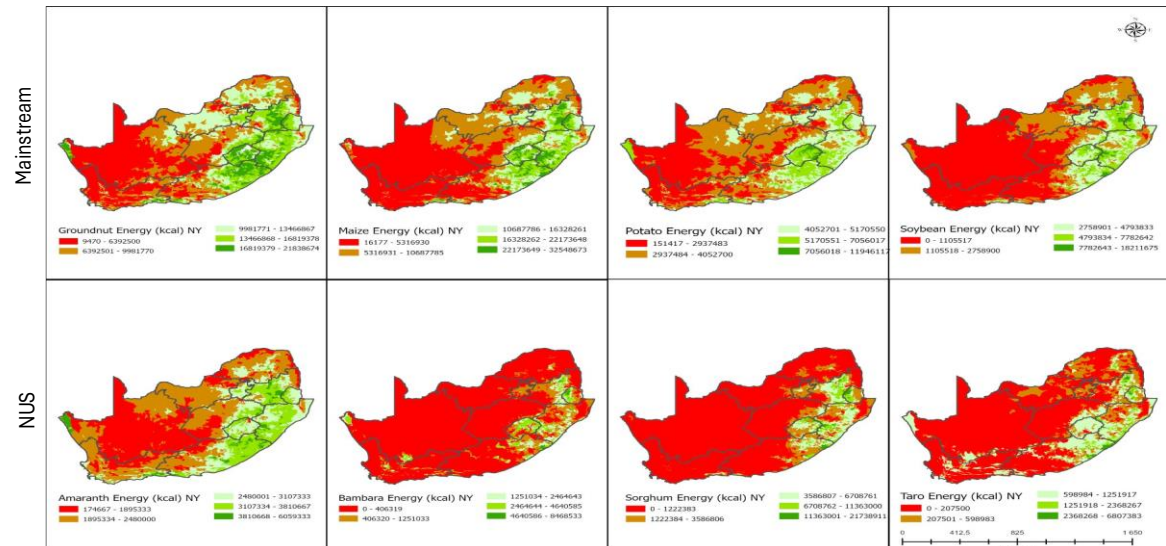
b. Energy

Nutritional Yields of energy (kcal ha^{-1}) for Mainstream crops were higher than those of NUS across the three time periods. Maize presented high NY of energy peaking at 32138848, 32548672, and 32031000 kcal ha^{-1} in 1961-1990, 2015-2044 and 2070-2099, respectively, compared to Sorghum with NY values for energy peaking at 23196588, 21738911 and 24596877 kcal ha^{-1} , respectively, across the different timelines. Groundnut also had higher energy content and a wider distribution across South Africa compared to Bambara groundnut, an underutilised Groundnut (Figure 5.3). Energy NY of Groundnut peaked at 20200300-27472485 kcal ha^{-1} in the 2070-2099 timeline, while the same peaked at 4544351-9222361 kcal ha^{-1} for Bambara. Potatoes had higher NY of energy and wider distributional patterns across South Africa compared to an underutilised tuber, Taro, across all timelines (Figure 5.3). Energy NY for Taro was predominantly higher in the eastern inland and coastal regions of South Africa, across the Eastern Cape, KwaZulu-Natal, and Mpumalanga, while energy NY of potatoes had a wider distribution across the country. Amaranth had a higher NY for energy and a wider distribution pattern compared to all the other NUS across the three timelines. Soybean presented higher NY of energy across parts of the Eastern Cape, KwaZulu-Natal, Mpumalanga, Limpopo, Gauteng, North West and the Free State across the three timelines.

1961-1990



2015-2044



2070-2099

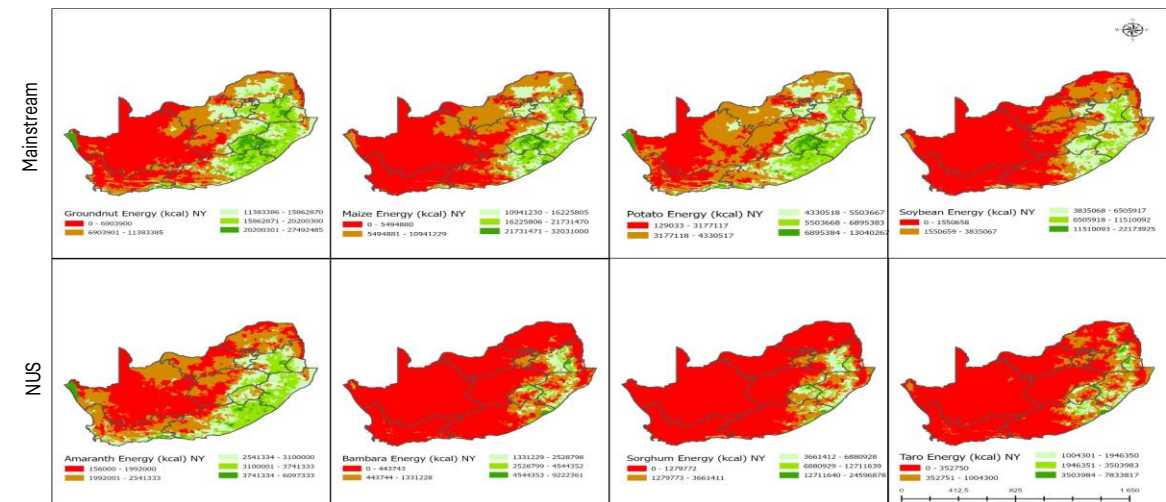
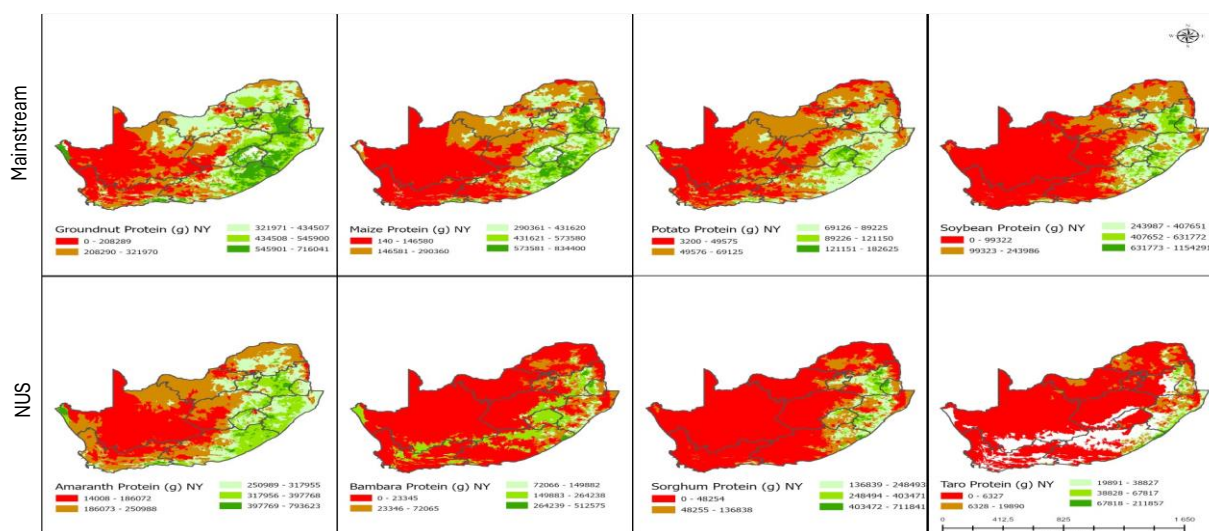


Figure 5.3: Nutritional Yields (NY) of Energy among Mainstream and Underutilised Crops across three timelines: 1961-1990; 2015-2044; 2070-2099.

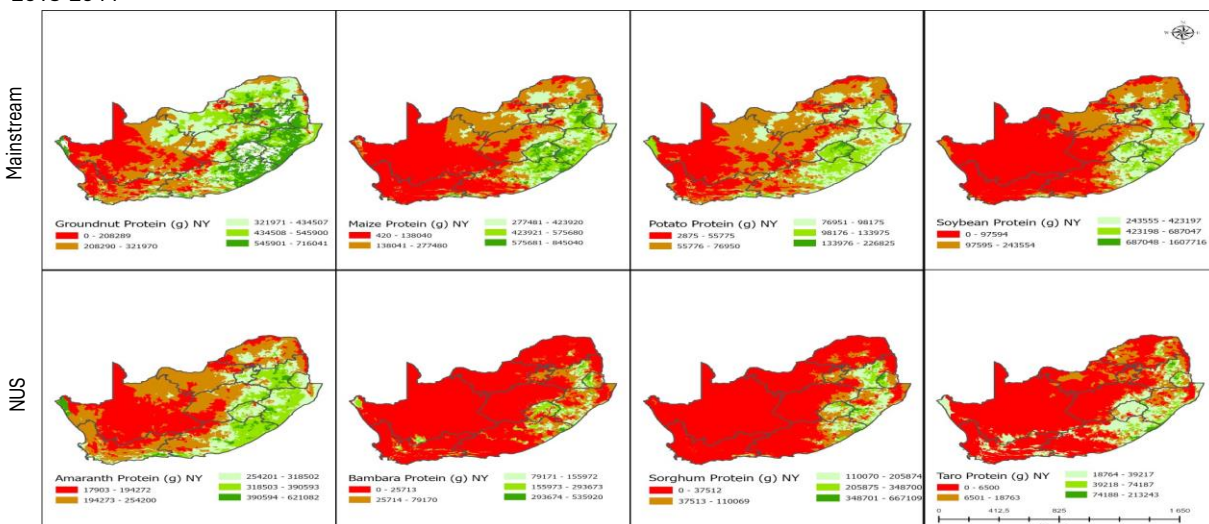
c. Protein

A significant range of protein content was seen between Mainstream and NUS crops across the three time periods. Nutritional Yields of protein (g ha^{-1}) were highest in Soybean, Maize, and Groundnut among the Mainstream crops, and Sorghum and Amaranth among NUS crops across all timelines. However, protein NY for Maize presented a slight decrease in the 2070-2099 timeline, while those of Soybean and Groundnut maintained a steady increase across all timelines, peaking at 1016103-1957500 and 813700-1107440 g ha^{-1} , respectively, in the 2070-2099 timeline. Potatoes had the lowest NY for protein among the Mainstream crops. Compared to another tuber, Taro, potatoes had a higher NY for protein and a wider distribution across all provinces in South Africa. However, Taro yielded significant protein NY in four provinces battling food insecurity and malnutrition, Eastern Cape, KwaZulu-Natal, Mpumalanga and Limpopo, which merits their inclusion in current agricultural systems to provide stability and diversity. Bambara groundnut also showed significant NY for protein in localised settings across South Africa; however, its distribution range narrowed in the 2070-2099 timeline (Figure 5.4).

1961-1990



2015-2044



2070-2099

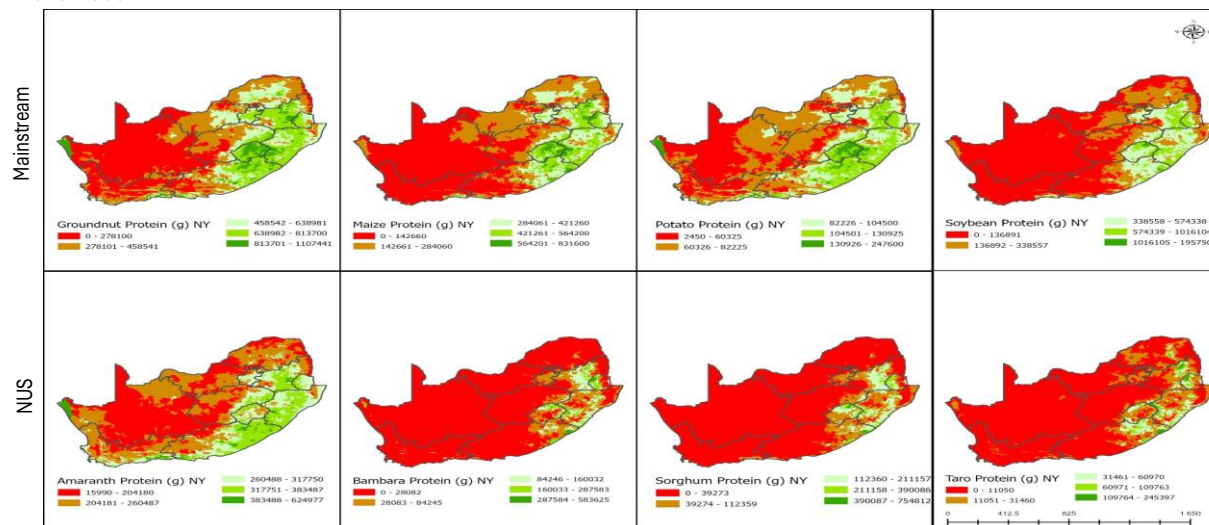
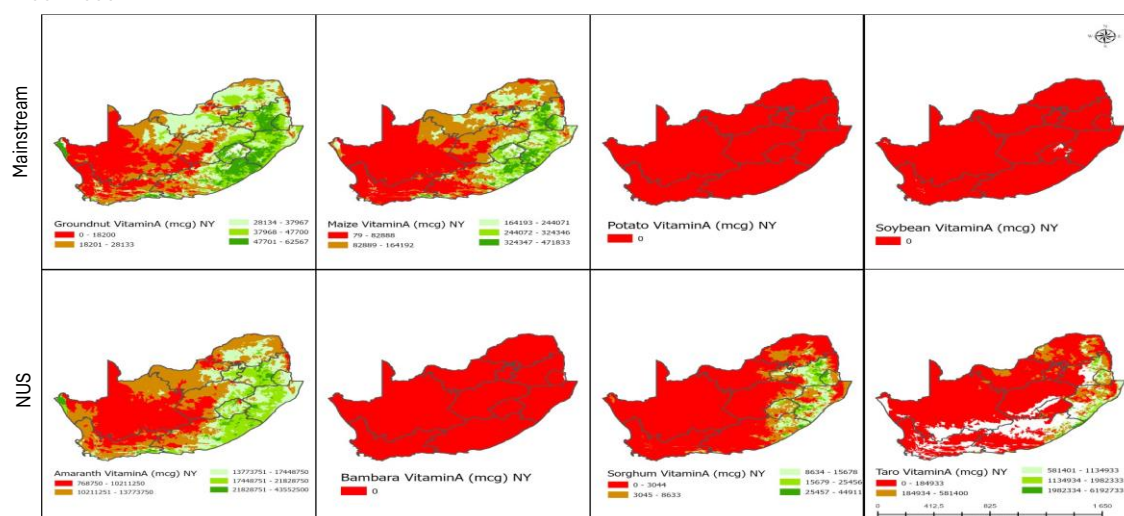


Figure 5.4: Nutritional Yields (NY) of Protein among Mainstream and Underutilised Crops across three timelines: 1961-1990; 2015-2044; 2070-2099.

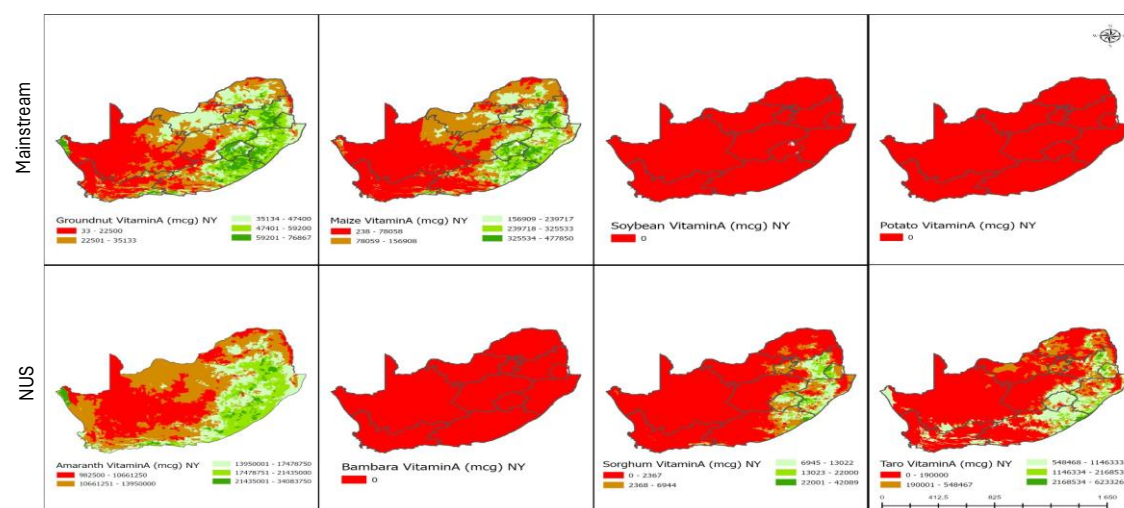
d. Vitamin A

Nutritional Yields of Vitamin A (mcg ha^{-1}) were absent for two of the four Mainstream crops, potato and Soybean and one NUS, Bambara, across all periods. Sorghum had lower NY of Vitamin A across the three time periods compared to Maize, which presented NY of up to 477850 (highest) and 470250 (lowest upper threshold) mcg ha^{-1} in 2015-2044 and 2070-2099, respectively. NY of Vitamin A in Sorghum decreased in 2015-2044, coming from the 1961-1990 period, and then increased within the same distribution zone again in 2070-2099, while NY of Maize slightly decreased in 2070-2099 (Figure 5.5). Groundnut presented a significant NY amount of Vitamin A compared to Bambara, which had zero yields across the three timelines. Amaranth had the highest NY of Vitamin A out of all the crops being studied across the three timelines, underscoring its potential as a valuable source of this vitamin, which is often lacking in people's diets in South Africa, particularly in marginalised settings. Further, Taro, which is an underutilised tuber, also demonstrated significant NY of Vitamin A in the Eastern Cape, KwaZulu-Natal, Mpumalanga and Limpopo, which are often associated with high rural populations, poverty and food and nutrition insecurity. The presence of this essential vitamin in more NUS crops compared to Mainstream crops highlights their potential to address contextualised nutritional deficiencies and improve the dietary diversity of vulnerable populations under different climate change scenarios.

1961-1990



2015-2044



2070-2099

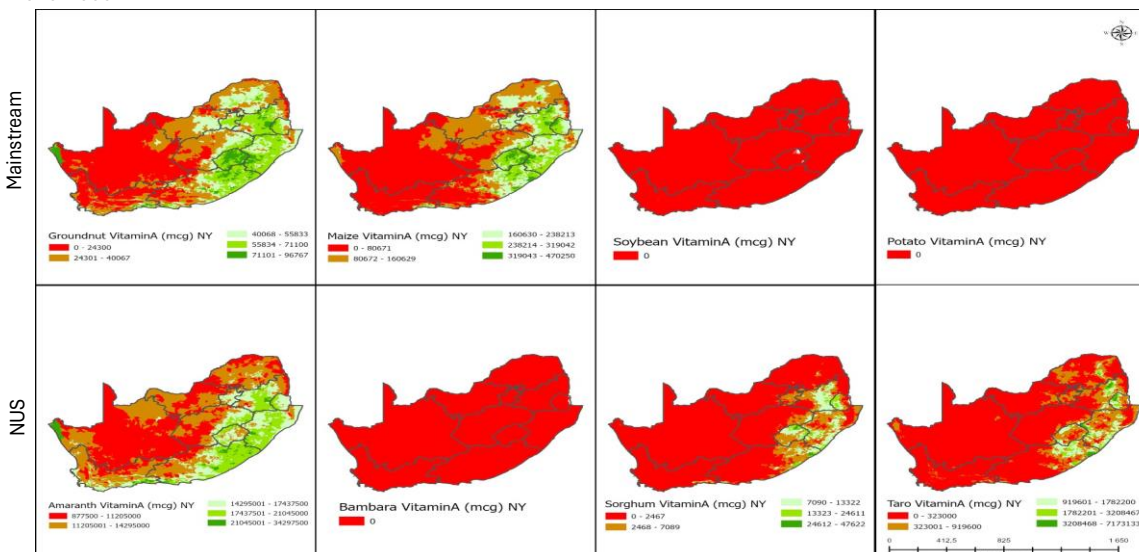
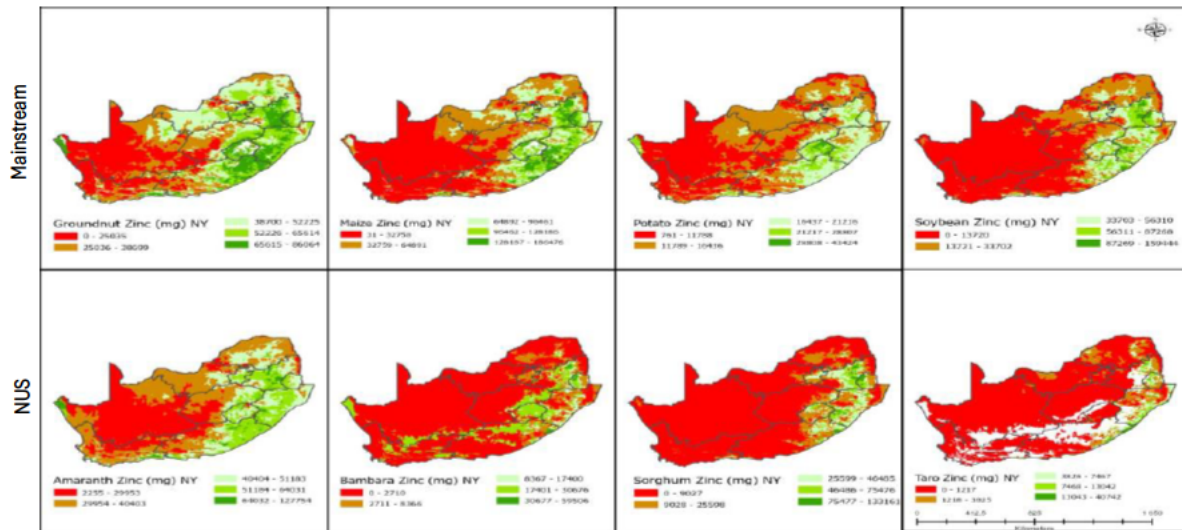


Figure 5.5: Nutritional Yields (NY) of Vitamin A among Mainstream and Underutilised Crops across three timelines: 1961-1990; 2015-2044; 2070-2099.

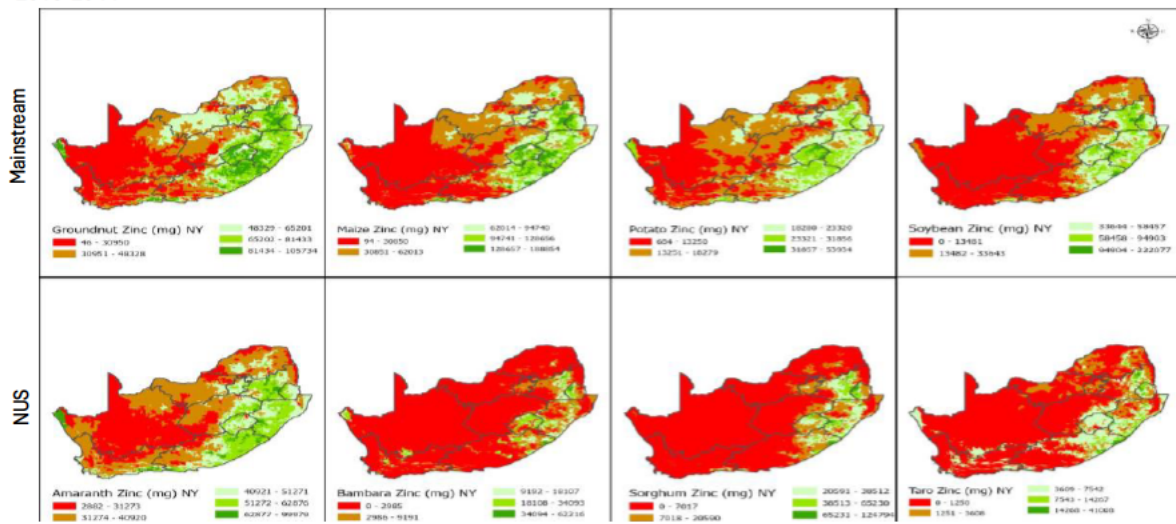
e. Zinc

Nutritional Yields for Zinc (mg ha^{-1}) were highest in Soybean and Maize across the three time periods. They showed an upward trend from 1961-1990 to 2015-2044 and slightly declined in Maize in 2070-2099, while the NY of Zinc in Soybean maintained an upward trend across similar distributional zones. Sorghum presented the highest NY of Zinc among the NUS across the three time periods, and these values gradually increased across the periods, peaking at $141199.89 \text{ mg ha}^{-1}$ in the 2070-2099 period. Amaranth also presented high NY for Zinc and had a wider distribution across the country compared to Sorghum and the other NUS. Bambara groundnut and Taro presented significant NY across similar distributional zones for Zinc across the three time periods. However, when compared to Groundnut, the NY of Bambara groundnut was low across the three timelines, although it improved gradually from 1961-1990-2070- 2099, peaking at $67754.17 \text{ mg ha}^{-1}$ in 2070-2099 compared to $59505.83 \text{ mg ha}^{-1}$ in 1961-1990 (Figure 5.6). Potatoes had higher NY for Zinc, stable suitability to climates and a wider distribution across the country in all three time periods compared to Taro.

1961-1990



2015-2044



2070-2099

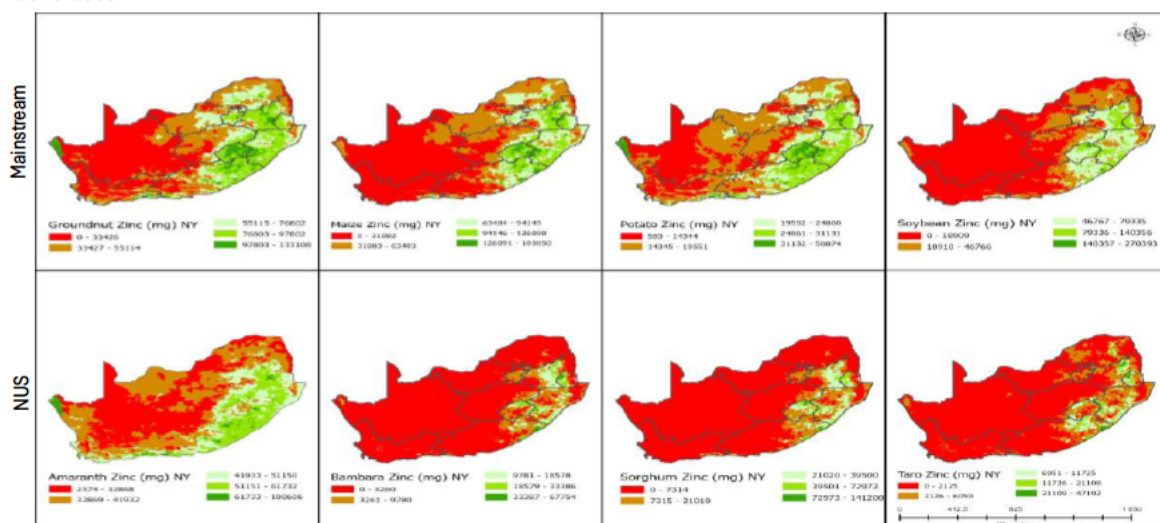


Figure 5.6: Nutritional Yields (NY) of Zinc among Mainstream and Underutilised Crops across three timelines: 1961-1990; 2015-2044; 2070-2099.

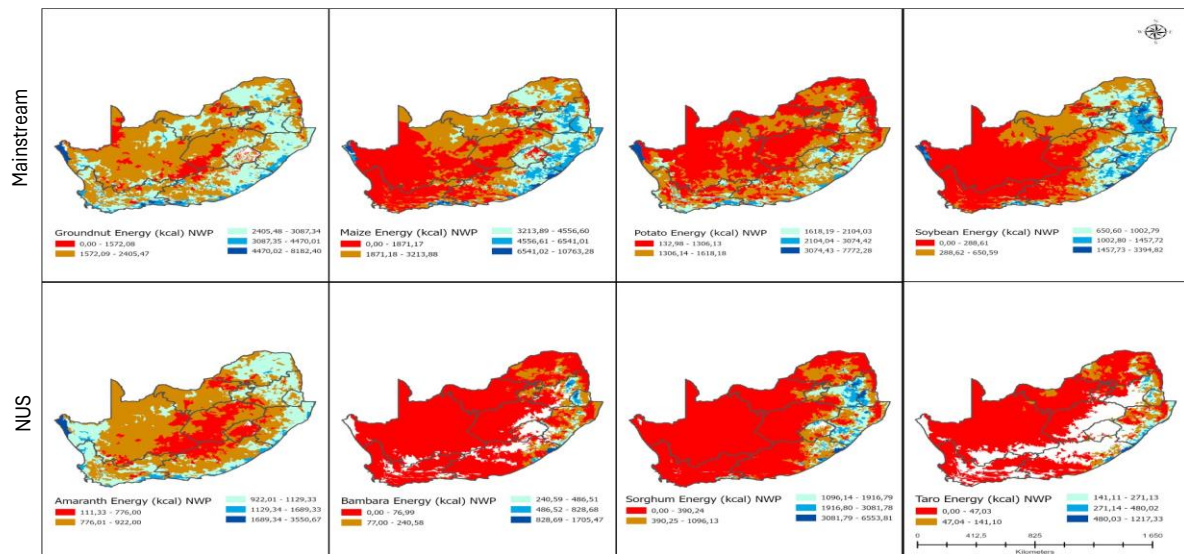
5.4.3 Examining Differences in Nutritional Water Productivity Between Selected Mainstream and Underutilised Crops

South Africa is a water-scarce country that is currently overexploiting its renewable water resources (Crookes et al., 2018; Du Preez and Van Huyssteen, 2020, Nhamo et al., 2020). Therefore, water use efficiency in this country's agriculture is essential to sustain agricultural production and productivity in local agri-food systems (Donnenfeld et al., 2028). Nutritional Water Productivity is a measure of nutrients produced per unit of water consumed. In this section, we present an analysis of the Nutritional Water Productivity of specific nutrients in Mainstream and NUS crops.

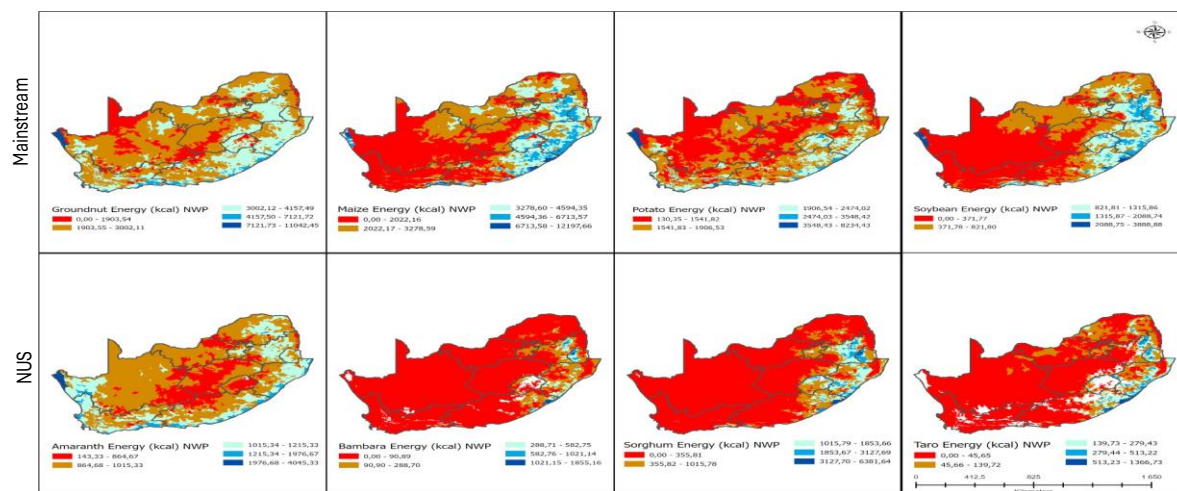
a. Nutritional Water Productivity: Energy

Energy NWP was higher among Mainstream crops across South Africa. Energy NWP was highest in Maize among all the crops studied, and it improved from 6541-10763 kcal/ha in 1990-1961 to 6778.29-13098.20 kcal ha⁻¹ in the 2070-2099 timeline. Despite being an underutilised crop, Sorghum also presented high and improving values of NWP for energy. Energy NWP of Sorghum slightly decreased in the 2015-2044 timeline but increased again in some localities in the 2070-2099 timeline, peaking at 7908.19 kcal ha⁻¹ in some localities, particularly in the Eastern Cape and south coast of KwaZulu-Natal. Among the tubers being studied, potatoes presented higher and increasing energy NWP that peaked at 4725-9830 kcal ha⁻¹ in some localities across a wider distribution zone in South Africa, while Taro presented lower but significant energy NWP in localised areas such as KwaZulu-Natal and the Eastern Cape, peaking at 1716.72 kcal ha⁻¹ in the 2070-2099 timeline. Groundnut also presented the high and increasing energy NWP. The energy NWP of Groundnut peaked at 4470-8182 kcal ha⁻¹ in the 1961-1990 period and 5057-9735 to 9735-15853 kcal ha⁻¹ in 2070-2099, peaking just above Maize NWP of energy. Bambara groundnut, on the other hand, presented the lowest values of energy NWP among NUS across all timelines. Amaranth presented significant energy NWP estimates across the three timelines in a wide distributional range in South Africa (Figure 5.7). Soybean presented lower but significantly increasing values of energy NWP in localised areas across the three time periods in South Africa.

1961-1990



2015-2044



2070-2099

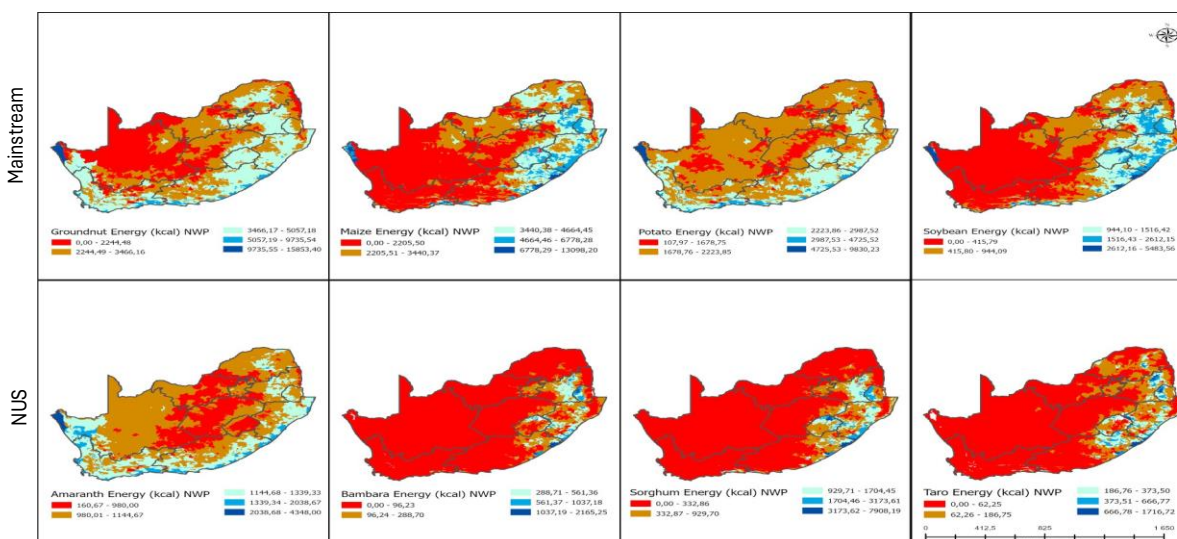


Figure 5.7: Nutritional Water Productivity of Energy Between Selected Mainstream and Underutilised Crops across three timelines: 1961-1990; 2015-2044; 2070-2099.

b. Nutritional Water Productivity: Iron

The Nutritional Water Productivity of Iron was highest in Amaranth compared to all crops studied. Amaranth presented the highest and increasing values of Iron NWP in a wide distribution across the three timelines in South Africa (Figure 5.8). The lowest ranges of Iron NWP in Amaranth were higher than the highest values seen in the other crops across the three timelines, ranging from 20-139 mg ha⁻¹ (lowest values in 1961-1990) to 366-782 mg ha⁻¹ (highest values in 2070-2099). Among the groundnuts, Bambara groundnut presented lower values of Iron NWP compared to Groundnut, which also had a wide distribution and higher NWP values across all timelines. An underutilised cereal, Sorghum, presented higher and increasing NWP values for Iron across the three time periods compared to Maize, a Mainstream cereal. Across the three timelines, Iron NWP for Sorghum peaked at 64-136, 65-132 and 66- 164 mg ha⁻¹, respectively, across the 1961-1990, 2015-2044 and 2070-2099 timelines. On the other hand, the highest values of Iron NWP in Maize peaked at 58-96, 60-109 and 60-116 mg ha⁻¹, respectively, along a wide distributional scale across the same timelines. Potatoes presented higher Iron NWP along a wide distributional zone across all timelines compared to Taro. Soybean also presented significant Iron NWP, particularly in some parts of the Northern Cape, Western Cape, Eastern Cape, KwaZulu-Natal, Mpumalanga and Limpopo, and these values increased significantly across the three timelines (Figure 5.8).

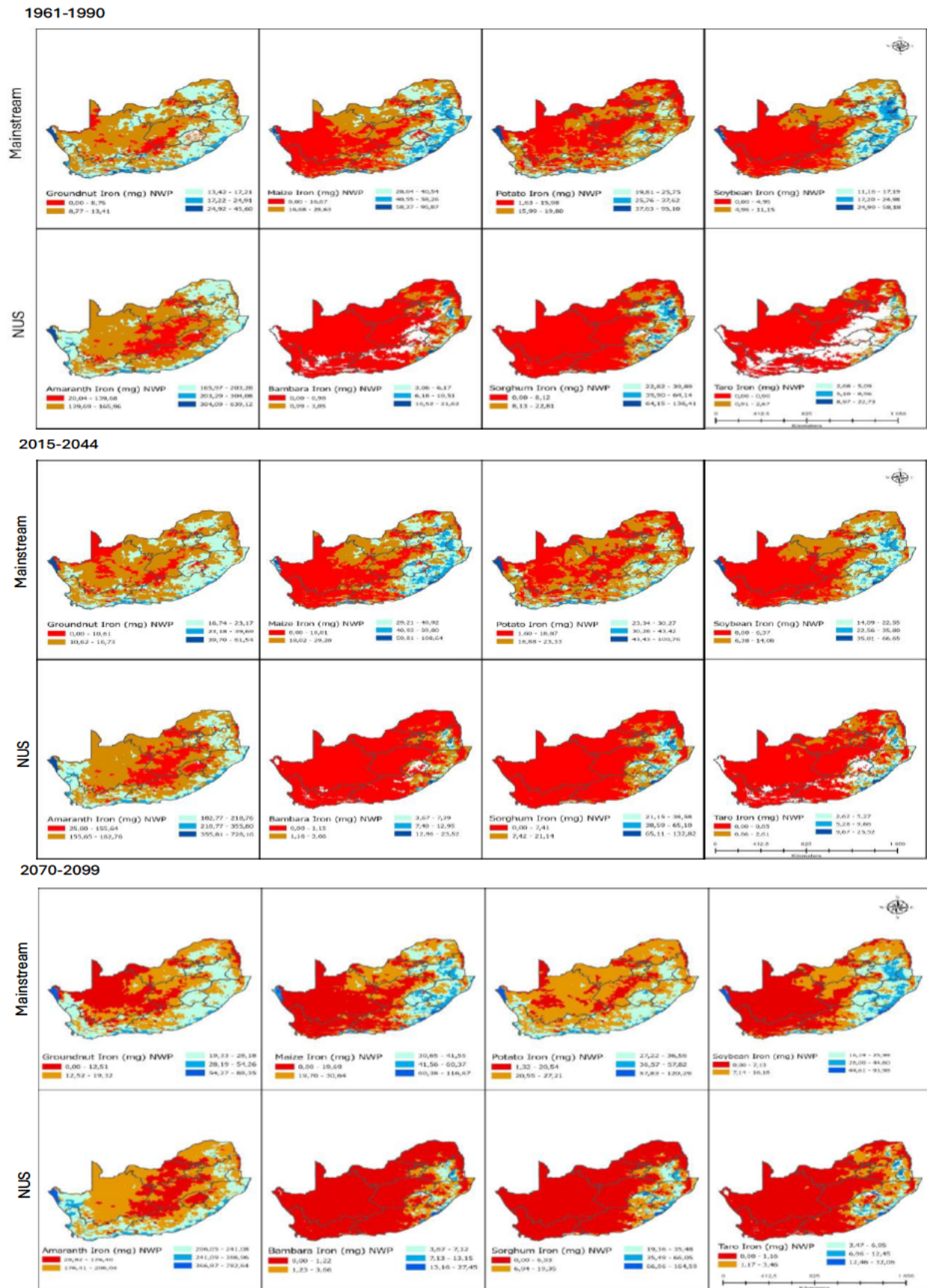
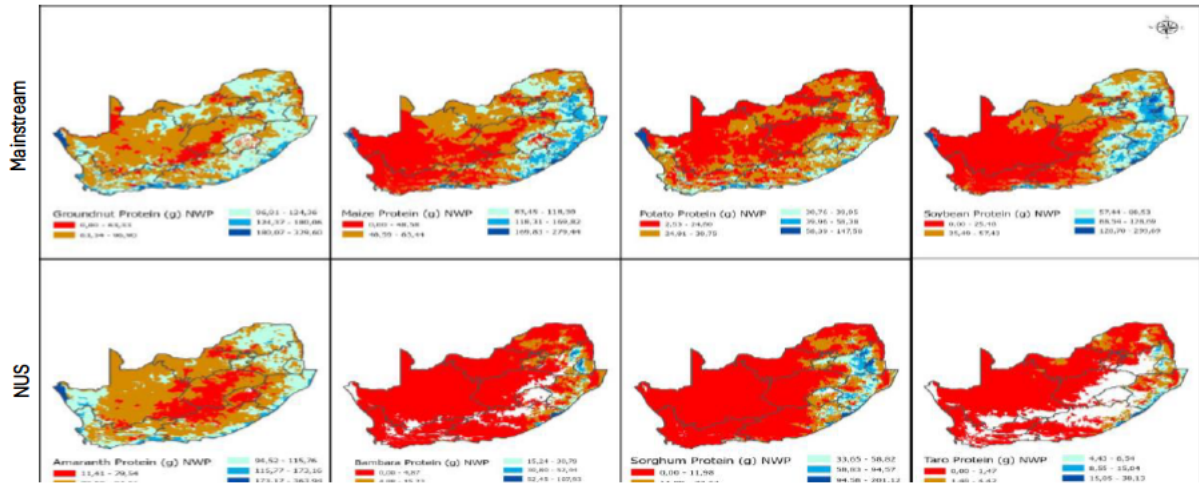


Figure 5.8: Nutritional Water Productivity of Iron between Selected Mainstream and Underutilised Crops across three timelines: 1961-1990; 2015-2044; 2070-2099.

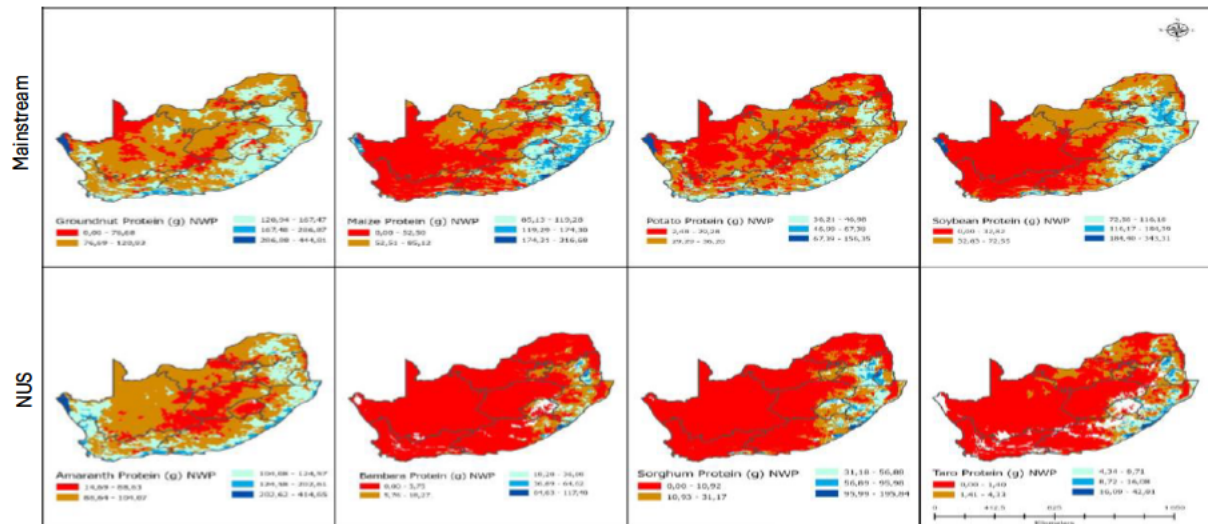
c. Nutritional Water Productivity: Protein

Mainstream crops had relatively higher Nutritional Water Productivity in terms of protein content compared to NUS. NWP of protein were higher and increasing in Groundnut, peaking at 180-329 g ha⁻¹ in 1961-1990; 286-444 g ha⁻¹ in 2015-2044 and 392-638 g ha⁻¹ in the 2070-2099 timeline. Compared to its Mainstream counterpart, Bambara groundnut had lower NWP in terms of protein content, peaking at 52-107 g ha⁻¹ in 1961-1990; 64.63-117.40 g ha⁻¹ in 2015-2044 and 65-137.03 g ha⁻¹ in the 2070-2099 timeline. Among cereals, Maize presented higher NWP in terms of protein content compared to Sorghum (Figure 5.9). NWP in terms of protein content, peaked at 169.83-279.44 g ha⁻¹ in 1961-1990; 174.3-316.68 g ha⁻¹ in the 2015-2044 timeline and 175.99-340.06 g ha⁻¹ in 2070-2099 for Maize and 94.58-201.12 g ha⁻¹ in 1961-1990; 95.99-195.84 g ha⁻¹ in the 2015-2044 timeline and 97.40-242.68 g ha⁻¹ in 2070-2099 for Sorghum. Among tubers, potatoes had higher NWP in terms of protein content and a wider distribution across the country compared to their NUS relative, Taro. However, NWP in terms of protein were highest along the coastline for both potatoes and Taro (Figure 5.9). Soybeans had the 2nd highest and increasing NWP for protein content among Mainstream crops. Amaranth had the highest protein NWP and the widest distribution across the country among NUS, presenting the highest values along the coastline, Mpumalanga and Limpopo in South Africa.

1961-1990



2015-2044



2070-2099

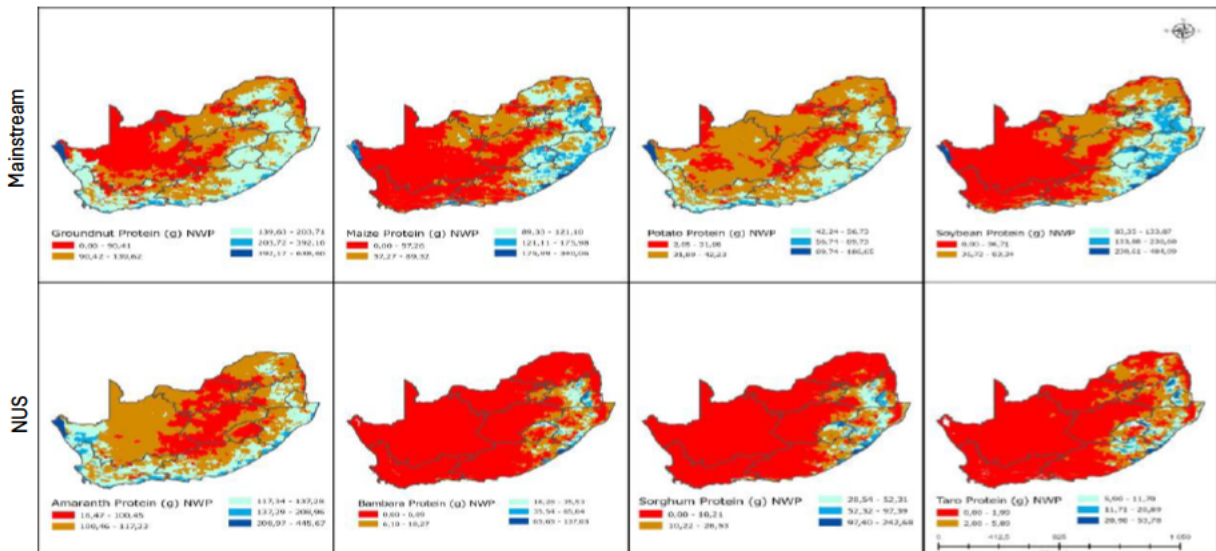
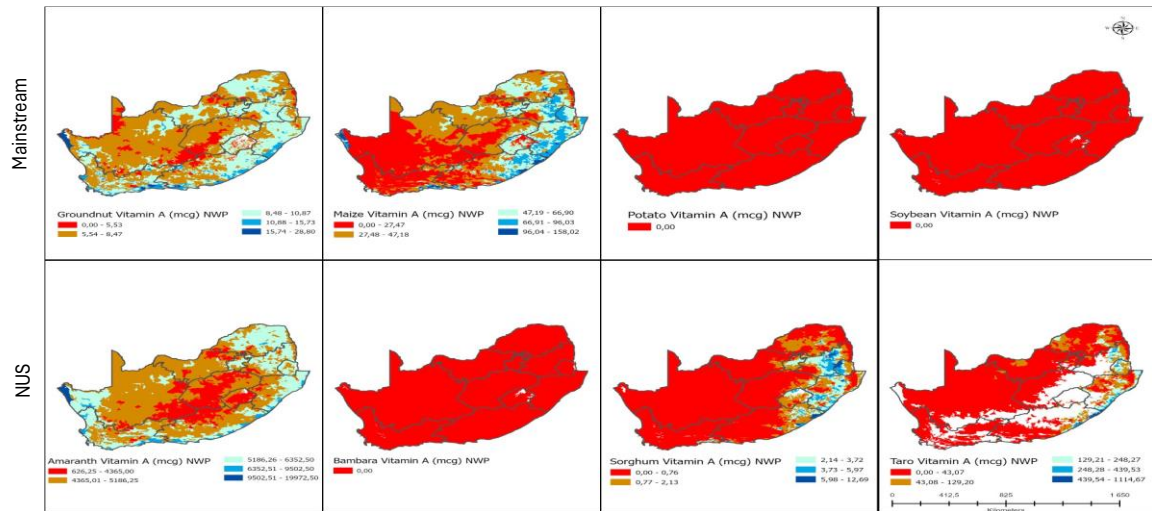


Figure 5.9: Nutritional Water Productivity of Protein between Selected Mainstream and Underutilised Crops across three timelines: 1961-1990; 2015-2044; 2070-2099.

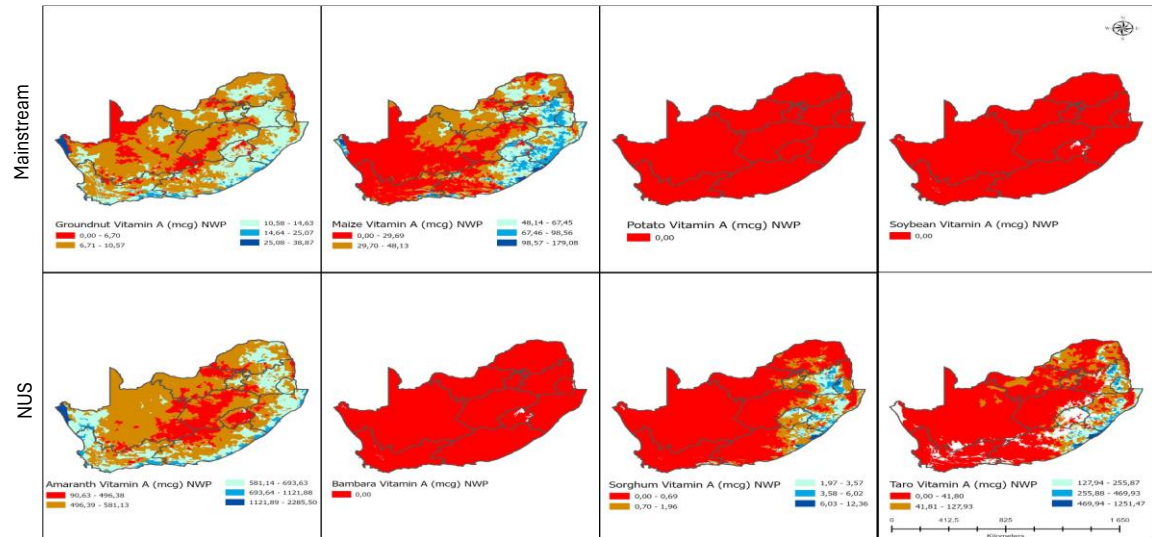
d. Nutritional Water Productivity: Vitamin A

Amaranth and Taro had the highest NWP in terms of Vitamin A content among all the crops being investigated (Figure 5.10). The NWP of Vitamin A content in Amaranth declined from predominantly 4365.01-5186.25 mcg ha⁻¹ across the country's interior and 5186.26- 9502.50 mcg ha⁻¹ along the coastline in 1961-1990 to predominantly 496.39-581.13 mcg ha⁻¹ along the country's interior and 581.14-1121.88 mcg ha⁻¹ along the coastline in the 2015-2044 timeline. The highest NWP in terms of Vitamin A content in Amaranth were highest in the 2070-2099 timeline, ranging from 5512.51-6438.75 mcg ha⁻¹ in the country's interior and 6438.76-11467.50 mcg ha⁻¹ along the country's coastal provinces, Mpumalanga and Limpopo. Groundnut had low but improving NWP in terms of Vitamin A content and a wider distribution across the country, with the highest values along the coastline (Figure 5.10). Maize had moderate but increasing levels of NWP in terms of Vitamin A content across the country, with higher and increasing values particularly in parts of the Western and Eastern Capes, KwaZulu-Natal, Mpumalanga and Limpopo across the three time periods. Compared to Maize, Sorghum had a narrower distribution path and extremely low NWP for vitamin A content, with the highest values falling within the lowest NWP range for this nutrient in Maize. Two of the four Mainstream crops (Potato and Soybean) and one of the four NUS crops (Bambara) being investigated had no NWP in terms of Vitamin A content.

1961-1990



2015-2044



2070-2099

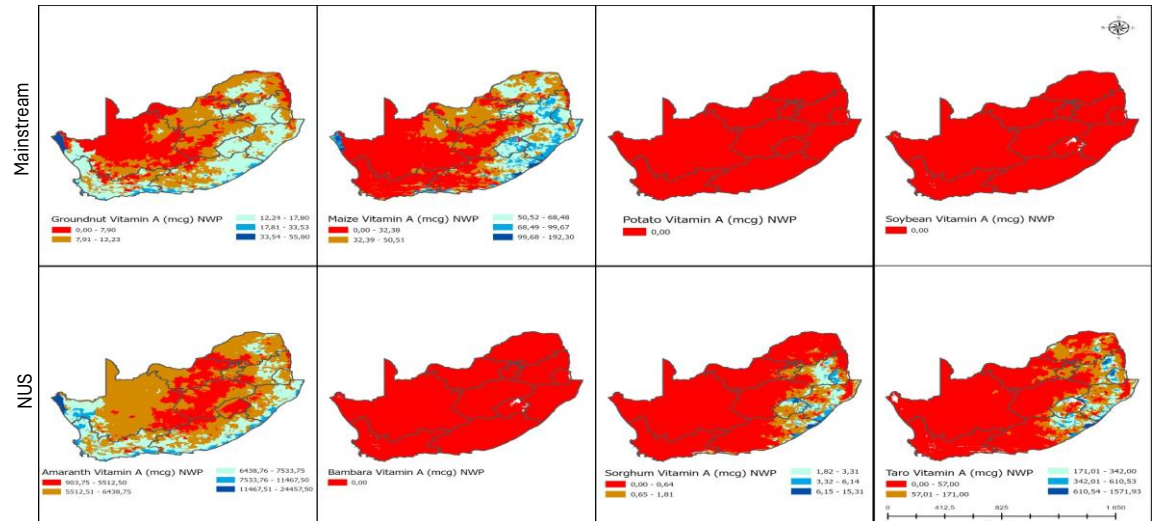
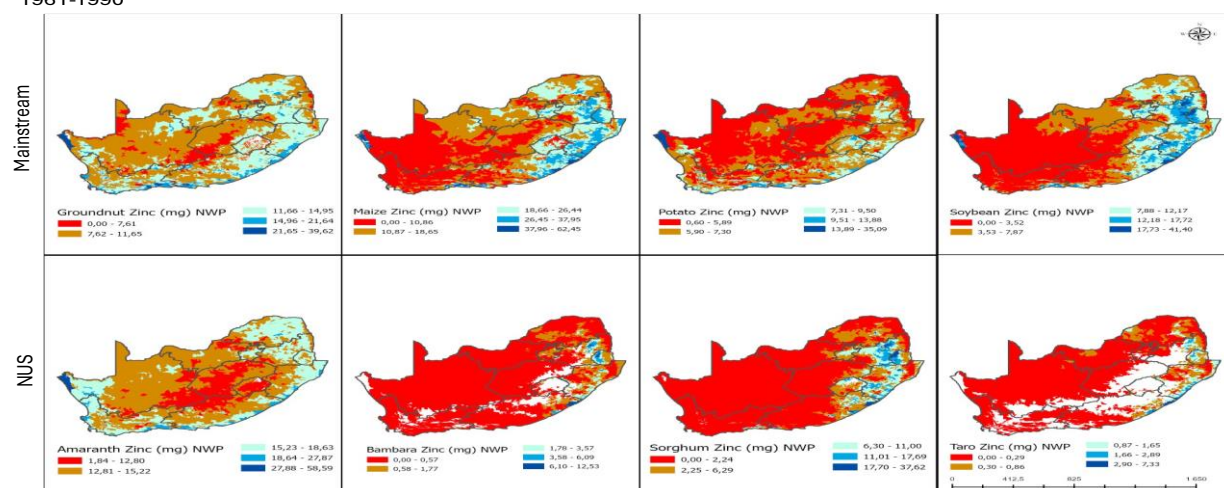


Figure 5.10: Nutritional Water Productivity of Vitamin A between Selected Mainstream and Underutilised Crops across three timelines: 1961-1990; 2015-2044; 2070-2099.

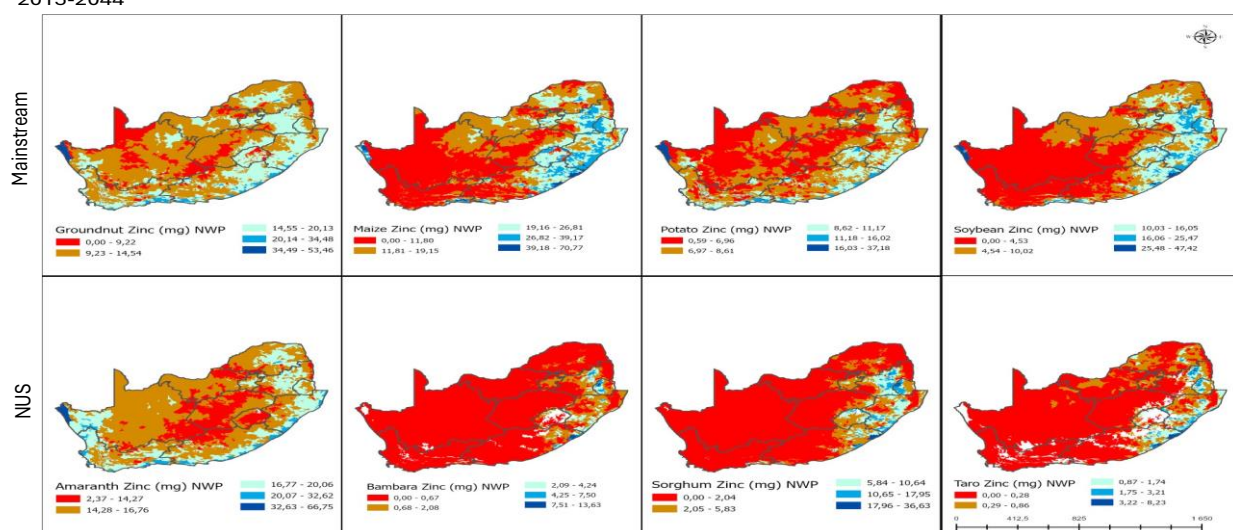
e. Nutritional Water Productivity: Zinc

Mainstream crops had higher Nutritional Water Productivity in terms of Zinc content compared to NUS (Figure 5.11). This higher productivity reflects on the effectiveness of advancements and optimisations achieved in Mainstream crop cultivation, which have resulted in superior nutrient yields of these crops per unit of water used in South African environments. Maize had the highest and increasing NWP for Zinc content among the Mainstream crops across the three time periods, peaking at 39.40-76.00 mg ha⁻¹ in the 2070-2099 period. Following Maize, among the Mainstream crops, groundnut also exhibited high and increasing NWP in terms of Zinc content across the three time periods, with a wider distribution path across the country (Figure 5.11). Potatoes and Soybeans also showed significant and increasing NWP for Zinc content across the country during all three time periods. However, potatoes had a wide distribution path across the country. In contrast, Soybeans had a more localised distribution path across parts of the Western and Eastern Cape, KwaZulu-Natal, Mpumalanga, and Limpopo. Among the NUS, Amaranth and Sorghum had the highest NWP in terms of Zinc content; however, Amaranth presented higher overall values across a wider distribution path. In contrast, the higher said values for Sorghum, peaking at 45.40 mg/ha in the 2070-2099 timeline, were localised in parts of the Eastern Cape, KwaZulu-Natal South Coast and parts of Mpumalanga, with some exceptions in the Western Cape. Bambara groundnut and Taro had the lowest NWP for Zinc, with a similar distribution across the three timelines.

1961-1990



2015-2044



2070-2099

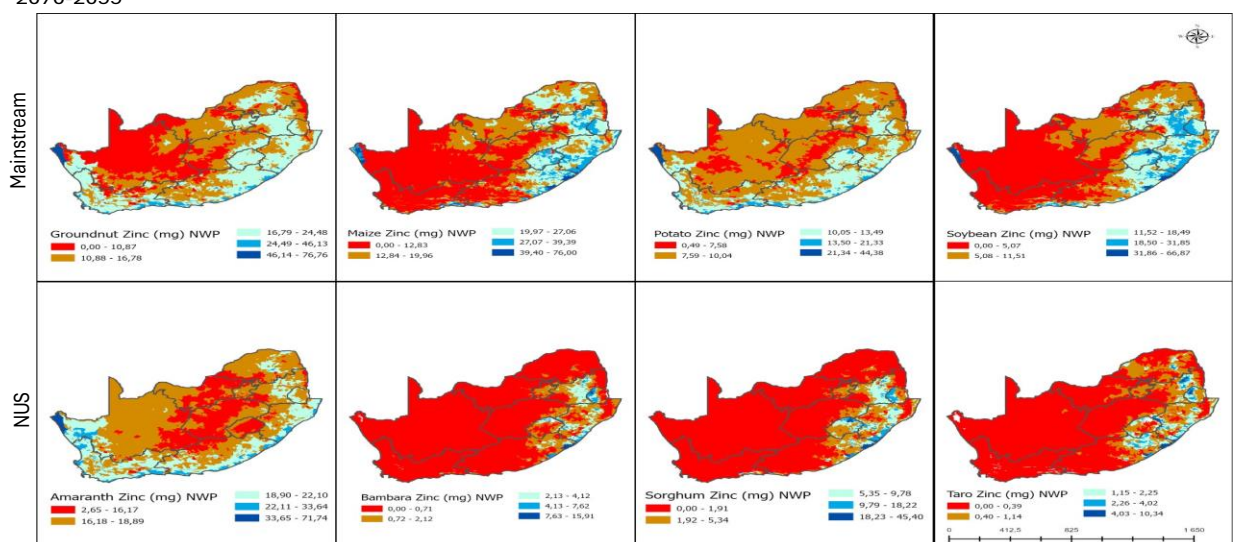


Figure 5.11: Nutritional Water Productivity of Zinc between Selected Mainstream and Underutilised Crops across three timelines: 1961-1990; 2015-2044; 2070-2099.

5.5 Discussion

5.5.1 Water Use Efficiency, NY and NWP between Mainstream and Underutilised Crops

Water use efficiency (WUE) is an important metric in agriculture in water-scarce regions (Halli et al., 2022, Yusuf, et al., 2024). Increasing water scarcity in SA warrants greater efforts to promote efficient natural resource use in agri-food systems to ensure their adaptability and sustainability under climate change (Chami and Moujabber, 2016; Donnenfeld et al., 2018). An understanding and comparative analysis of WUE, NY, and Nutritional NWP for Mainstream and Underutilised crops is among the endorsed research strategies under the National Water Resource Strategy III, aimed at improving the sustainability and water-use efficiency within existing agri-food systems (NWRS-3, 2023). The comparison between NUS and Mainstream crops can highlight possible pathways to incorporate strategic crops to optimise water use, improve the production and productivity of agri-food systems and improve food and nutrition security outcomes under changing environmental conditions in the country. However, successfully integrating NUS into agri-food systems may be constrained by scaling challenges, including limited agronomic research, seed availability, regulatory support, and market acceptance (Ndlovu et al., 2024). This underscores the need for holistic strategies that address socio-economic, institutional, and infrastructural barriers, aligned with improvements in water and agricultural productivity, primarily in the country's water-stressed landscapes. From a global perspective, the Food and Agriculture Organisation (e.g., FAO Future Smart Food, 2020) and the High Level Panel of Experts (HLPE, 2019) advocate for coordinated policy and market interventions to support the integration of NUS to improve diets and the sustainability and resilience of agri-food systems.

5.5.1.1 Mainstream crops

Post the Green Revolution, Mainstream crops such as maize, potato, groundnut, and soybean dominate SA agri-food systems due to their high-yielding varieties, agronomic advances and economic importance (Mabhaudhi et al., 2018; Nhamo et al., 2022). However, this reliance on a select few crops risks eroding genetic diversity in existing agri-food systems, increasing their vulnerability to pests and climate variability, and, as an approach, sidelining crops that could enhance food security, nutritional, and ecological resilience (DeFries et al., 2015). As it is, Mainstream crops face an increasing threat from climate change and changing local environments, making the current agri-food systems unsustainable (Kumar et al., 2022; Nhamo et al., 2022). This necessitates new approaches to agri-food systems, prioritizing diversification to stabilise food production, and natural resource use sustainability and nutritional yields (DeFries et al., 2015;

Renard and Tilman, 2019). The results of this study demonstrate that potato and maize consistently achieved the highest yields and WUE among Mainstream crops across the three time periods, reflecting targeted agronomic improvements. However, most Mainstream crops continue to exhibit low Nutritional Yields (NY) of important nutrients, particularly Iron and vitamin A, which are critically deficient in the South African context (Faber and Wenhold, 2007; Govender et al., 2021). This exposes the trade-offs and risks of yield-centric approaches within the existing agri-food systems, which overlook the diversity and nutritional value of the agri-food system (Renard and Tilman, 2019; Drastig et al., 2023). Mainstream crops showed higher NY for energy, Zinc, and protein. Furthermore, regarding Nutritional Water Productivity (NWP), mainstream crops predominantly dominate NWP in terms of energy, protein, and zinc content. While the introduction of Mainstream crops has enabled some improvements in the existing agri-food systems, it has masked critical trade-offs for freshwater resources (water scarcity impact), soil health, nutritional yields from nutrient-dense crops and long-term resilience of agri-food systems (DeFries et al., 2015; Mabhaudhi et al., 2018; Drastig, et al., 2023). Climate risks to these crops are also critical as they lack adaptability to the local environments to which they were introduced, as they are transitioning due to climate change (Mabhaudhi et al., 2018; Nhamo et al., 2022).

To address these challenges, agri-food systems need to be transformed and contextualized to be nutrient-sensitive, adaptable, and diverse (HLPE, 2019; Renard and Tilman, 2019; FAO Future Smart Food, 2020). DeFries et al. (2015) proposed that such transformation could emerge from the sustainable, nutrient-sensitive intensification of agri-food systems through incorporating multiple crop varieties such as the NUS to increase the nutritional value of the agri-food systems. This approach is supported by various research at different scales (HLPE, 2019; Renard and Tilman, 2019; FAO Future Smart Food, 2020) and has been recommended to improve the stability, sustainability and efficiency of agri-food systems and can be tailored to prioritize specific nutritional yields to meet contextualized dietary requirements.

5.5.1.2 Underutilised crops

NUS included in this study include amaranth, Bambara, sorghum and taro. These crops have been receiving increasing recognition owing to their suitability and adaptability to local climates, their richness in nutrients, and their low input requirements. This makes them a multi-risk resilience adaptation option and positions them as prime candidates for the intensification of sustainable agri-food systems in marginalised environments (McMullin et al., 2021; Mabhaudhi et al., 2022; Nhamo et al., 2022; Willis et al., 2024; Yusuf, et al., 2024).

Due to their high adaptability, NUS often thrive under resource-stressed conditions, such as in the arid/semi-arid regions, including South Africa (Mabhaudi et al., 2018; Ndlovu et al., 2024). Water Use Efficiency among these crops was highest in amaranth among all crops studied in this research. However, while this underscores its potential for water conservation, Water Use Efficiency (WUE) alone may obscure trade-offs in factors such as absolute yields, market integration, acceptance, and nutrient delivery associated with this crop. This necessitates holistic evaluations to ensure that its water efficiency translates into improved productivity, profitability of integrating these crops and their contribution to nutrition security in marginalised environments. Despite their exclusion from WUE improvement efforts, all the other NUS studied also exhibited significant and progressive increases in WUE across specific regions in the Eastern Cape, KwaZulu-Natal, which are some of the country's poorest provinces, and Mpumalanga across the three timelines. Some NUS, such as amaranth, also have the shortest time to maturity of 20-45 days (Mugiyo et al., 2021), which makes the plant important for contributing to inter-seasonal food availability, accessibility, and micronutrient security.

NUS, like amaranth and sorghum, although overlooked in research and crop improvement efforts (Ndlovu et al., 2024), demonstrated the highest NY for Iron among all crops studied across the three periods. However, their high yields for Iron must be weighed against factors such as socio-cultural acceptance to ensure that these nutritional offerings translate into improvements in dietary Iron status on the ground. Bambara groundnut and soybeans presented lower but increasing levels of Iron. Nutritional Yields of energy and protein were significantly lower in NUS across all timelines; however, amaranth presented notable and increasing values for both NY energy and protein. Taro and Bambara groundnut also showed notable NY for protein in niche environments in provinces that battle with food insecurity and malnutrition, namely the Eastern Cape, KwaZulu-Natal, Mpumalanga and Limpopo, which merit their integration into current agricultural systems to improve production stability and diversity across the country. NY of Vitamin A were absent in Bambara. However, the NY of Vitamin A was highest in amaranth among all crops studied, while Taro also showed significant values of NY of Vitamin A. The presence of this essential vitamin in more NUS crops compared to Mainstream crops highlights their potential to improve dietary diversity and address critical nutritional deficiencies among vulnerable populations under different climate change scenarios. Zinc deficiency is among the most prominent deficiencies in Sub-Saharan Africa, including South Africa, particularly among children in marginalised settings (Gupta et al., 2020). Considering this, efforts to eradicate such deficiencies need to prioritise the incorporation of crops that are naturally high in Zinc NY in existing agri-food systems to ensure accessibility of this essential micronutrient to marginalised populations. Sorghum and Amaranth presented the highest NY of Zinc among the NUS across the three time periods. In comparison, Bambara groundnut and taro also presented significant NY of Zinc across the three time periods.

Energy NWP was lower in NUS, which may reinforce yield-nutrient trade-offs. However, sorghum, taro, and amaranth presented significant and improving values of energy NWP across the three time periods. NWP of Iron was highest in amaranth among NUS. The NWP values for Iron were also higher in sorghum compared to maize. NUS had lower NWP in terms of protein content. However, all NUS crops showed notable values across all periods, and amaranth had the highest values of NWP protein among the NUS. Amaranth and taro had the highest NWP for Vitamin A content. Amaranth and sorghum also presented the highest, but localised NWP in terms of Zinc content across all three time periods. The results on WUE, NY and NWP of NUS underscore their potential as valuable crops for improving agrobiodiversity, sustainability, nutritional quality and natural resource use efficiency in SA. Given country-specific challenges with nutritional deficiencies, these crops can also significantly help address micronutrient deficiencies under conditions of increasing water scarcity and changing natural environments. However, translating this potential into resilient, nutrition-sensitive agri-food systems demands overcoming existing gaps in agronomic research, verifying the nutrient bioavailability of NUS, and establishing institutions to strengthen their value chains and infrastructure, ensuring sustained production and adoption in marginalised environments.

5.5.2 Considerations for sustainability and nutrition sensitivity of South African agricultural systems under climate change

The findings of this study reveal specific differences in WUE, NY, and NWP among NUS and mainstream crops, highlighting the importance of diversifying these agri-food systems to improve food security and address targeted nutrient deficiencies across provinces. Incorporating NUS would mean a transformation against the homogenisation of agri-food systems and prioritising locally adapted crops that can withstand localised climatic variabilities and changes to supplement the Mainstream, crops-dominated agri-food system (DeFries et al., 2015; McMullin et al., 2021; Mabhaudhi et al., 2022; Nhamo et al., 2022; Willis et al., 2024). Further, incorporating NUS would constitute an agroecological approach to achieving water efficiency, diverse and productive agri-food systems, and sustainable natural resource management simultaneously (HLPE, 2019; Mabhaudhi et al., 2022; Willis et al., 2024). NUS, however, have narrower distributional zones across the country. Therefore, strategically adopting a combination of both Mainstream and NUS crops to target specific micronutrient and mineral deficiencies in South Africa will leverage the strengths of both crop types. This approach can help construct water-efficient, diverse, and resilient agri-food systems that improve food and nutrition security outcomes within safe planetary boundaries.

5.6 Conclusions

Climate projections for South Africa indicate inevitable regionally variable shifts in precipitation and air temperature. This necessitates contextualised strategies for climate change adaptation, particularly within the agri-food systems context. These strategies should aim to maximise the sustainability of natural resource use while safeguarding resilient agricultural production to achieve food and nutrition security within safe planetary boundaries. We conducted a comparative analysis of Water Use Efficiency, Nutritional Yields and Nutritional Water Productivity between NUS, which are considered potential alternatives to conventional agri-food system staples and Mainstream crops. The comparative analysis of their WUE, NY, and NWP across similar and distinct agroecological zones reveals complementary mineral and micronutrient profiles among these crop groups. The findings underscore the importance of integrating both in existing agri-food systems, particularly in marginalised areas afflicted by natural resource scarcity, food insecurity and nutritional deficiencies. The incorporation of a variety of NUS and Mainstream crops into agri-food systems will improve environmental benefits, dietary diversity, and opportunities for improved nutritional benefits and health outcomes for humans, particularly in marginalised areas across the country under different climate change scenarios. The findings of this study present a key opportunity for future research. There is an urgent need for South Africa to invest in generating local, verifiable nutritional composition data for prioritised NUS crops: Amaranth, Sorghum, Taro, and Bambara, to validate the model inputs and outputs of the study. There is also an important opportunity to pilot interventions focused on examining contextual social/market/cultural barriers for priority NUS to design pathways to breaking these barriers and ensure that the nutritional potential of these NUS is realized at the household level. Future research can also consider using summary maps or comparative heatmaps for each nutrient rather than repeating maps for specific timelines.

5.7. References

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CHAPTER 6: GENERAL DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Introduction

Among the most significant threats to existing agri-food systems in sub-Saharan Africa, including South Africa, is climate change. Over the past decade, the country has experienced hydrometeorological and climatological extremes that are becoming more frequent and intense. These challenges exacerbate water scarcity, agricultural production, and socio-economic and socio-ecological challenges on the ground across the country, creating an interplay of factors that have negative implications for food and nutrition. Under such circumstances, transformative adaptation measures are needed to promote the sustainability of natural resource use, implement food and nutrition-sensitive agri-food systems, and enhance the productivity sustainability and resilience of existing agri-food systems under climate change.

NUS, known by different names to many people and, in a way, reflecting their multiple values across cultures, are an important subset of agrobiodiversity that could provide multi-risk resilience across different systems. More recently, they are being promoted as opportunity crops, emphasising their potential as locally available resources for some of the world's grand challenges relating to food and nutrition security, sustainable livelihoods, natural resource management, biodiversity conservation and utilisation, and food systems transformation under climate change.

The overall aim of this work was to conduct an interdisciplinary study to assess, interconnected challenges of climate risks for water and agri-food systems, food and nutrition insecurity and natural resource management in South Africa. We further evaluate the transformative potential of NUS integration into agri-food systems to support ecosystem and human health within safe planetary boundaries under climate change. By promoting the integration of NUS, we highlight their potential to transform and strengthen local agri-food systems by leveraging locally available, adapted, multi-risk-resilient, and diverse crops that respond to current and future challenges in water, food, and nutrition.

6.2 Summary of Chapters

To realise this and develop context-specific, spatially explicit agri-food systems adaptation solutions, we highlighted gaps in the utility of NUS through a systematic literature review (chapter 2). **Chapter 2** addressed the first research question and objective. The PRISMA guideline for systematic reviews was

followed. The results of the systematic review showcase evidence of the ability of NUS to contribute to food and nutrition security, climate change adaptation, dietary diversity, ecosystem services, and livelihoods. The research findings showed that current mainstream agri-food systems are among the prominent underlying causes of food and nutrition insecurity and poverty in SSA. NUS, on the other hand, are being promoted as a solution to such challenges. The promotion of NUS bodes well for agri-food systems transformation in the region within the frameworks of production sustainability and resilience and equity for people and the planet.

We further explore NUS' potential to transform South African agri-food systems (chapters 2 and 5) for environmental sustainability and human health within safe planetary boundaries under climate change (chapter 3). **Chapter 3** speaks to the second research question and objective. This chapter examines projected climate risks and impacts on water and agriculture using the Climate Moisture Index (CMI) and the Thermal Heat Index (THI). The study results show a heterogeneous decrease in rainfall across the study sites alongside distinct increases in air temperatures. These conditions suggest an increased likelihood of water and heat stress, which will exceed optimal thresholds for crop production under future climates.

Chapter 4 assesses the relationship between the coping strategies of smallholder farming households and food and nutrition security outcomes using the Household Food Insecurity Access Scale (HFIAS) and Household Dietary Diversity Score (HDDS). The study results indicated that the currently adopted climate risk coping strategies are neither efficient nor sustainable in supporting food and nutrition security amid prevailing and projected climate risks and changes.

Lastly, to address our overall goal, we integrated an understanding of climate risks and existing gaps in food and nutrition to position NUS within target environments under current and projected climate change (Chapter 5). This final investigative chapter assesses distinctions in Nutritional Yield (NY) and Nutritional Water Productivity (NWP), specifically focusing on Iron, Zinc, vitamin A, Energy, and Protein, between Mainstream crops and NUS under climate change. The study results highlight the diversity in the mineral and micronutrient profiles of different crops and indicate that some NUS showed higher NY and NWP for Vitamin A, Iron, and Zinc, which are typically deficient in rural populations.

The overall results of the study highlight the multi-dimensional and multi-risk resilience opportunities of NUS to address food and nutrition insecurity in Sub-Saharan Africa, including South Africa, under climate change. Our overall findings underscore the complexity of addressing climate risks. They highlight the need for climate-informed and context-specific transformative adaptation frameworks and strategies. These strategies need to be grounded in supporting sustainable natural resource management and enhancing the climate resilience of agri-food and agro-ecological systems to ensure food production resilience and food and nutrition security outcomes under climate change.

6.3 Contributions to new knowledge

This thesis contributes to the growing knowledge base on NUS, highlighting their potential to support multi-risk resilience, spatially explicit, and regionally differentiated climate change adaptation strategies that address food and nutrition insecurity in marginalised areas facing rising water- and temperature-related climate risks. The contribution of this study to new knowledge is mentioned below:

- This research provides an interdisciplinary approach to addressing the complex yet interconnected challenges within the agri-food system and food and nutrition insecurity under climate change in South Africa.
- This research provides initial observations into how NUS are utilised in SSA, highlighting existing gaps and potential for the utilisation of these crops as a climate change and multi-risk adaptation strategy within local agri-food systems under climate change. The study maps the research contributions of different countries on the topic, identifies evidence gaps, and offers policy recommendations for transformation in the region.
- The third chapter translates well-established climate projections into context-specific risk assessments for water and agri-food systems. The chapter applies the THI and CMI indices to highlight long-term climate risks to water and agri-food systems in three study sites where climate risk coping strategies are not informed by climate risk detection. The chapter underscores the urgent need to simplify climate risk detection and tools at the local level to improve coping and adaptation strategies and resilience.
- The final investigative chapter presents a comparative analysis of NY and NWP between specific mainstream and NUS under dryland rainfed conditions across 5838 sub-catchments in South Africa to showcase evidence of the ability of NUS crops to intensify South African agri-food systems. The chapter highlights the need to prioritize NWP over the traditional yield-centric approaches in the agri-food systems. This research presents the first insights into the topic, especially at the country-level scale.

6.4 Limitations

I did not collect primary data for this thesis. As a result, the greatest challenge was acquiring high-quality data for the different chapters at the appropriate scales. Some data, such as crop nutrient content, which was needed to compute NY for the different crops, was not available for South Africa specifically, so I used data from West Africa instead, which presents a risk of some degree of variability in nutrient density

and may slightly affect the accuracy of NY and NWP calculated for South Africa. This also highlighted gaps in the evidence on NUS' nutritional value/content. I would also like to highlight that using only the HFIAS and HDDS in Chapter 4 is a limitation. Both instruments depend on short recall periods and rely on given information. This introduces recall and desirability biases, which can lead researchers to report over- or underestimates of true food security and dietary intake. The HDDS overlooks portion sizes, frequency and nutrient adequacy. The HFIAS can be sensitive to seasonal variation and short-term shocks, which can influence the overall conclusion on food insecurity. Both tools also overlook food quality and cultural differences in food classification. Future research could address these limitations and include metrics to counter these biases.

6.5 Conclusions

NUS remain gendered and stigmatised crops that are marginalised in research and in agri-food systems. While they are now receiving growing recognition, this is still non-systemic, and existing policies and regulations continue to hinder their development, limit their integration into agri-food systems, and undermine local food sovereignty. However, the targeted adoption of NUS is key to transforming local agri-food systems into equitable, inclusive, multi-risk resilient, healthy, and sustainable systems under a changing climate.

Understanding climate risks is important for formulating adaptation strategies that align NUS with target environments that match their specific attributes, especially at the local scale. Our analysis showed that climate risks were heterogeneous across the study sites, highlighting the need for regionally differentiated adaptation strategies. The THI and the CMI showed increasing dryness and heat stress across the study sites from the present to the future climates. The increasing climate risks to water pose a threat to rainfed agriculture and highlight an urgent need for adaptive measures that build resilience. These solutions should not only focus on addressing biophysical constraints, but also on addressing gaps in food and nutrition, which are the primary outcomes of a sustainable agri-food system.

Households across the study sites primarily relied on limited, unsustainable, and asset-depleting coping strategies, such as using their own savings and social safety nets, to cope with climate risks. Alarmingly, some households had no coping strategies, highlighting high vulnerability levels. However, households that adopted limited coping strategies had better food and nutrition outcomes. This highlights the need for and importance of well-designed, effective adaptation strategies to ensure food and nutrition

security. Long-term adaptation solutions are preferred to coping strategies, as the latter often come at the expense of long-term resilience.

Addressing the twin challenges of increasing climate risks and food and nutrition insecurity requires a paradigm shift. In this regard, NUS offers a transformative adaptation solution, as they possess attributes that make them well-suited to addressing both challenges. The deployment of NUS within vulnerable regions should be done in a responsible and targeted manner that harnesses this potential to transform vulnerable and marginalised agri-food systems under climate change. Our results showed that although mainstream crops had higher WUE, NUS had higher NY and NWP of specific vitamins and minerals, which are often deficient in rural populations in South Africa. This means that NUS could be deployed in such contexts, not as a replacement for mainstream crops, but as an alternative solution targeting NWP in water-scarce and food-insecure hotspots, mainly in rural areas. The outcome of this would be improved NWP, crop and dietary diversity, as well as sustainable, resilient and healthy local agri-food systems under climate change.

6.6 Key recommendations

It is now widely known that the mainstream agri-food systems are unsustainable and have failed to deliver on the eradication of food and nutrition insecurity and poverty. This thesis advocated for NUS as part of the solution to transforming agri-food systems, particularly by strengthening the resilience of local agri-food systems. Based on the evidence gathered in this thesis, the following recommendations apply to South Africa and the broader Sub-Saharan Africa region:

- **Regional policy inclusion:** At the regional level, future policy revisions need to explicitly require the integration of NUS indigenous knowledge systems and informal seed systems, which are both largely maintained by women, into formal research and development agendas. This would help remove institutional, market and socio-cultural barriers to the adoption and mainstreaming of strategic (high NWP) NUS at different scales. Following that, governments could implement incentives at different levels to support the development of women- and youth-led enterprises along NUS value chains, thereby strengthening the socio-economic well-being of the guardians of NUS.
- **Targeted and responsible NUS deployment:** The findings of the study indicate that NUS remain gendered, stigmatised, and their recognition and integration are not universal or systemic, which presents challenges for scaling up. The deployment of NUS must be systemic, inclusive, equitable and targeted to ensure that they are matched to the contexts across the social, economic, environmental and nutrition domains leaving no one behind.

- For the deployment on NUS to be realised, there is a need to establish a **National Cross-Sectoral NUS Working Group**, comprising key departments, i.e. agriculture, water, health, and social development. This working group would have a clear mandate to operationalize the Integrated land, crop and nutrition mapping and to oversee resource allocation for strategic NUS integration. The working group would also need to ensure the inclusion of contextually important NUS in provincial and district development plans and oversee the allocation of funds to support different processes to be undertaken for NUS integration.

- **Climate action and adaptation planning for improved water and food security:** The results of the study indicate a progression towards drier and hotter climates across the study sites. Climate-informed anticipatory and adaptation planning is therefore crucial for building sustainable and resilient agri-food systems, as well as for improved water and food security.

- **A shift from coping to transformative adaptation:** The study results highlight the complexity of addressing climate change impact at different scales. Given this complexity and the lack of adaptive capacity, the coping strategies currently adopted by farming households are primarily reactive. Transformative strategies that improve food and nutrition security while building resilience and agency are needed to reduce the vulnerability of these households under climate change. Rural development agendas in the country need to start incorporating elements of climate action, including improving access to climate information and capacity development for climate change awareness and resilience.

- **Linking water to food and nutrition security:** Water forms a crucial element of food production, which has direct food and nutrition security outcomes. Integrating elements of agricultural water management into adaptation planning strategies for agricultural production to combat food and nutrition insecurity ensures water-use efficiency, sustainable natural resource use, and improved resilience of agricultural production.

- **Systemic approaches:** The results of the study indicate the existence of policies that perpetuate structural barriers to transformation at a local level. There is a need for inclusive systemic approaches that break down these barriers and integrate climate-smart innovations into participatory governance models that are co-designed with local communities. These approaches will ensure equitable and sustainable development and improved food and nutrition security outcomes under changing climates.

- **Linking food-security measures with indigenous agricultural practices:** Empirical research linking food-security measures with indigenous agricultural practices to examine the contribution of NUS to food security and food systems' resilience is important and would inform the strategic deployment of these crop species.

6.7 Supporting Policy Recommendations

Existing policies and strategies, while in some instances recognising NUS, inadvertently reinforce dependence on mainstream crops, are exclusive, lack contextualisation, and do not focus on interventions that are sensitive to local environments and food and nutrition security outcomes. Based on the evidence generated in this thesis, the following policy recommendations can be made:

- **Policy harmonisation:** The study highlights a need for urgent and necessary policy harmonisation to address identified gaps and incoherences across food, nutrition, environmental, health and socio-economic domains. This harmonisation will be instrumental in ensuring alignment with the Sustainable Development Goals, particularly SDGs 1 (no poverty), 2 (zero hunger), 3 (good health and wellbeing), 5 (gender equity), 13 (climate action) and 15 (life on land).

- **NUS Mainstreaming:** Mainstreaming NUS needs to be integrated and prioritised as a transformative adaptation strategy towards resilient and sustainable agri-food systems in South Africa and the greater SSA region. Main policies, such as the Comprehensive Africa Agriculture Development Plan (including the Kampala declaration), the Draft National Indigenous Foods Strategy, and the National Food and Nutrition Security Strategy, need to be nutrition-sensitive and incorporate detailed action plans on the targeted and responsible deployment of these crops as a principal strategy to combat food and nutrition insecurity in water-scarce environments in the region.

- **Climate action:** Climate action and adaptation planning measures also need to incorporate anticipatory and transformative strategies for improved water and food security in the country, which is projected to be warmer and drier. South Africa is currently revising its National Climate Change Adaptation Strategy and National Adaptation Plan. This offers an opportunity to mainstream NUS, as part of agrobiodiversity, into sector adaptation plans as part of transformative measures towards climate change adaptation.

- **Integrated land-crop-nutrition mapping:** The Conservation of Agricultural Resources Act could be updated to recognise NUS as an agricultural resource, and for the inclusion of integrated assessments and mapping across different dimensions, such as land, crop and nutrition, to ensure improved agriculture, environment and health outcomes. This approach would ensure that agri-food systems are pro-nutrition and are grounded in sustainability.

Taken together, our findings show that sustainable food-system transformation in a changing climate demands a paradigmatic shift away from yield-centred agriculture towards diversity- and nutrition-sensitive

systems. When integrated through climate-informed, inclusive and water-efficient pathways, underutilized crops offer a scientifically grounded and contextually relevant solution for building resilient, equitable, and sustainable agri-food systems in South Africa and the wider sub-Saharan region.