Modelling Climate Change Impacts on Maize and Soybean Yields in Central and Eastern Provinces of Zambia

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Submitted in partial fulfilment of the requirements for the degree of
M.Sc. in Climate Change and Development

December 2020

African Climate & Development Initiative
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Abstract

It is widely recognised that the unfavourable impacts of climate change on agriculture production may add up significantly to the developmental challenges of ensuring food security and reducing poverty. In Zambia, climate change impact assessments on crops are mainly carried out using large spatial scale climate data, jeopardizing on local scale impacts and adaptation capability that reveal the range of agronomic conditions under which farmers in specific areas operate. Through two major maize and soybean producing provinces in Zambia, this study enhances the understanding of district production variations under location specific climate change. This study aims at providing a climate change impact assessment in the light of three Global Climate Models (GCMs), under two Representative Concentration Pathways (RCPs), and a crop simulation model Agrometshell (AMS). This allows for an exploration of crop production choices best suited at district scale, to feed into larger provincial and national future production programs. Two future climate periods were selected to cover both near (2020 – 2039) and long-term (2050 – 2069) climate. It was shown that the impacts of climate change on crops in Central and Eastern provinces will be beyond historical natural variation and will vary across districts and crops. Maize yields in majority of the districts will be impacted negatively whilst soybean yields will moderately benefit from future climate as five out of eleven districts studied are projected to have yield increases. These results suggest that climate change will increase the risk of food insecurity in the provinces studied and the country considering that maize is a central crop in overall agricultural crop production. Soybean which may offer an opportunity to balance with some maize loss could be accounted for in policy making to achieve future food security. This study improves knowledge and understanding of the impacts of climate change on district agricultural food production systems, and the need of good location specific knowledge to better address the challenge of climate change.

Dedication

To my mother, Rabecca Chongo Kasolo

Acknowledgments

I wish to communicate my heartfelt appreciation and gratitude to the following people and Institutions:

- First, I thank God Almighty, for being my strength throughout this work and for granting me the wisdom to successfully complete this thesis. All the praise and honour go to him.
- Special and sincere thanks go to my supervisor, Dr Olivier Crespo for his passion, inspiration, friendly approach, patience (those long-hours online meetings during the Corona Virus pandemic), timely feedback, suggestions, support and assistance with the thesis and being there whenever I needed help; without whom this thesis would not be possible.
- My gratitude goes to the University of Cape Town (UCT), African Climate & Development Initiative (ACDI) and Department of Environmental and Geographical Sciences (EGS) for their intellectual support. My research and masters would not have been possible without the platform you provided me with. Many thanks to you.
- My sincere gratitude goes to the Beit Trust Scholarship, whose assistance is beyond financial help to ensuring that the well-being of a scholar is taken care of throughout the duration of this masters. You made realize that anyone can be another person's keeper even beyond their site.
- I give credit to the Copperbelt University (CBU) through the School of Natural Resources (SNR) for according me a platform to do my master's degree.
- The Zambia Meteorological Department and the Ministry of Agriculture through the Modelling system for Agricultural impacts of climate change (MOSAICC) for providing me with the climate and crop data used in this study.
- Special thanks to Rodrigo Manzanas for providing me with more climate data.
- Many thanks go to my family, my mother, my siblings and friends who contributed largely in various ways in keeping me driven and focused. My achievements are indebted to your love, support, and encouragements. Many thanks to you for believing and wishing the best for me.

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List of Acronyms

Acronym	**Meaning**
AMS	Agrometshell Model
AR5	Fifth Assessment Report
CAN-ESM2	Canadian Earth Systems Model Second Generation
CARE	Cooperative for Assistance and Relief Everywhere
CMIP5	Coupled Model Intercomparison Project Phase 5
CNRM-ESM	National Centre for Meteorological Research Earth Systems Model
ENSO	El Nino Southern Oscillation
ESM	Earth System Models
FANRPAN	Food, Agriculture and Natural Resources Policy Analysis Network
FAO	Food and Agriculture Organisation
FISP	Farmer Input Support Program
FRA	Food Reserve Agency
GCM	Global Climate Model
GDP	Gross Domestic Product
GHG	Green House Gases
Ha	Hectare
IPCC	Inter-governmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
MoA	Ministry of Agriculture
MPI-ESM-MR	Max-Planck Institute of Meteorology Earth Systems Model of Mixed Resolution
NPCC	National Policy on Climate Change
RCP	Representative Concentration Pathway

SD	Standard Deviation
SE	Standard Error
SSA	Sub-Saharan Africa
T	Tonnes
TNC	Third National Communication
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
ZMD	Zambia Meteorological Department

1 CHAPTER ONE: INTRODUCTION

1.1 Background

Agriculture is a vital sector in many Sub-Saharan African countries for national development, food production (mainly for local consumption), income generation and employment creation. The agriculture sector is a major contributor to the Zambian economy, contributing between 16 to 20% of the national Gross Domestic Product (GDP) (Jain 2007, NPCC, 2016; Arslan, 2018; Third National Communication [TNC], 2020). It employs and provide livelihood for about 70% of the population (FAO, 2015b; FAO, 2016a; TNC, 2020). Maize occupies a central position in crop production as a staple food crop and a primary crop for smallholder farmers (Chapoto et al., 2015). At least 83% of the smallholder farmers in Zambia grow maize for both subsistence and income, thus playing an important role in the livelihoods of most rural-based resource constrained farmers (Mulenga et al., 2017; Mubanga and Steyn, 2020).

Soybean on the other hand is the fourth most important crop in Zambia after maize, groundnuts and sunflower in terms of number of households growing it, area planted and tonnage (Lubungu et al., 2013). Recently, soybean has been identified as the most preferred legume in Southern Africa, compared to common bean and cowpea because it is preferred by growers for economic reasons (Murithi et al., 2016). Soybean offers an attractive price in Southern Africa as it is a key ingredient in the feed processing industries (Murithi et al., 2016) and improves soil fertility (Meyer et al., 2018). Thus, soybean provides smallholder farmers with an opportunity to diversify their incomes at the household level and to enhance their food and nutritional security. Production of soybean in the country has been growing steadily, with a total area under production increasing from about 20, 000 ha in 2003 to 120, 000 ha in 2014 (Hichaambwa et al., 2014). Meyer et al. (2018) estimated that the growing area under soybean production has been expanding at a rate of 15% per year between 2006 and 2016.

In Zambia where about 75% of the farming population is under rain-fed agriculture, climate change is an ever present and threatening issue to the overall agricultural crop production (Jain, 2007; Arslan, 2018). The production of maize and soybean in the country is threatened with frequent extreme climatic events attributed to climate change.

Mulungu and Ng'ombe (2019) describes maize as a highly sensitive crop especially to high temperatures despite being a warm season crop. For instance, maize yield decline by 9% under a combined high temperature of greater or equal to 35°C and a 25.4 mm reduction in rainfall (Mulungu and Ng'ombe, 2019). For this reason, a number of studies have investigated the impacts of climate change on maize yields in Africa, and Zambia in particular, and have suggested that maize will be amongst the most negatively affected crops with significant yield reductions due to anticipated future climate patterns (Jones and Thornton, 2003; Makondo et al., 2014; Mulenga et al., 2015; Wang et al., 2015; Chisanga et al., 2017; Winemana and Crawford, 2017; Mulungu and Ng'ombe, 2019). Since maize remains a source of staple food and food security and is generally grown as a monocrop, the impacts of climate change on maize crop production will pose adverse effects on the overall Zambia's agriculture production.

Similarly, studies such as Craft et al. (2015), Fraisee et al. (2008), Jin et al. 2017, Mishra and Cherkauer (2010) and Zipper et al. (2016) that have observed drought, a climatic extreme to be a major limiting factor in soybean production. These studies investigated the impact of drought on soybean yields and production in the United States of America (USA), Paraguay, China, USA, Korea, and Brazil, respectively. Munene et al. (2017) assessed soybean suitability in Kabwe, a district in Central Zambia, and suggested climate change and poor soil fertility as the main factors affecting soybean production. Unlike for maize, there are only few studies addressing the effect of climate change on soybean growth and yields in Zambia.

1.2 Challenges in crop production

The Fifth Assessment Report (AR5) of the Inter-governmental Panel on Climate Change (IPCC, 2013) defines climate change as "a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, that persists for an extended period, typically decades or longer". The United Nations Framework Convention on Climate Change (UNFCCC) on the other hand outline that "climate change is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods" (IPCC, 2013). The increase in atmospheric greenhouse gas concentration is changing both the global and regional climates (IPCC, 2013). According to the same report, the global average temperature from both land and ocean have increased by 0.85°C (0.65 to 1.06°C) between the period 1800 to 2012 (IPCC, 2013). About 0.74 ± 0.18°C temperature increase occurred during the last one hundred years (1906 to 2005) (IPCC, 2013). By the end of the 21st century, the African continent is projected to experience rising temperatures of 1 to 2°C coupled with increased frequency and intensity of extreme climates including droughts, dry spells, floods among others (IPCC, 2013). In addition, the IPCC (2014b) found that under Representative Concentration Pathway (RCP) 8.5, temperature increase over large areas of Africa will range from 3 to 6°C from mid until end of the 21st century, while low concentration pathway (RCP 2.6), the average temperature rise may be limited to 2°C. Africa has also been experiencing annual rainfall variations, in terms of seasonal distribution, volume, onset and cessation coupled with more erratic patterns (IPCC, 2013). Although the impacts of climate change vary from region to region, the rising temperatures and varying rainfall distributions will most likely impede production of rain-fed agriculture especially in developing countries like most African countries (IPCC, 2013).

Southern Africa is mainly semi-arid with high rainfall variations, characterised by frequent occurrence of droughts and floods (Zinyengere et al., 2014). The region is considered to be one of the most vulnerable to impacts of climate variability and change due to low coping and adaptive capacity (IPCC, 2014b). Temperature projections from Global Climate Models (GCMs) over Southern Africa suggest an increase ranging between 0.6 to 1.4°C by 2030 (McSweeney et al., 2010). The latest IPCC-AR5 reiterates that future temperature projections over Southern African region will continue to increase and this increase will be larger than the global temperature increase, averaging over 3°C increase by the end of the 21st century (IPCC, 2014b). Despite projections varying among GCMs, Southern Africa is often projected to experience a reduction in rainfall (IPCC, 2014b). Zinyengere et al. (2014) outline that the Coupled Model Intercomparison Project Phase 5 (CMIP 5) and multi-model ensemble projections over Southern Africa show a mean rainfall decline in the range of 0 to 20% by the end of the 21st century (IPCC, 2014b). This rainfall changes will result in a 13% reduction in crop productivity by the 2100 (IPCC, 2014b). In addition, high rainfall variations in Southern Africa, realising in variable onset and cessation, have strong implications on rain-fed crop yields (Reasons et al., 2006). Projected rainfall change in distribution patterns will likely play a major role in mostly reducing crop yields and ultimately crop production, with consequences for regional food crises. Other studies have shown that the frequency and intensity of drought events in Southern Africa are likely to increase (Arslan, 2016; Arslan, 2018; Reasons, 2017).

1.3 Problem statement

Zambia is one of the Southern Africa countries being affected by climate variability and change. The annual average temperature over the country has increased by 1.3°C from 1960 to 2003 and was twice the global temperature increase average during the same period, whereas the annual rainfall has declined by 2.3% per decade from 1960 to 1990 (McSweeney et al., 2010; Chisanga et al., 2017). Additionally, Libanda et al. (2019) found that since the 1980s, the frequency and intensity of drought and floods have increased, thereby affecting food and water security and livelihoods of communities. Concurrently, the rainy season is becoming shorter coupled with delay in onset and early cessation (Hachigonta et al., 2008).

Owing to the country's low coping and adaptive capacity, Zambia is also highly vulnerable to climate change related risks (Arslan, 2018). Crop production varies each year due to the adverse impacts of climate variability and change (National Agriculture Policy [NAP], 2016). In recognition of the importance of agriculture to the Zambian economies and livelihoods, extensive research focusing on the potential impact of climate change on crop production in the country need be conducted to ensure food security.

1.4 Study rationale

One of the leading approaches for evaluating the impacts of climate change on crop production consist of modelling crops response to future climate. GCMs and crop model provide practical support to derive the general relationship between crop yields and climate changes. However, coarse GCMs resolution hardly match the spatial resolution needed to assess climate impacts on crops at local scales such as district or province (Hewitson and Crane, 2006) and need to be downscaled using either statistical or dynamical downscaling techniques. To understand the impacts of climate change at local scales, crop models need location specific data to characterise soils, climate, agricultural practices or crop cultivars (Lobell et al., 2008; Thornton et al., 2011). While there has been considerable progress in understanding climate change impacts on agriculture yields and production in Zambia (e.g Jain, 2007; Chisanga et a., 2017; Mubanga and Steyn, 2020; Mulungu and Ng'ombe, 2019), only a limited number of studies have employed downscaled climate and location specific data to assess the impact of future climate on crop growth and yields. One such a study was performed through the Modelling System for Agricultural Impacts of Climate Change (MOSAICC) project and assessed climate change impacts country wide on several future crop yields in Zambia (Syampaku et al., 2019). In this study, soybean crop was not studied.

A holistic use of downscaled GCMs climate data and crop simulation models is important in assessing the site-specific impact of climate change on crop growth and yield (Rauff and Bello, 2015). This offers an opportunity for scientists, planners and policy makers in sensitizing and guiding farmers to make informed decisions that relates to proper selection of crops, cultivars, planting dates and irrigation water application and scheduling (Rauff and Bello, 2015). Consequently, identifying the local impacts of climate change on specific locations is recommended to inform site specific measures to enhance future food security and livelihoods, and hope to reduce climate change risks for detrimental impacts.

In addition, recognizing the importance of maize and soybean crops to food security and income generation and the potential to increase their production in Zambia, and the future changing climate, this research seeks to project the future likely impacts of climate change on soybean yields in Central and Eastern provinces of Zambia. Such studies are essential in that future climatic conditions will play an important role in determining crop output and food security. Moreover, GCMs projections over Zambia point out that rainfall in agro-ecological region I, IIa (location of Central and Eastern provinces) and IIb has decreased and will continue with the same trend (Arslan et al., 2015b), yet this is where the bulk of maize and soybean production is concentrated in the country. The study focuses on analysing the sensitivity of crop yields on the basis of yield functions.

1.5 Aim, objectives and thesis outline

The aim of this study was to assess the future impacts of climate change on maize and soybean yields in Central and Eastern Provinces of Zambia.

Toward the achievement of this aim, the thesis builds from the following objectives:

1. To identify specific climatic and water balance parameters influencing maize and soybean yields per district under observational conditions and thereafter build yield functions for simulating crop yields.
2. To simulate the impacts of climate change on crop yield relative to the baseline (historical mean crop yield).
3. Analyse maize and soybean yield changes in terms of standard deviation and maps per district.
4. To classify the impacts agreement of the three GCMs under the two Representative Concentration Pathways (RCP 4.5, RCP 8.5).

1.6 Thesis outline

The thesis is divided into five chapters. Chapter 1 provides an introduction and a brief background of the study together with the aim and objectives. Chapter 2 presents the literature review, the state current knowledge and information relating to the importance of agriculture to Zambia's economy as well as how climate change effects agriculture is in Chapter 2. Chapter 3 explains both the climate and the crop data used, tools and the methods used in this study, while Chapter 4 presents and discusses the in-depth results. The yield functions per crop per district addresses objective1 while projected impact of future climate on crop yields spatial analysis of the mean yields projected changes address objectives 2, 3 and 4. Chapter 5 concludes the study by providing a summary of the key findings reflecting on the study's aim and objectives and offers contribution towards curbing the likely future impacts of climate change in the country.

2 CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter explores the state of agriculture for food security and employment creation in Sub-Saharan Africa (SSA) and Zambia in particular. Thereafter, the study provides information on the major crops, their importance and value (maize and soybean) to the overall agriculture sector. Further, the chapter presents the current status of climate change in the country and future climatic projections for the country is provided. Further, the study presents the approaches used in climate change impact studies including Global Climate Models (GCMs), Representative Concentration Pathways (RCPs), statistical downscaling of GCMs and crop simulation models. The chapter concludes with how climate change impacts agriculture production and some measures that can be implemented to adapt agricultural systems to climate change is provided.

2.2 Agriculture

2.2.1 Agriculture in Sub-Saharan Africa and Zambia

Agriculture is one of the major contributors to the economy of many African countries. It contributes to about 30% of the total African countries' Gross Domestic Product (GDP), with 70% of the African population directly dependent on it as a source of livelihood (Jain, 2007; Tumbo et al., 2012). In Zambia, agriculture is a priority sector contributing significantly to poverty reduction and national development. The 2017 Seventh National Development Plan (7NDP) identified agriculture as a key sector for support to diversify the economy away from the traditional mining sector. In Zambia, agriculture serves as a major source of household income and is the largest contributor to job creation (7NDP, 2017), employing about 85% of the total country's labour force (Neubert, et al., 2011). In addition, the sector provides about 16 to 20% to the country's GDP (Jain, 2007; Neubert, et al., 2011; National Policy on Climate Change [NPCC], 2016). The contribution of the sector to GDP fluctuates due to the over-reliance on seasonal unreliable and unpredictable rainfall (Jain, 2007; NPCC, 2016). Additionally, 75% of the farming population in the country are smallholder farmers located mainly in rural areas and depend largely on rain-fed agriculture (Jain, 2007; Arslan, 2018; TNC, 2020), making agriculture a significant support to the rural economy. The Food, Agriculture and Natural Resources Policy Analysis Network (FANRPAN, 2009) established that 97.4% of the rural households in Zambia are involved in agriculture and this constitutes about 45% of the total population. A number of crops are grown throughout the country including maize, soybean, cassava, millet, sorghum, sweat potatoes, and many others for various uses such as food, feed formulation, processing, fodder and among others.

2.2.2 Major crops and their importance in Zambia

2.2.2.1 Maize

Maize (*Zea mays* L.) is one of the commonly grown grain crops around the world and serves as a staple food in most sub-Saharan Africa (SSA) countries (Jones and Thornton, 2003). In Zambia, maize occupies a central position in the overall agriculture crop production because it is a national staple food and a primary crop for smallholder farmers (Chapoto et al., 2015; Alfani et al., 2019). It is the largest source of calories and is the primary food for 82% of Zambian households, hence it is a strategic and important food security crop in the country (FAO, 2016a; Mubanga and Steyn, 2020). Smallholder farmers contribute about 79% of national maize production (Makondo et al., 2014). The production of maize in Zambia is heavily supported by the government with the country spending about 50 – 80% of its annual agriculture budget on the crop primarily aimed at achieving national maize and food security (Tembo and Sitko, 2013; Chapoto et al., 2015). This support is mainly in the form of input and output subsidies through the cornerstone program known as the Farmer Input Support Program (FISP) and an institution called the Food Reserve Agency (FRA) (Tembo and Sitko, 2013; Chapoto et al., 2015). These two combined accounted for about 29% of the total agriculture expenditure between 2004 and 2013 as well as reaching 60% of the budget towards the poverty reduction programme budget (Alfani et al., 2019).

Maize production in the country is concentrated in the Central, Eastern and Southern provinces of Zambia (Jain, 2007; Sitko et al., 2011) and occupies more than 70% of the total area cultivated in these provinces. Mulenga et al. (2017) demonstrated that at least 83% of the smallholder farmers in Zambia grow maize for both subsistence and household income, highlighting its importance to farmer's livelihoods. A significant proportion of maize produced by smallholder farmers is for subsistence use and the remainder is normally sold to the government through a maize crop marketing program: the FRA (Tembo and Sitko, 2013). FRA has become the highest buyer of maize produced by smallholders in the country (FAO, 2016a).

While maize remains an important crop in SSA, yields are lower compared to developed countries levels (Mulungu and Ng'ombe, 2019). In Zambia, regardless of the importance of maize as a staple crop and the concerted efforts by the government towards its production, the country continues to face challenges of low and variable maize yields averaging 1 – 2 tons per hectare, compared to the world average of 5.5 tons per hectare (Amondo et al., 2019). Amondo et al. (2019) describes maize to be the most vulnerable crop to climate change impacts. In the whole of SSA, lower maize yields are mainly attributed to drought stress as well as to other factors such as soil infertility, low input availability, weeds, pests and diseases and lack of efficient irrigation system (Zinyengere et al., 2015).

2.2.2.2 Soybean

Soybean (*Glycine max* L. Merr) is an important legume grown worldwide. The crop originated from China and was later introduced into the United States of America (USA) and then Brazil (Miransari, 2015). In Africa; South Africa, Nigeria, and Uganda are the leading producers of the soybean crop, contributing 35%, 27% and 8.5% to the overall production, respectively (Hichaambwa et al., 2014; Murithi et al., 2016). On the other hand, Zambia is the second largest producer of soybean in southern Africa (after South Africa), producing about 260, 000 tons per year with an estimated annual growth rate of 14% (Murithi et al., 2016). Sinclair et al. (2014) observed that Zambia is among the countries in Africa most suitable for soybean production, especially in the northern part which receives early seasonal rainfall suitable for soybean early sowing. Unlike maize which is mainly produced by small scale farmers, a large portion of soybean production in Zambia come from commercial farmers who contribute 85% of the total soybean production with smallholder farmers contributing the remainder 15% (Lubungu et al., 2013; Hichaambwa et al., 2014).

Soybean offers one of the largest sources of vegetable oil and protein for animal feed (Miransari, 2015) and accounts for 54% of the global oilseed production (Hichaambwa et al., 2014). It has the highest protein content (40 – 42%) and is second among legume crops (after groundnut) in terms of oil content (18 – 22%) (Hichaambwa et al., 2014; Miransari, 2015; Murithi et al., 2016; Munene et al., 2017).

Central, Eastern and Northern regions are the largest producers of soybean in the country (Ekanayake and Iskandarani, 2013; Lubungu et al., 2013), with Eastern province holding the largest number of smallholder producers, contributing about 42% of the country's smallholder soybean production (over 2001 to 2010). Similarly, Ekanayake and Iskndarani (2013) estimated that 38% of the national soybean production in 2013 was grown in Eastern province. The 2013 soybean value chain analysis in the Eastern province revealed that soybean is the fourth most important crop, after maize, groundnuts, and sunflower, in terms of the number of households growing it, tonnage and area planted (Lubungu, et al., 2013).

Soybean has numerous uses such as feed for livestock, food for humans, as well as the production of soy inks, non-toxic adhesives, candles and paints among others (Munene et al., 2017). Soybean has been used to supplement diets, especially in developing countries due to the health benefits of soy proteins (Murithi et al., 2016). Studies have advanced several benefits of soybean consumption including the improvement of the diet of children and women thereby contributing to poverty reduction (Khojecly et al., 2018). This benefit of soybean is particularly essential in SSA diets where protein deficiency is high and common (Khojecly et al., 2018). In Zambia, soybean is mainly used as a key ingredient in animal feed formulation, with a small portion for human consumption, i.e., poultry feed (72%), pig feed (9%), dairy feed (6%), fish feed (2%) and human consumption (11%) (Technoserve, 2011). Soybean is an attractive legume crop, as it has the ability to fix atmospheric nitrogen (N_2) into the soil, thus improving soil fertility (Sinclair et al., 2014). For example, soybean can fix 44 – 103 kg of nitrogen per hectare per year. This shows that soybean requires little or no fertilizer application, making it an ideal crop for resource constrained smallholder farmers.

Despite the number of benefits that soybean provides, its cultivation remains limited in Zambia. Limited access to high yielding soybean seed, soybean inoculum, unreliable soybean market and poor incentives to support soybean production are some of the challenges affecting soybean production in the country (Lubungu et al., 2013). Technoserve (2011) note that the efforts by government towards maize crop production such as the FRA institution make cropping of other crops like soybean unattractive to smallholder farmers. However, Meyer et al. (2018) presents the poor maize marketing conditions (delayed payment by FRA) and the high levels of government intervention as challenges for maize growers, where soybean growers receiving cash upon delivery can be attractive.

2.3 Climate

2.3.1 Climatology of Zambia

Zambia is a landlocked country located in the southern part of Africa. The annual rainfall in the country is strongly influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ), shifting of the Pacific Ocean's El Nino Southern Oscillation (ENSO) and the Congo Air Boundary (Chisanga et al., 2017). Zambia experiences three major climatic seasons, namely; (i)- a cool, dry winter season which occurs between May and July with lowest temperature between 13^{o}C and 26^{o}C; (ii)- a hot, dry season occurring between August and October with temperatures ranging between 26^{o}C and 38^{o}C; (iii)- and a warm, wet season occurring from November to April with temperature ranging between 27^{o}C and 34^{o}C (Neubert, et al., 2011). Rainfall in the country is mostly received during the warm, wet season (Hachigonta and Reason, 2006) and this is when most of the country's agricultural activities take place. Zambia is dry from April to October, and this explains why the rainfall pattern is best described as unimodal (Reason, 2017).

Zambia is divided into three agro-ecological regions, primarily based on the amount of rainfall received in each season of the year (Figure 2.1) (Tunza. Eco-generation.org., 2014). Region I cover the semi-arid Southern and Western parts of the country. It mainly covers the valley areas with an elevation ranging from 300 to 900 m. The region receives the lowest, most unpredictable and poorly distributed annual rainfall below 800 mm resulting in short growing periods. This makes the region to be considered as a drought prone area, where dry spells are common (NPCC, 2016). Region II is subdivided into two sub-regions, namely; IIa and region IIb with an elevation between 900 to 1200 m. It stretches from the Eastern, Central and parts of the Western provinces of the country. It receives moderate and an even distribution of rainfall between 800 to 1000 mm and has fertile soils. Of all agro-ecological regions, region IIa has the highest agricultural potential and is suitable for all common crops grown in Zambia. The high rainfall agro-ecological region III covers the Northern, North-Western and Copperbelt provinces of the country. This region receives over 1000 mm annual rainfall which creates a semi-humid climate and is associated with high leaching of soils resulting in a relatively low agriculture production.

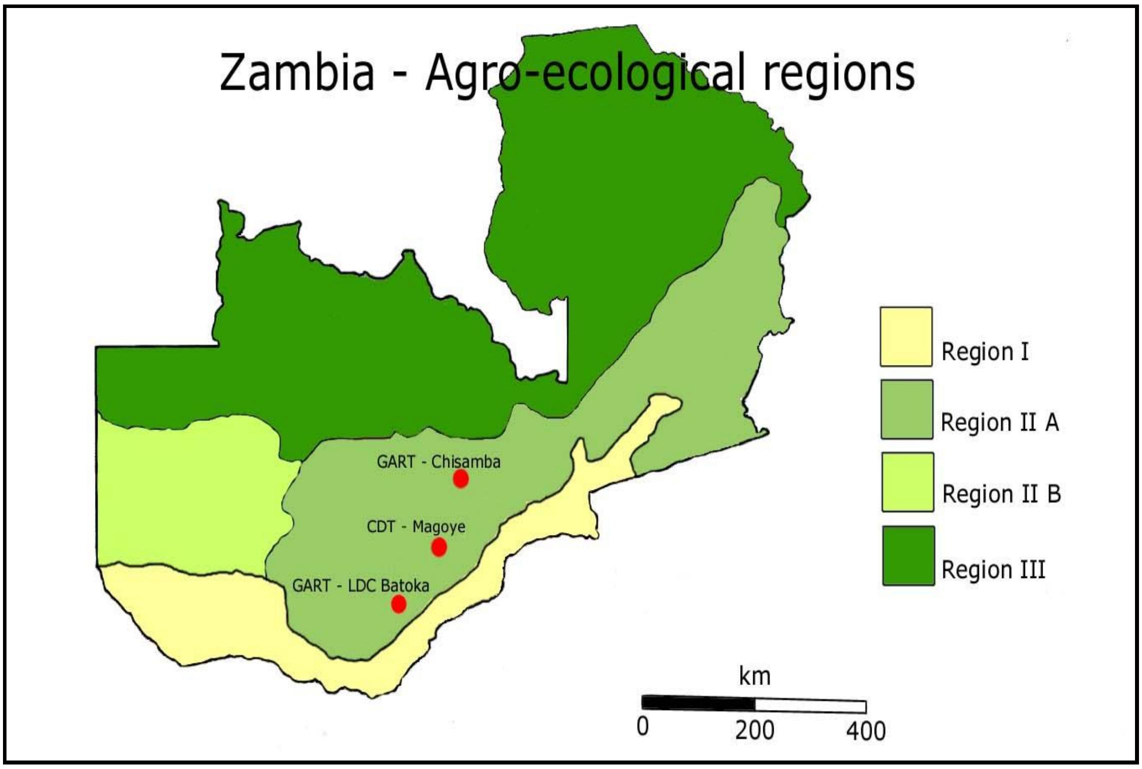


Figure 2.1: The three agro-ecological regions in Zambia. Source: Tunza. Eco-generation.org. (2014).

2.3.2 Future climate projections

2.3.2.1 Temperature

The mean annual temperature in Zambia has increased by 1.3^{o}C at an average rate of 0.29^{o}C per decade from 1960 to 2003, and this increase is twice the global average temperature increase over the same period (NAPA, 2007; McSweeney et al., 2010; NPCC, 2016; Irish Aid, 2018). Although the projections for Zambia vary depending on the model assumptions, most models project temperature increases ranging from 1.2 to 3.4°C by 2060 and 1.6 to 5.5°C by 2090 relative to the period of 1961 to 1990 (McSweeney et al., 2010; NPCC, 2016). The TNC (2020) highlight that projections for 2021 to 2050 have shown an increase in the duration of heatwave and a decrease in the length of the cold spell relative to baseline 1971 to 2000. In addition, the TNC (2020) projects 0.59 to 1.32°C under RCP 4.5 and 1.45 to 2.08°C under RCP 8.5 by 2021 to 2050 relative to 1971 to 2000.

2.3.2.2 Rainfall

In all regions of the country, the annual total precipitation has been reducing since 1960 due to the frequent occurrence of drought events (McSweeney et al., 2010). The mean annual rainfall has reduced by an average rate of 1.9 mm per month which is equivalent to a 2.3% reduction per decade since 1960 to 1990 (McSweeney et al., 2010; Chisanga et al., 2017; Irish Aid, 2018). Although a decrease in the mean annual rainfall is projected in future, projections suggest an increase in the intensity and decrease in frequency of rainfall over Zambia from the middle of the 21st century onwards (NPCC, 2016; Libanda and Ngonga, 2018). Agro-ecological region I is projected to have rainfall increase January-February-March (JFM) and October-November-December (OND) under both RCP 4.5 and RCP 8.5 by 2050 (TNC, 2020). Agro-ecological region II is expected to experience minimal rainfall decrease in JFM under RCP 4.5 and in OND under RCP 8.5 by 2050 (TNC, 2020). Agro-ecological region III on the other hand is expected to have a decrease in seasonal precipitation under RCP 4.5 and RCP 8.5 by mid-21st century relative to 1971 to 2000 (TNCC, 2020).

2.3.2.3 Climate projections

The frequency and intensity of drought and flood events have increased over the past three decades, and the severity of these events will likely continue to increase under less frequent and more intense rainfall as projected, with potential for shortened rainy season (crop growing period) (NPCC, 2016; 7NDP, 2017). This in turn affects food and water security, water quality and many other sectors. As a result, the livelihoods of many, especially rural dwellers, have been affected adversely (NPCC, 2016; 7NDP, 2017). Several studies have noted that the frequency and intensity of drought events in Zambia and Southern Africa as a whole are likely to increase in the future (Jain, 2007; Arslan, 2018; Libanda and Ngonga, 2018). The NPCC (2016) established that about 75% of the country's natural disasters result from extreme climate events such as droughts and floods. Zambia is vulnerable to adverse impacts of climate change due to its geographical location (constant variation in seasonal unimodal rainfall), multiple socio-economical stressors and low adaptive capacity (NPCC, 2016). Given such climate sensitivity, change in rainfall frequency and intensity for example, can prove highly detrimental to economic activities (Gannon et al., 2018). Additionally, Zambia is ranked number 15 on the global list of countries most vulnerable to climate change (Cooperative for Assistance and Relief Everywhere [CARE], 2017).

2.3.3 Modelling climate

Global Climate Models also known as General Circulation Models (GCMs) are very important tools used to study climate variability and change. GCMs are defined as mathematical equations that represent the components of the climate system (land, ocean, atmosphere, sea and ice sheets) using physics to reproduce the observed characteristics of recent climates (Hewitson et al., 2014). The Intergovernmental Panel on Climate Change (IPCC, 2007b) defines a GCM as a numerical illustration of the climate system based on the physical, chemical and biological properties of its components and their interactions and feedback processes. Therefore, GCMs can be used to simulate the current (baseline) and future global climate. In GCMs, the atmosphere is divided into 3-dimensional grid boxes over the globe with a coarse horizontal resolution of size between 250 and 600 km (IPCC, 2007b).

In simulating climate, GCMs are fed with initial conditions. In the case of future climates, a necessary required input for climate models is the future greenhouse gases (GHG) concentrations. Since the future climate is not uniformly determined, various future GHG concentrations scenarios called Representative Concentration Pathways (RCPs) have been proposed in the Fifth Assessment Report (AR5) by the IPCC to represent the possible future climate state depending on the amount of greenhouse concentration (IPCC, 2014b). Currently four different categories of RCPs are present, namely; RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 developed for the IPCC Fifth Assessment Report (AR5) and they correspond to different levels of radiative forcing of the atmosphere by the end of the 21st century relative to pre-industrial levels. Respective of these RCPs, mean temperature increase ranges from 1.0°C, 1.8°C, 2.2°C to 3.7°C by the end of the 21st century (Taylor et al., 2012). RCP 8.5 and RCP 2.6 are the highest and lowest concentration pathways respectively, while RCP 4.5 and RCP 6.0 are intermediate concentration pathways (Taylor et al., 2012).

The GCMs having a coarse spatial resolution, are not well suited for impact assessment studies at regional or local scales (Hewitson and Crane, 2006). For this reason, GCM outputs are downscaled to increase their spatial resolution making them better suited for regional and local scale impact assessment studies (Hewitson and Crane, 2006). In this regard, two downscaling techniques, dynamical and statistical, are commonly used to bridge the gap between GCMs and local scales (Hewitson and Crane, 2006). Dynamical downscaling makes use of Regional Climate Models and is based on quantitative equations that govern the atmosphere on a finer grid of about 10 to 50 km (Wilby and Wigley, 1997; Hawkins and Sutton, 2011). Statistical (or Empirical) downscaling on the other hand, depends on statistical tools that link the large-scale atmospheric variables (predictors) to local variables (predictands) (Wilby and Wigley, 1997). Statistical downscaling of climate data is easy to run and achieve resolutions only limited by the input observed climate data (Wilby and Wigley, 1997). Where data is sufficient, statistical downscaling generate climate data set of suitable resolution for local and small-scale crop simulation. Statistical crop models make use of observational climate derived from statistical downscaling to develop statistical relationships between climate and crop yields (Lobell and Burke, 2010). Statistical crop models, however, rely on sufficient ground data and are limited by historical variable ranges. In addition, statistical crop models assume that the same past relationships of crop yields and climate will hold in the future and may not be the case (Zinyengere et al., 2013). This type of model, however, provides an insight on how future climate will affect crop yields and has been applied in this present study.

2.4 Climate change and agriculture

2.4.1 Impact of climate change on agriculture

About 80% of the area under crop production globally is under rain-fed agriculture and nearly 60% of the total food production is sensitive to climate change impacts, especially in semi-arid and arid areas dominated by smallholder farmers (Turral et al., 2011). Climate change already affects lives of people either directly or indirectly through reduced crop yields, leading to increased prices of food and reduction of food security (Gregory et al., 2005). Several studies have noted that Southern Africa agriculture is particularly vulnerable to rainfall variability because it is dominated by smallholder farming agriculture, mainly rain-fed, with little or no supplementary irrigation (Tumbo et al., 2012; Arslan, 2015; Libanda and Ngonga, 2018). These farmers often experience crop failure and low crop productivity (Amondo et al., 2019). Zinyengere et al. (2015) adds that besides erratic rainfall regimes, most dry land farmers in Southern Africa operate under harsh condition such as infertile soils and/or sub-optimal input levels which subsequently affect crop yields. Climate change will likely amplify these already existing challenges. Other factors such as lack of finances and infrastructure, lack of adequate knowledge on best management practices, and frequent occurrence of pests and disease incidences, further exacerbate the impacts of climate change on crop production in the region (Zinyengere, et al., 2015; Amondo, 2019). Not only does climate change affect individual smallholder farmers livelihoods who are the least able to adapt, but it also affects communities through reduced access to food products and poverty reduction through income generation (Jones and Thornton, 2003).

In Zambia, the impact of climate change on agriculture has already been felt with the Northern part experiencing extreme wetness, whilst the Southern region experiences increased occurrence of droughts and dry spells (Somanje et al., 2017). Most climate projections studies agree that there will be an increase in the frequency and intensity of drought and floods, and this will affect agriculture productivity especially smallholder farmer with minimal adaptation capacity (NPCC, 2016; Arslan, 2018; Libanda and Ngonga, 2018). High rainfall variability negatively affects the growth of crops, livestock, and fisheries and significant rainfall shortages at critical stages of a crop growth is disastrous and often leads to depressed crop productivity and production. Rainfall variability affects agriculture and maize yields in Southern Africa are projected to decline by 30% without undertaking adaptation strategies (Lobell et al., 2008). Similarly, maize being a sensitive crop to daytime temperatures of above 30°C (Lobell et al., 2011), the projected 2°C increase in temperatures in most parts of SSA, its production is envisaged to be negatively affected. The key climate variables that influence the growth and development of soybean crop on the other side include rainfall, temperature and the length of daylight (photoperiod) among others (Sinclair et al., 2014).

Future projections for large scale studies are showing that climate change will lead to a -18% and -30% decline of crops by 2050s and by the end of the 21st century respectively (Zinyengere et al., 2015). As a result, climate change will increase the number of people living below the poverty line in Zambia especially subsistence farmers who depend heavily on rain-fed agriculture with low adaptive capabilities (NPCC, 2016).

With extreme climatic events attributed to climate change projected to continue affecting crop production (IPCC, 2007b), there is need to employ integrated assessment modelling methods to develop an understanding of the future climate change impact on crop production, such as maize and soybean. Most studies on climate change impacts in the region have been conducted at large Southern African scale with few studies only focusing on Zambia specifically. Climate change is a global phenomenon with local impacts varying from a location to the other, and country focused projections are essential to avoid only relying on broad/coarse information resulting from regional projections (Byg and Salick 2009). Future policy, planning and decision-making addressing climate change impacts on agriculture require local and country level projections of climatological parameters, and their impact on national agricultural systems. Only a few such local studies exist in Zambia, with only limited research using a combination of GCMs, downscaled data and crop simulation models (Chisanga et al., 2017).

2.4.2 Simulating agriculture production

Crop simulation models are computerized representations of crop growth, development, and yield, simulated through quantitative equations depending on the soil conditions, climate and management options (Hoogenboom et al., 2004; Fodor et al., 2017). They are tools used to calculate crop yield and other important soil and plant parameters as a function of climate, soil conditions, specific characteristics of the plant and agricultural management practices (Jones et al., 2017). The science of crop models began in the 1960s due to interest-driven activities during the Cold War which needed the unplanned purchase of large volumes of wheat by the Soviet Union in 1972 (Jones et al., 2017). With the development of crop models, risks associated with crop management in the face of climate change and variability can be simulated (Fodor et al., 2017). Crop models are also used to understand the relationships between climate and crop growth in terms of plant growth, development, and yield in response to moisture, temperature, solar radiation and nutrient changes. They are often used in yield projection in the face of the changing climate (Fodor et al., 2017; Jones et al., 2017). Processed based crop models are applied at local scales because they require site-specific and homogenous data as inputs. Such crop models, including the Decision Support System for Agrotechnology Transfer ([DSSAT]; Jones et al., 2003) and the Agricultural Production Systems Simulator ([APSIM]; Keating et al., 2003) have been applied widely on climate change impacts on agriculture studies (Fodor et al., 2017). Currently, the version of DSSAT suit of models comprises of simulation models for different crop types such as cereals, legumes and root crops (Fodor et al., 2017). DSSAT and APSIM models are also used in the calculation of soil heat, water and nitrogen requirements depending on the soil-plant-atmosphere dynamics and management options of the field (Jones et al., 2003; Keating et al., 2003). The APSIM model in addition is able to simulate large numbers of crops including pastures, trees, and weeds (Keating et al., 2003).

Water balance models are very robust models are mostly applied under water stressed conditions (Wabal, 2010), relying on the water air/plant/soil cycle, are also used in the simulation of climate change impacts on crops. Examples of water balance models include AquaCrop, CropSyst, SAPWAT, SWAMP and Agrometshell (AMS) model. AquaCrop for example differentiates the soil evaporation from crop transpiration, simulates the root development, the water stresses, and expansion of the canopy and provides biomass production and yield estimates. Agrometshell models on the other side describe the relationship between the soil-plant-atmosphere system and gives out the variables that are used as inputs in yield estimations (WABAL, 2010). AMS models is designed to simulate soil water balance at local scales, implying that they can be applied at the district or province level. This type of model AMS was used because it is simple and require less input data to run in providing useful insights about climate change impacts on crops.

2.4.3 Adapting agriculture to systems to climate

To ensure food security and sustained income generation, it is critical to adapt agriculture systems to climate change. Schelenkler and Lobell (2010) highlights that there is only little margin for food security and livelihoods improvements under climate change in the Southern Africa region without adaptation. Adaptation forms an important component in climate change impact studies, and ranges from small on-farm amendments including water management, soil management and agronomic practices such as planting time, crop varieties, tillage practices among others, into more advanced activities such as change of crops, investing in irrigation mechanism, or even transformational activities including new production systems, change of livelihoods and migration (Zinyengere et al., 2013). On-farm adjustments are the most immediate responses, especially for smallholder farmers because of their short-term planning capacity, ease of implementation and low costs (Araujo et al., 2016). These strategies offer farmers an opportunity to cope with unfavourable climatic conditions and mitigate some of the negative impacts of poor seasons.

3 CHAPTER THREE: MATERIAL AND METHODS

3.1 Introduction

This chapter starts by providing detailed information of the study area, data, and data sources. It then presents a comprehensive description of the Agrometshell (AMS) model including the simulation approach used to assess the impacts of climate change on maize and soybean yields in the eleven districts studied. Later, the chapter presents an account on how the yield functions were built and the methods used to simulate historical and future impacts of climate change on crop yields.

3.2 Study area

The study areas of this research were Central and Eastern provinces of Zambia (Figure 3.1). These areas are among the largest crop producer in the country including maize and soybean (Ekanayake and Iskandarani 2013; Lubungu et al., 2013; Sitko et al., 2011). Both Central and Eastern provinces are located in agro-ecological region IIa of Zambia with altitudes between 900 and 1200 m. Agro-ecological region IIa has a high agricultural potential because soils are fertile and receive annual rainfall between 800 and 1000 mm (Neubert, et al., 2011), making the region well suited for agriculture purposes. The region is suitable for almost all the common crops grown in Zambia. Smallholder farmer's dependant on rain-fed agriculture dominate the farming population in Central and Eastern provinces. As per country situation, a large portion of agriculture land in Central and Eastern provinces is under maize production (about 83%) (Mulenga et al., 2017), with soybean production area expanding at a rate of 15% per year between 2006 and 2016 (Hichaabwa et al., 2014; Meyer et al., 2018). Besides maize being the staple crop in these provinces, other crop such as beans, groundnuts, cotton, sunflower, sorghum, pumpkins, and cassava are grown to diversify diets (Lubungu et al., 2013; Sitko et al., 2011).

Maize and soybean crops were selected based on their importance in Zambia at local and national level. The selection involved considering major factors including crops of greater importance for national food security, crops cultivated on a wide area within Zambia and economical value of a crop. A total of eleven (11) districts from Central and Eastern provinces were selected for this study because they had yield datasets with time series covering a sufficiently long time period. Eastern province was a particularly relevant study area because the province is projected to be the most affected by climate change in the country (Libanda and Ngonga, 2018). Moreover, past GCMs simulations over Zambia point out that rainfall in agro-ecological region I, IIa and IIb has decreased (Arslan et al., 2015). With Central and Eastern provinces being the leading producer of maize and soybean, whilst comprising a large number of smallholder farmers who largely depend on rainfall, reducing rainfall could have large negative impacts on crops.

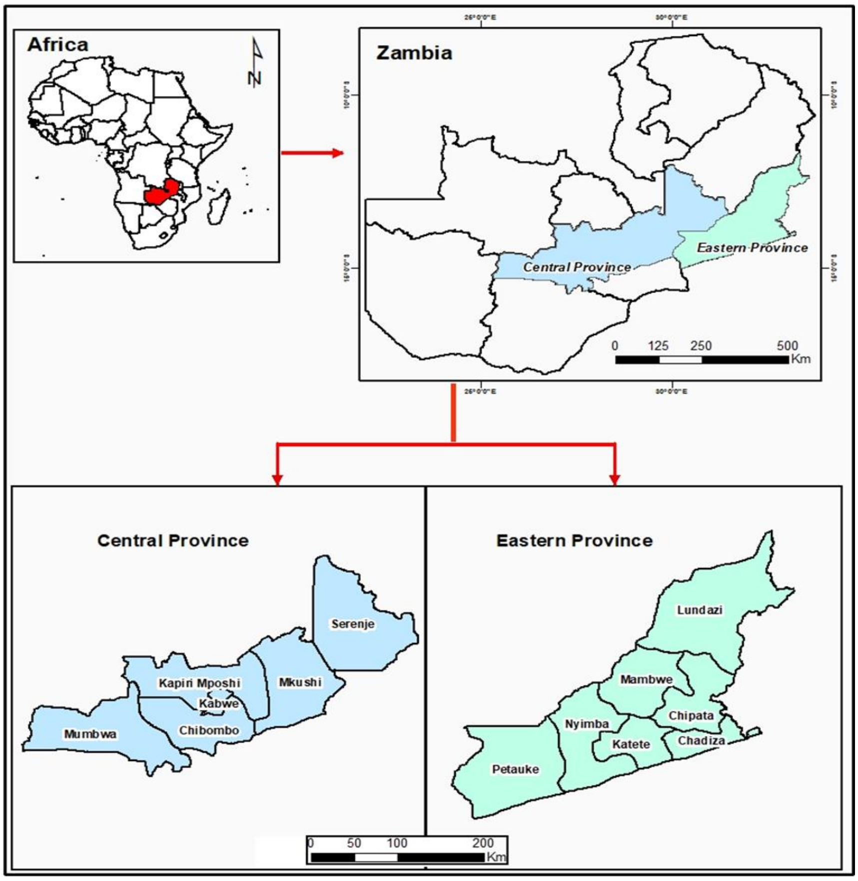


Figure 3.1: Location of Zambia in Africa (top left), location of Central and Eastern provinces in Zambia (top right) and the districts in each of the two provinces (bottom).

3.3 Sources of data

3.3.1 Crop yield data

Crop yields data for maize and soybean from the eleven districts of the study areas were obtained from the Ministry of Agriculture (MoA), Zambia. From the available data, a subset was developed with annual yields covering a 20-year period (1994 to 2013) at district level for both maize and soybean. This period was selected because it had sufficient datasets to be used in the study. Yields from this database represent actual farmers' crop yields as recorded by the MoA in the respective districts. The yields data were in metric tonne per hectare (t/ha). Tables 3.1 and 3.2 show the yields data obtained in each district for the study period, for maize and soybean, respectively.

Table 3.1: Maize yields (t/ha) data by district in Central and Eastern provinces in Zambia (1994 to 2013). Source: District data from MoA. NA represents missing data.

	Central Province						**Eastern Province**				
Year	**Mumbwa**	**Kapiri Mposhi**	**Kabwe**	**Chibombo**	**Mkushi**	**Serenje**	**Petauke**	**Katete**	**Chipata**	**Chadiza**	**Lundazi**
1994	1.31	NA	1.38	NA	1.30	1.47	NA	1.70	0.75	1.28	NA
1995	0.81	NA	1.74	NA	2.73	1.61	NA	1.52	1.24	1.30	NA
1996	2.16	NA	2.41	NA	3.55	2.34	NA	1.86	1.53	1.87	NA
1997	1.41	NA	2.22	1.37	2.47	1.24	1.26	1.07	1.26	1.45	1.23
1998	1.33	1.83	1.65	2.03	1.93	2.00	1.15	1.12	1.30	1.22	1.41
1999	1.82	1.74	4.08	2.00	2.86	2.29	1.65	1.38	1.52	1.26	1.41
2000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2001	1.34	0.73	1.48	1.26	1.24	1.18	1.21	1.03	1.07	0.86	1.11
2002	0.87	0.97	0.79	1.01	1.44	1.13	1.32	1.14	1.21	1.18	1.15
2003	1.36	2.51	3.21	3.81	3.79	1.49	1.69	0.88	2.14	3.20	1.88
2004	1.73	2.42	4.37	2.27	5.45	1.59	1.47	1.60	1.56	1.89	1.33
2005	0.73	0.69	3.37	0.73	0.59	1.05	0.73	0.60	0.99	0.83	1.06
2006	1.51	1.94	1.25	1.78	1.63	2.14	1.21	1.62	1.50	1.30	1.39
2007	1.89	1.61	2.79	2.69	1.70	1.51	0.97	0.66	1.49	1.14	1.12
2008	1.56	2.19	2.15	0.57	2.51	1.54	1.07	1.09	1.54	1.37	1.54
2009	0.82	1.36	0.77	0.21	1.47	1.02	1.10	1.66	1.04	1.20	1.38
2010	2.65	2.02	1.74	2.97	2.98	3.10	1.70	1.30	2.25	1.85	2.06
2011	2.49	2.04	2.77	2.07	2.35	3.19	1.82	1.53	1.99	1.95	2.04
2012	2.42	2.63	2.97	2.24	2.85	3.06	2.20	1.83	2.29	2.14	1.88
2013	1.47	2.46	2.45	1.79	2.80	2.96	1.76	1.70	2.10	1.99	2.11
Average	**1.56**	**1.81**	**2.30**	**1.80**	**2.40**	**1.89**	**1.39**	**1.33**	**1.51**	**1.54**	**1.51**
Provincial average	**1.96**						**1.46**				

Provincial S.D	**1.04**	**0.61**
Provincial S.E	**0.10**	**0.06**

Maize yields data for the study period was 89% complete. Annual yields in all the districts ranged from 0.21 t/ha (Chibombo 2009) to 5.45 t/ha (Mkushi 2004) over time. Over the study period, the average yields ranged from 1.33 t/ha in Katete to 2.40 t/ha in Mkushi. Relatively high maize yields in the districts are seen in Chibombo, Kabwe, Kapiri Mposhi, Mkushi and Serenje as a response of the government support towards maize growing, i.e., a program known as Farmers Inputs Support Program (FISP) and an institution called Food Reserve Agency (FRA) which markets maize. Maize inputs such as seeds and fertilizers are subsidized making it an attractive crop for farmers to grow. The highest average yields were recorded in 1996, 1999, 2004, 2010, 2011, 2012 and 2013 having an annual average yield over 2 t/ha. Lowest yields of 1.03 t/ha, 1.09 t/ha and 1.11 t/ha were recorded in 2005, 2009 and 2002, respectively. Mkushi district recorded the highest average yield of 2.40 t/ha followed by Kabwe with 2.30 t/ha. In contrast, lowest average yields over the study period were observed in Katete (1.33 t/ha) followed by Petauke (1.39 t/ha). Additionally, it was noticed that the districts in Central province had the larger average yield of 1.96 t/ha compared to 1.46 t/ha in Eastern province. However, crop yield data in Central province are more spread with S.D and S.E values of 1.04 and 0.10 while the datasets in Eastern province have a lower variation having S.D and S.E values of 0.61 and 0.06, respectively.

Table 3.2: Soybean yields (t/ha) data by district in Central and Eastern provinces in Zambia (1994 to 2013). Source: District data from MoA. NA represents missing data.

	Central Province						**Eastern Province**				
Year	**Mumbwa**	**Kapiri Mposhi**	**Kabwe**	**Chibombo**	**Mkushi**	**Serenje**	**Petauke**	**Katete**	**Chipata**	**Chadiza**	**Lundazi**
1994	0.85	NA	1.00	NA	1.02	1.02	NA	0.41	0.62	0.58	NA
1995	1.21	NA	1.14	NA	1.79	0.00	NA	0.28	0.71	1.26	NA
1996	1.03	NA	1.17	NA	1.62	1.26	NA	0.56	0.81	1.33	NA
1997	2.07	NA	1.69	1.70	0.95	NA	NA	0.78	0.79	1.12	0.78
1998	0.45	0.19	0.05	1.44	1.86	1.76	0.52	0.23	0.56	0.00	0.75
1999	NA	0.45	NA	1.38	0.67	0.30	0.63	0.79	0.47	0.62	0.59
2000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

2001	0.93	0.64	1.04	1.25	NA	0.25	0.08	1.45	0.66	0.50	0.56
2002	0.75	0.74	2.18	0.41	NA	1.00	0.22	NA	0.60	0.66	0.54
2003	NA	NA	0.99	3.25	1.84	NA	NA	NA	NA	NA	0.48
2004	0.44	0.82	2.94	1.44	2.13	0.69	0.48	0.10	1.41	0.58	0.63
2005	0.63	2.53	0.78	1.88	2.07	0.69	0.38	0.62	1.13	2.15	0.71
2006	0.58	0.72	2.24	2.27	2.23	0.68	0.73	0.42	0.57	2.15	0.86
2007	0.52	0.54	1.50	1.55	1.65	0.53	4.48	0.40	0.37	0.76	0.75
2008	0.84	1.09	1.76	1.22	1.52	0.67	0.85	0.90	0.44	0.95	1.00
2009	0.55	0.90	1.65	1.80	1.75	0.80	0.54	0.90	0.76	1.30	0.73
2010	1.30	1.10	0.80	1.60	1.45	1.40	0.80	0.40	0.80	1.00	0.60
2011	2.87	1.77	2.77	3.25	3.71	2.18	1.55	0.58	0.92	2.41	2.10
2012	0.82	1.31	2.13	2.26	2.69	1.30	0.74	0.63	0.99	0.62	0.57
2013	1.11	1.32	2.25	2.27	2.81	0.95	0.86	0.83	0.91	0.92	0.75
Average	**1.00**	**1.01**	**1.56**	**1.81**	**1.87**	**0.91**	**0.92**	**0.63**	**0.75**	**1.05**	**0.78**
Provincial average	**1.36**						**0.82**				
Provincial S.D	**0.87**						**0.61**				
Provincial S.E	**0.08**						**0.06**				

Soybean was not a common crop in Zambia in the 1980s and 1990s and unlike maize, shows some discontinuities in several districts. Overall, annual yields ranged from 0.00 t/ha (Serenje 1995) to 4.48 t/ha (Petauke 2007) over time. This indicate that there was a complete crop failure in Serenje district in the year 1995. However, over the study period, the average yields ranged from 0.63 t/ha to 1.87 t/ha with Katete (Mkushi) recording the lowest (highest) yields. All the districts in Central province had total average yields above 1 t/ha except for Serenje which has an average yield of 0.91 t/ha, while all but Chadiza district see average yields below 1 t/ha in Eastern Province. Across the years, yields greater than 2 t/ha only occurred in 2011 while yields below 1 t/ha were recorded in 1994, 1995, 1998 and 2001. As for maize, soybean yields in Central province districts are larger than those in Eastern province. In soybean again, the yield datasets in Central province are more variable with S.D and S.E values of 0.87 and 0.08 whereas the datasets in Eastern province have a lower variation with S.D and S.E values of 0.61 and 0.06, respectively.

Both lower average maize and soybean yields in Eastern concur with marginal production systems in the province, and the most likely to be affected by climate change in the country (Libanda and Ngonga, 2018). This implies that crop production in Eastern province is not as suitable as in Central province.

3.3.2 Climate data

Three Earth System Models (ESMs); CAN-ESM2, CNRM-CM5 and MPI-ESM-MR, part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) where used in this study. The three GCMs were used as they had complete data for historical and two Representative Concentration Pathways (RCP 4.5 and RCP 8.5). CMIP5 ESMs integrate additional components that describe the interaction of the atmosphere with the use of soil and vegetation (Taylor et al., 2012). They explicitly take into account atmospheric chemistry, aerosols and the carbon cycle (Taylor et al., 2012). The CAN-ESM2, CNRM-CM5 and MPI-ESM-MR couples together the interactive carbon cycle of the atmosphere, land-vegetation, terrestrial and oceanic global climate models (GCMs) (Chylek et al., 2011; Giorgetta et al., 2013; Voldoire et al., 2013). These new generation of models are driven by the recently defined forcing of atmospheric composition, the historical forcing for current climate conditions and the Representative Concentration Pathways (RCPs) for future scenarios (Moss et al., 2010).

The ESMs data from each GCM contained downscaled daily gridded minimum and maximum temperatures (°C), and rainfall (mm) data at a resolution of 50 x 50 Km. These datasets were obtained from the Zambia Meteorological Department (ZMD), in conjunction with the Modelling System for Agricultural Impacts of Climate Change (MOSAICC Zambia). Downscaling of both temperature and rainfall data was done by ZMD, where data was collected using statistical downscaling techniques as it is faster and computationally inexpensive (Jain et al., 2018). Jain et al. (2018) outline that "statistical downscaling relies on empirical/statistical models that link the large-scale atmospheric variables governing the climate of a region (predictors) with the target variable/s (predictands) of interest at the local/regional scale (predictors: daily precipitation, maximum and minimum temperature)". Before selecting the study periods, the observed climate data covered a period of 1981 to 2014, while modelled climate data covered a baseline period (1961 to 2000) and future climates (2010 to 2069). An observational subset data ranging from 1994 to 2013 was used to match crop yield data. For each of the three GCMs, future climate data were modelled under two RCPs; RCP 4.5 and RCP 8.5.

Table 3.3: Earth system models from which climate scenarios were obtained.

ESM Name	Modelling centre	Institution acronym	Resolution Latitude x Longitude	Scenarios and period used
CAN-ESM2	Canadian Centre for Climate Modelling and Analysis, Canada	CCCMA	2.81°× 2.81°	Hist: 1961 – 2000 RCP 4.5: 2010 – 2069 RCP 8.5: 2010 – 2069
CNRM-CM5	National Centre for Meteorological Research, France	CNRM-CERFACS	1.4° × 1.4°	Hist: 1961 – 2000 RCP 4.5: 2010 – 2069 RCP 8.5: 2010 – 2069
MPI-ESM-MR	Max Planck Institute for Meteorology, Germany	MPI	1.875°×1.875°	Hist: 1961 – 2000 RCP 4.5: 2010 – 2069 RCP 8.5: 2010 – 2069

3.3.3 Crop-related data

3.3.3.1 Reference Evapotranspiration (ETo*)*

Reference Evapotranspiration (ETo) was computed with the ETo calculator, a software developed by the Land and Water Division of the Food and Agriculture Organisation (FAO) (Raes, 2009). It calculates ETo of a particular area using the Penman-Monteith method, which is recommended as the standard method for the calculating ETo (Allen et al., 1998).

Data needed in the calculation of ETo includes maximum and minimum air temperatures, maximum and minimum Relative Humidity (RH), wind speed, vapour pressure and solar or shortwave radiation which can be loaded into the software as daily, dekad and/ or monthly in various units. The ETo calculator also offers to compute ETo with only maximum and minimum temperature data available. In that case, missing climatic data were estimated according to procedures outlined in Allen et al. (1998) and Steduto et al. (2012). In the present study, only maximum and minimum temperatures were available, and approximation of the other climate variables was done according to Allen et al. (1998) and Steduto et al. (2012).

3.3.3.2 Crop coefficients

The crop specific coefficient (Kc) and the determined ETo from Allen et al. (1998) at four stages of the crop growth were used to compute the actual evapotranspiration of a crop (ETc) using the equation: ETc = Kc x ETo (Allen et al., 1998).

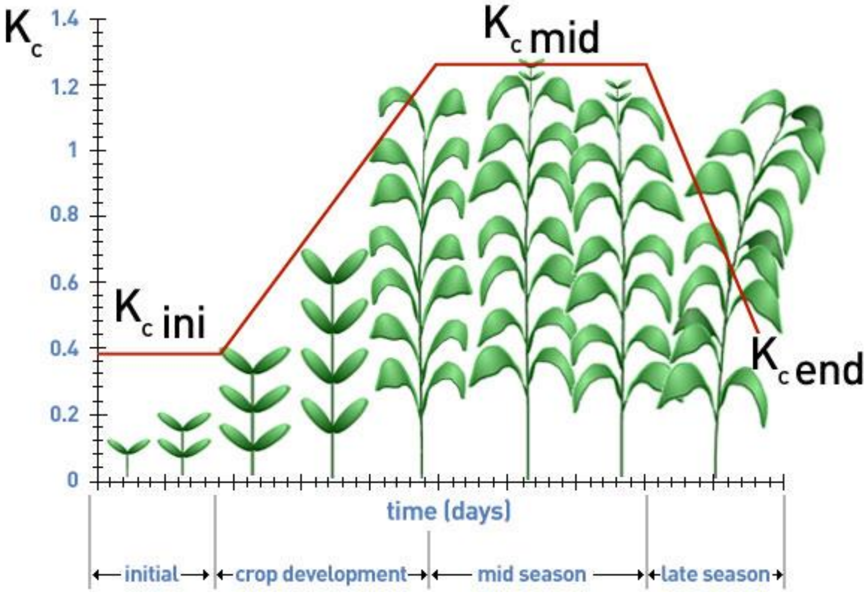


Figure 3.2: General crop coefficient curve for the single crop coefficient approach. Source: Allen et al., (1998).

Tables 3.4a and 3.4b below represents the length of each growing stage for maize and soybean, and their respective crop coefficients.

Table 3.4: Crop water requirement coefficients for maize (a) and soybean (b) at each stage of a plant cycle. Source: Allen et al., (1998).

(a)	**Stages of Development for maize**				
Crop Characteristics	Initial	Crop development	Mid-season	Late season	Total
Stage length, in days	25	40	45	30	140
Crop coefficients (Kc)	0.3	0.3 – 1.2	1.2	0.5	

(b)	**Stages of Development for soybean**				
Crop Characteristics	Initial	Crop development	Mid-season	Late season	Total
Stage length, days	20	35	60	25	140
Crop coefficients (kc)	0.4	1.25	1.25	0.5	

3.4 Agrometshell model (AMS)

This study applied the Agrometshell (AMS) model to simulate historical and future yields. The AMS crop model was developed through a collaboration of the Food and Agriculture Organization (FAO), Environment and Natural Resources Service, Agrometeorological Group and the United Nations Regional Early Warning System (Mukhala and Hoefsloot, 2004). AMS is a water balance model (Doorenbos and Kassam, 1979) designed for crop forecasting purposes. The model engages with issues of food security and disaster management and finds a wide range of applications in fields such as climatology, agrometeorology, hydrology, agronomy, and used by food security economists, food security experts, humanitarian aid specialists, disaster management specialists and many others. The AMS model has been widely used by the Regional Remote Sensing Unit (RRSU) for food security assessment (Mukhala and Hoefsloot, 2004) and suits our study well as it requires minimal data, for instance as compared to other complex models such as Decision Support System for Agro-technological Transfer (DSSAT) (Jones et al., 2003) or Agricultural Production System Simulator (APSIM) (Keating et al., 2003).

AMS is a user-friendly tool and has a "*visual menu*" that offers easy access to valuable functions. The program relies on a database that combines weather, climate and crop data needed to perform the simulations. The FAO Crop Specific Soil Water Balance in AMS is operated into two modes, namely; "*monitoring mode*" and "*risk analysis mode*" (Mukhala and Hoefsloot, 2004). In the monitoring mode, analyses are performed for one growing season and covering many stations in a specific area, a country or a province for instance. This is usually performed from the beginning of the growing season to harvest time. In this mode, early warning information can be extracted before harvest time to make operational decisions. The risk analysis mode on the other hand covers the same type of analysis, but for one station only and over many years. This mode, which was used in this study, provides valuable information on the suitability of a particular crop. Under the risk analysis mode, the water requirement is computed and presented by year or season.

Inputs needed to run the AMS water balance model include climate variables, crop parameters and soil information. It requires daily, dekad and/or monthly climate variables of actual and normal rainfall, and actual and normal potential evapotranspiration. The crop parameters needed include:

- the type of crop for which water balance is being calculated,

- the planting dekad (1 to 36),
- growing cycle length in dekads,
- pre-season crop coefficient and for each developmental stage,
- the percentage of effective rainfall (as a function of the terrain and type of soil) and,
- the irrigation amounts were applicable are needed to drive the crop model.

In several cases, the necessary phenological information was not available, and in those cases, we used information derived from the FAO-Irrigation paper 56 (Allen et al., 1998). Since planting in the region occurs mostly after the onset of rainfall, a planting rule was implemented, setting planting on the first dekad, when 20mm and 25mm of rainfall are received in the first and second dekads, respectively. The length of the maize and soybean (Table 3.4a and 3.4b) growing seasons was set to be 140 days as indicated in Allen et al. (1998). The soil water holding capacity (WHC) per district was obtained from the Harmonised World Soil Database (HWSD) portal.

The datasets were formatted to suit AMS file format and used to simulate the water balance variables for each district (as a 'station' in AMS). Dekadal actual rainfall dataset from 1994 to 2013 were first loaded in AMS. Thereafter normal rainfall data were input into AMS, normal rainfall was calculated by finding the average rainfall in each dekad for the whole growing season. The estimated ETo (Eto calculator) was also input into AMS over the same period. For both maize and soybean, the planting dekad, cycle length, soil water holding capacity, effective rainfall, pre-season crop coefficients for each district were entered separately in AMS.

After running the simulation, AMS produces a number of outputs as shown in Table 3.5 including water excess (WEX), water deficit (WDEF) and actual evapotranspiration (ETA) for each of the four stages of growth, that is initial (i), vegetative (v), flowering (f), ripening (r) and for the total growing period (t) as well as water satisfaction index (INDXLatest, 100 meaning fully satisfied) and all variables above for the total growing cycle. Table 3.5 gives an example of outputs for the Chibombo district, Zambia.

Table 3.5: Chibombo (Zambia): example of AMS outputs.

Summary with all parameters (2020 – 2040)															
Year	INDXLatest	WEXi	WEXv	WEXf	WEXr	WEXt	WDEFi	WDEFv	WDEFf	WDEFr	WDEFt	ETAi	ETAv	ETAf	ETAr	ETAt
2020	74	0	0	0	42	42	-54	-62	-53	-17	-186	0	74	346	108	528
2021	72	0	0	0	79	79	-43	-61	-93	0	-197	11	75	306	125	517
2022	53	0	0	0	0	0	-54	-96	-157	-32	-339	0	40	242	93	75
2023	63	0	0	0	10	10	-43	-90	-130	0	-263	11	46	269	125	451
2024	52	0	0	0	0	0	-54	-80	-129	-78	-341	0	56	270	47	373
2025	80	0	0	20	69	89	-54	-33	-53	0	-140	0	103	346	125	574
2026	69	0	0	0	0	0	-53	-58	-110	0	-221	1	78	289	125	493
2027	63	0	0	15	181	196	-41	-69	-133	0	-243	13	67	266	125	471
2028	59	0	0	0	0	0	-50	-76	-168	0	-294	4	60	231	125	420
2029	81	0	0	8	61	69	-35	-62	-40	0	-137	19	74	359	125	577
2030	82	0	0	0	40	40	-54	-68	-8	0	-130	0	68	391	125	584
2031	69	0	0	0	42	42	-48	-86	-90	0	-224	6	50	309	125	490
2032	64	0	0	0	58	58	-27	-87	-146	0	-260	27	49	253	125	454
2033	79	0	0	24	77	101	-54	-93	0	0	-147	0	43	399	125	567
2034	74	0	0	0	19	19	-47	-29	-101	-9	-186	7	107	298	116	528
2035	53	0	0	0	169	169	-54	-130	-130	0	-314	0	6	269	125	400
2036	81	0	0	95	74	169	-50	-81	-6	0	-137	4	55	393	125	577
2037	60	0	0	0	0	0	-48	-93	-50	-95	-286	6	43	349	30	428
2038	76	0	0	0	0	0	-53	-5	-101	-9	-168	1	131	298	116	546
2039	81	0	0	47	0	47	-40	-47	-32	-15	-134	14	89	367	110	580
2040	63	0	0	0	0	0	-31	-105	-146	0	-282	23	31	253	125	432

INDXLatest is mostly variable to specify how much water has been available to the plant during the growing season, with 100 signifying that the plant has been satisfied fully while 0 indicate that the plant has been stressed of water. Table 3.6 provides the relationship between the potential yield and the INDXLatest.

Table 3.6: Classification of water limited performance (adapted from Martin et al., 2000)

Expected percentage of maximum (potential) yield	**Classification of crop performance**	**INDXLatest**
>100	Very good	100
90-100	Good	95-99
50-90	Average	80-94
20-50	Mediocre	60-79
10-20	Poor	50-59
<10	Complete failure	<50

3.5 Building the yield functions

3.5.1 Trends and de-trending yields

While the observed yields are affected by both climatic and non-climatic factors (such as improved technology, improved management practices or change in policies), this study considered only yield changes in response to annual climate variability. It was assumed that variations in annual yields are mostly a response to climatic factors while long-term changes (trend) were mostly a response to non-climatic factors. Since this study focused on the effects of climatic conditions over relatively short period of times (20 years), the yield response was examined as a response to annual climatic variation within those periods. Crop yields were tested for linear trends as means of detecting the effects of long-term non-climatic factors. This was achieved by performing a regression on the observed yields. Removing the fitted values from the absolute yields, then allows to de-trend yield and isolate annual yield anomalies as largely affected by climate variability. The trends are defined by the equation below:

$$y_1 = \beta T + \alpha \qquad \text{(Equation 3.1)}$$

where

- y_1 is the yield trend line,
- β is the rate of yield change per year,
- T is the time in years,
- α is the intercept (yield when T = 0).

The de-trending process was done per crop per district.

3.5.2 Correlation and regression

3.5.2.1 Correlation

Crop yield anomalies are largely a response to climate variability, such as inter-annual rainfall and temperature variations, or water balance parameters (WBP), such as water deficit/excess and crop water requirement commonly referred to as water satisfaction index (WSI). The climate variables correlated with yield included minimum temperature (Tna, Tnn, Tnm for average, lowest and highest minimum temperatures for the crop growing season respectively), maximum temperatures (Txa, Tnn,Txm for average, lowest and highest maximum temperatures for the crop growing season respectively) and rainfall (Ra, Rn and Rm for average, minimum and maximum total rainfall for the crop growing respectively). Correlations between yield anomalies, climate and WBP was then computed. Variables that were highly correlated to yield anomalies, having a correlation variation greater or equal to 0.8 were selected and used in regression.

3.5.2.2 Regression

After performing correlations and selecting variables, stepwise regression analysis was used to compute the best estimate of the yield as a function of climate and water balance variables by multiple regression. The regression computes the slopes and intercepts for each variable. Variables with $p < 0.05$ were used to build the yield function because they were considered statistically significant. The selection process resulted from a stepwise regression leading to the building of the yield regression models per crop per district. At each step, the variables with the highest p-value were eliminated, choosing variables with a lower p-value ($p < 0.05$). In some cases, variables with a p-value a little greater than 0.05 were also considered. Finally, the crop yield function was built by linearly regressing a few selected variables amongst climate and water balance with the observed de-trended yield and then validated.

The equation below shows a multiple linear regression function:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + \dots b_n x_n \qquad \text{(Equation 3.2)}$$

Where

- Y is the simulated yield anomaly
- $X_1, X_2, X_3 \dots X_n$ are variables,
- $b_1, b_2, b_3 \dots b_n$ are computed slope coefficients, and
- a is the intercept.

Yield functions were built for each district and for each crop. Yield functions were an important factor of this study, as they identify the combination of climate and WBP best explaining the annual variations of observed crop yields. These yield functions established with observed data were simulated later with modelled historical and future climate, in order to compute modelled yields, and assess crop yield changes from historical to future climate.

The tentative yield function, a model function that compute the yield as response to climate and WBPs was assessed using the R^2 and F-test parameters. R-squared (R^2) indicates how much variation of a dependent variable is explained by the independent variable(s). It was used in this study to characterise how well the regression model fits the observed data. R^2 ranges from 0 to 1 with 0 denoting none of the variability in the data being captured by the regression model and 1 indicating that the regression model captures all the variability in the data. The closer R^2 is to 1, the better the function captures the yield annual variability. The probability levels for the F-test determines whether the value of the R^2 is statistically significant or not. F-test values of less than 0.05 show that the value is statistically significant while values greater than 0.05 show that the value is statistically non-significant. To assess the importance of each variable in the regression function, a variable with a larger value was divided by variables with smaller values.

Assessing trends and de-trending yields, correlation and regression were performed to address objective one.

3.5.3 Validating yield functions

Appreciating the accuracy of the yield functions would further allow to build degrees of confidence in the function and its outputs. Unfortunately, the validation of the yield functions was not possible in this study since the observational 1994 to 2013 and historical 1981 to 2000 datasets covered largely different time periods. Despite this gap, the observation of mean yields and its change from historical to future periods remain highly relevant, while the study acknowledge the lesser confidence in observing annual variations of simulated yield anomalies.

3.6 Simulating baseline (historical) and future crop yields

After building the yield functions using the observed data, historical and future yields were simulated using modelled climate data. Yields anomalies were simulated in AMS using climate data from three GCMs, namely; CAN-ESM2, CNRM-CM5, MPI-ESM-MR (Chylek et al., 2011; Giorgetta et al., 2013; Voldoire et al., 2013). Modelled historical yields cover a 20- year period from 1981 to 2000. Future maize and soybean yields were simulated under RCP 4.5 and RCP 8.5 for two future time periods: the near future (2020 to 2039) and the far future (2050 to 2069). Historical and future yield simulation resulted from employing related climate data and holding all other factors constant (soils and crop parameters) in the yield function addressing objective two.

To assess the effects of climate change on future yields, the difference between future and historical yield anomalies under each GCM were analysed. The average yield changes from a period to another (i.e., historical to future) were characterised as a scale of historical standard deviation, allowing to qualify the change amplitude in comparison to the natural historical variability. Where the future mean yield deviated from the historical mean yield by less than a historical standard deviation, there was a marginal change. In that case, there was no change in yields as the future mean yield remains within the historical natural variability. Alternatively, if the future change in mean yield is larger than a standard deviation, climate change had a moderate effect on crop yields. That effect was qualified as “moderate” from 1 to 3 standard deviations, and “large” beyond the threefold standard deviation (decrease or increase). This was done in order to address objective three. The district projections for maize and soybean crops were also presented spatially by GCM, by RCPs and by future periods (2020 - 2039 and 2050 - 2069). The GCMs agreements were also offered by RCP and by time period, as an indicator of confidence of projected changes.

To further build confidence in future yield change projections, the study analysed the agreement of projected changes across GCMs and/or RCPs. Where all GCMs were projecting a mean yield change of the same direction (increase or decrease) larger than one standard deviation, there was a “full” agreement on that change. Comparably where all GCMs are projecting a mean yield change lesser than one standard deviation, there was full agreement of no or marginal change. On the contrary, where all GCMs agree on the direction of change (increase or decrease) but not on the amplitude, the agreement was qualified of “moderate” when 2/3 where moderate or large changes. Finally, any conflicting projections in direction of change (increase and decrease) including at least one change larger than one standard deviation, was qualified as disagreement. This was done to address objective four.

4 CHAPTER FOUR: RESULTS

4.1 Introduction

This chapter presents the yield functions containing the climate and water balance parameters influencing maize and soybean yields per district. Then the following section presents the simulated impacts of climate change on future crop yields, as a result of the analysis of differences between simulated historical mean yields and simulated future mean yields, in two future time periods, for two RCPs. In addition, the chapter presents the similarities and contrasts among simulated crop yields across the three GCMs.

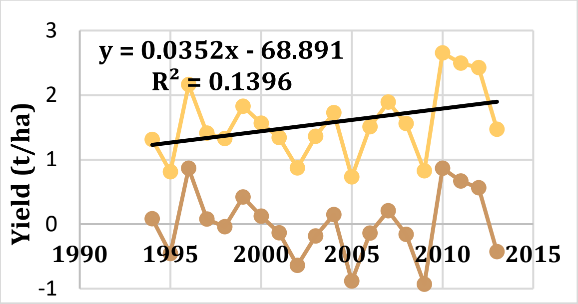
4.2 Yield functions per crop per district

In the process of building yield functions, observed yields and observed climate were used, as well as water balance parameters derived with those observed data. Crop yields are affected by both climatic and non-climatic factors. In this study, focus is given to effect of climatic factors on yields and hence the need to remove the effects of non-climatic factors.

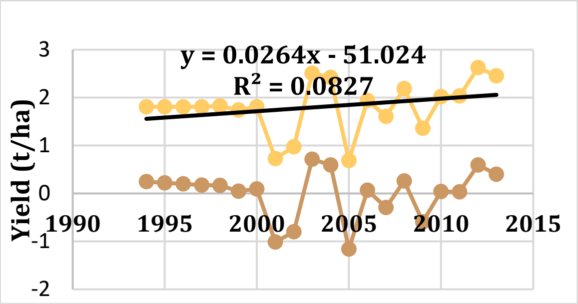
4.2.1 De-trended maize yields

The study areas of this research are located in the same agro-climatic region with similar altitudes. Figure 4.1 and Figure 4.2 show the actual yields, trends and de-trended yields of maize and soybean, respectively. The districts and provinces are arranged from a coarse West to East direction according to their geographical location.

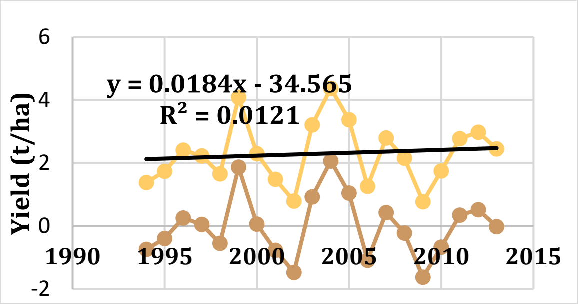
Districts in Central Province



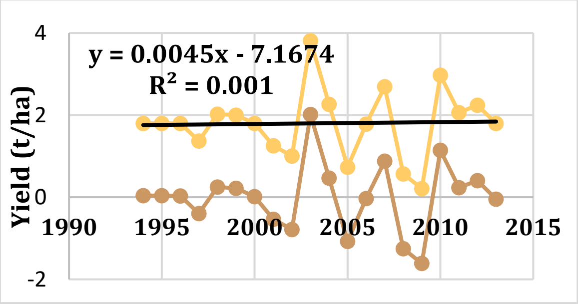
Mumbwa, F(prob) = 0.105



Kapiri Mposhi, F(prob) = 0.219

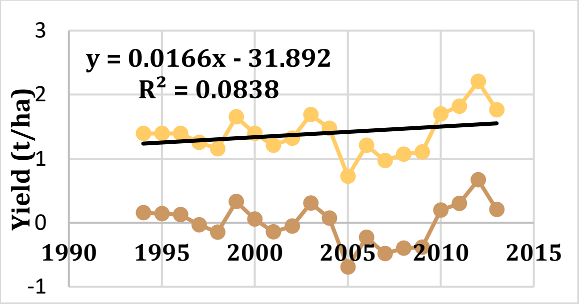


Kabwe, F(prob) = 0.645

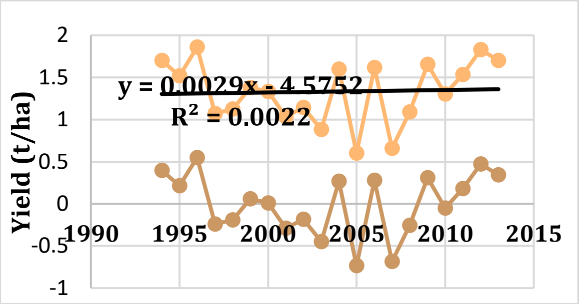


Chibombo, F(prob) = 0.894

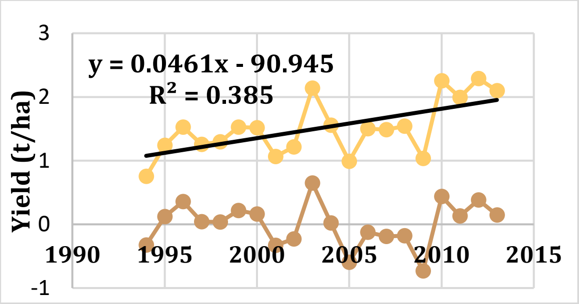
Districts in Eastern Province



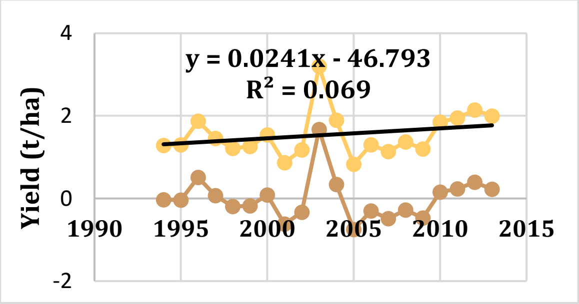
Petauke, F(prob) = 0.216



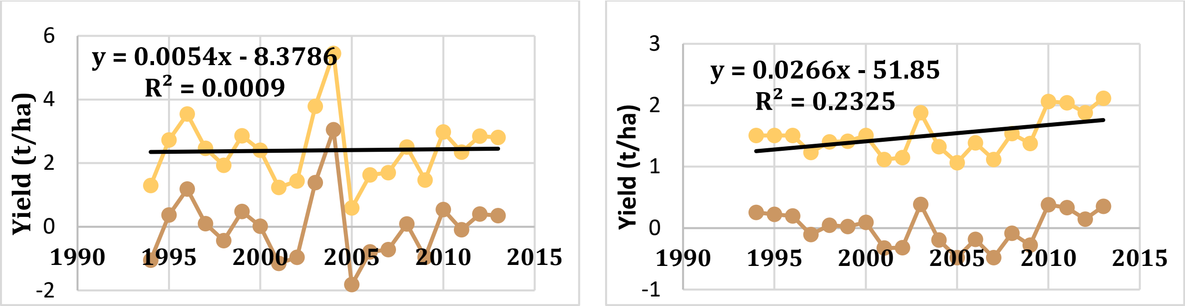
Katete, F(prob) = 0.844



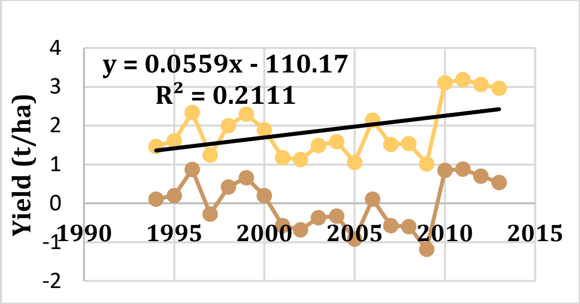
Chipata, F(prob) = 0.004



Chadiza, F(prob) = 0.263



Mkushi, $F_{(prob)}$ = 0.903 Lundazi, $F_{(prob)}$ = 0.031



Serenje, $F_{(prob)}$ = 0.042

Figure 4.1: De-trended maize yields. Observed yield (orange), observed yield linear trend (black) and de-trended yield or yield anomalies (brown).

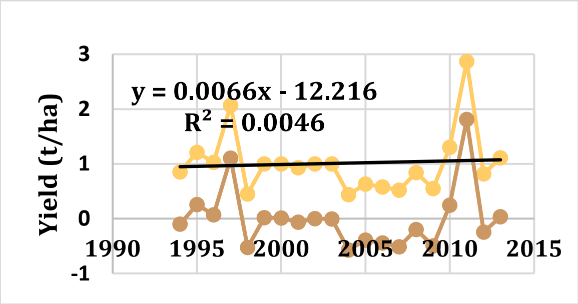
Despite most of the trend lines being statistically insignificant, maize yields in all the districts of the two provinces are showing increasing trends of different slopes (Figure 4.1). Irrespective of the slopes in all districts being close to zero, no district has recorded a negative trend. However, based on statistical features of trend lines, the trends in most of the districts are insignificant except for Chipata, Lundazi and Serenje having F–test values of 0.004, 0.031 and 0.042 respectively. The least significant trends have F-test values larger than 0.05 in Mkushi, Chibombo and Katete with F-probabilities of 0.903, 0.894 and 0.844 and slopes of 0.005 t/ha/year, 0.005 t/ha/year and 0.003 t/ha/year respectively. On the contrary, the significant trends seen in Chipata, Lundazi and Serenje districts have larger slopes denoting that the yields in these districts increased by 0.046 t/ha/year, 0.027 t/ha/year and 0.056 t/ha/year, respectively.

In most of the districts, low maize yields are recorded in the years 2002, 2005 and 2009. It concurs with observation that 2002, 2005 and 2009 were marked as moderate drought years with a comparatively severe drought occurring in the year 2005 (Libanda et al., 2019). This can explain why maize yields reduced in these years as maize is sensitive to droughts. In the same study (Libanda et al., 2019), 2004 was found to be a fairly wet year, which could explain higher than normal maize yields recorded in most of the districts this year.

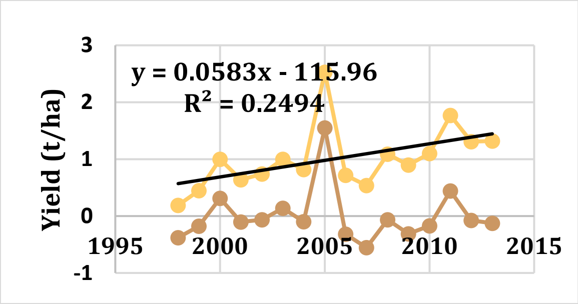
4.2.2 De-trended soybean yields

As for maize, the districts and provinces are arranged from a coarse West to East direction according to their geographical location.

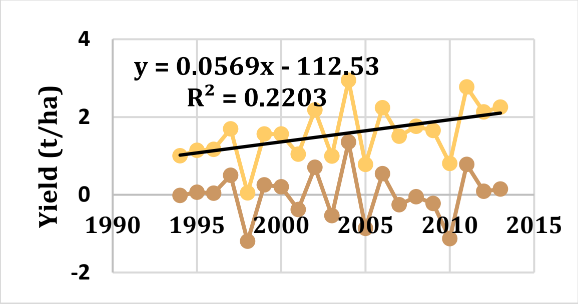
Districts in Central Province



Mumbwa, $F_{(prob)}$ = 0.775

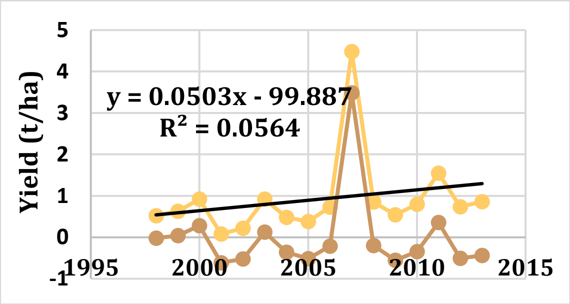


Kapiri Mposhi, $F_{(prob)}$ = 0.049

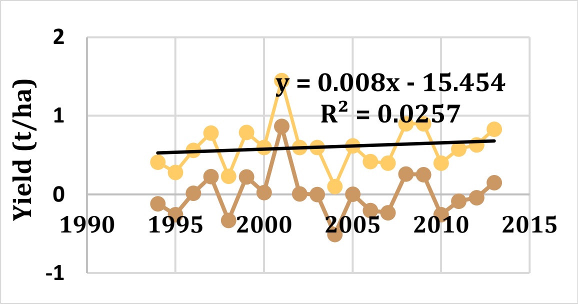


Kabwe, $F_{(prob)}$ = 0.037

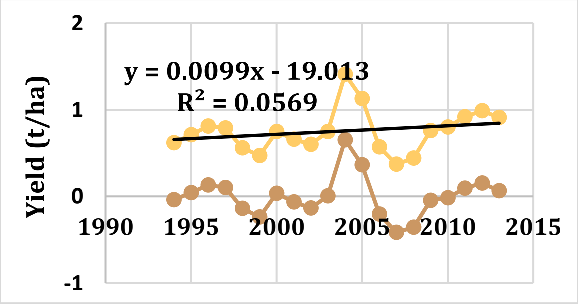
Districts in Eastern Province



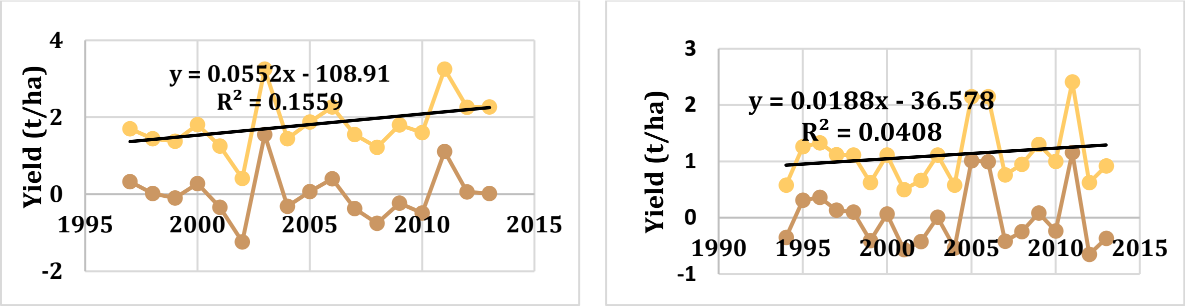
Peatuke, $F_{(prob)}$ = 0.375



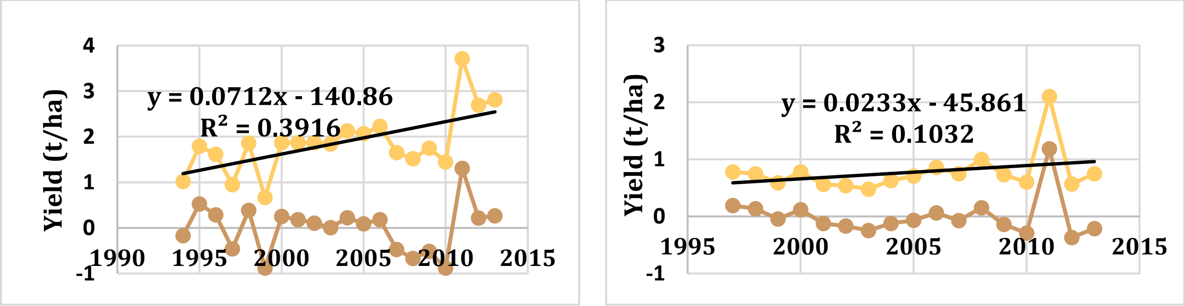
Katete, $F_{(prob)}$ = 0.500



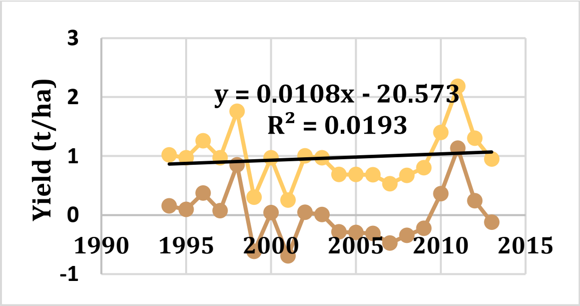
Chipata, $F_{(prob)}$ = 0.311



Chibombo, $F_{(prob)}$ = 0.117 Chadiza, $F_{(prob)}$ = 0.393



Mkushi, $F_{(prob)}$ = 0.003 Lundazi, $F_{(prob)}$ = 0.209



Serenje, $F_{(prob)}$ =0.559

Figure 4.2: De-trended soybean yields. Observed yield (orange), observed yield linear trend (black) and de-trended yield or yield anomalies (brown).

Out of all districts, only Mkushi, Kabwe and Kapiri Mposhi have statistically significant increasing trends with F-test values of 0.003, 0.04 and 0.04 respectively. The corresponding slopes of Mkushi, Kabwe and Kapiri Mposhi are of 0.07 t/ha/year, 0.057 t/ha/year and 0.058 t/ha/year respectively. In contrast, the least significant yield trends are in Mumbwa, Serenje and Katete with F–test values of 0.76, 0.56 and 0.50 and slopes increasing marginally by 0.007 t/ha/year, 0.01 t/ha/year and 0.008 t/ha/year respectively.

In most of the districts, higher soybean yields where recorded in the year 2011. This can be explained by an expectation of above-average soybean selling prices after harvesting, thereby encouraging farmers to grow large quantities of soybean in that year (Lubungu et al., 2013).

Overall, both maize and soybean are experiencing increasing yield trends during the study period: 1994 to 2013. This long-term yield increase, for both maize and soybean, is largely the response to long term changes, including improvement in crop management, technology as well as other non-climate factors.

4.2.3 Regression functions per crop per district

De-trended observed yields were correlated with climate observations and water balance parameters (WBP) of the same periods. The climate variables correlated with yield include minimum temperature (Tna, Tnn, Tnm for average, lowest and highest minimum temperatures for the crop growing season respectively), maximum temperatures (Txa, Txn,Txm for average, lowest and highest maximum temperatures for the crop growing season respectively) and rainfall (Ra, Rn and Rm for average, minimum and maximum total rainfall for the crop growing respectively). It also includes WBP obtained by simulating AMS with observed climate. The WBP include water satisfaction index (INDXLatest), water excess (WEX), water deficit (WDEF) and actual evapotranspiration (ETA) for the total growing cycle and the three latest for each stage of the crop growing cycle, specifically, initial (denoted *i*), vegetative (denoted *v*), flowering (denoted *f*) and ripening (denoted *r*). Variables that are strongly correlated with the de-trended yields and showing low correlation to other variables were preferred to build the yield function.

The intercept (a) and slopes (b) coefficients of each variable (see equation 3.2), obtained as a result of the regression process, define the yield functions. These functions will later be used to simulate yield anomalies under modelled historical and future conditions (1981 to 2000, 2020 to 2039 and 2050 to 2069). Table 4.1 and Table 4.2 are showing the adopted yield functions for simulating maize and soybean yields using the regression function described in equation 3.2.

Table 4.1: Adopted regression functions for predicting maize yields.

Province	Districts	Yield function
Central	Mumbwa	$Y= 13.194 + 0.035\ Ra - 0.047\ Rn - 0.233\ Tnn$; $R^2 = 0.47$, F-Test = 0.038
	Kapiri Mposhi	$Y = 39.53 - 0.032\ WDEFv - 1.933\ Txa - 0.037\ Rn$; $R^2 = 0.79$, F-Test = 0.040
	Kabwe	$Y= -9.845 - 0.02\ WDEFv + 0.116\ Ra - 0.345\ Rn$; $R^2 = 0.69$, F-Test = 0.040
	Chibombo	$Y = -37.394 - 0.641\ Txn + 4.493\ Tna - 0.804\ Tnn$; $R^2 = 0.88$, F-Test = 0.029
	Mkushi	$Y = 105 + 0.276\ INDX - 0.068\ WDEFv - 4.727\ Txa$; $R^2 = 0.87$, F-Test = 0.040
	Serenje	$Y= 4.484 - 0.022\ Rn - 0.181\ Txm - 0.298\ Tnn$; $R^2 = 0.36$, F-Test = 0.127
Eastern	Petauke	$Y= -1.976 - 0.008\ WEXr - 0.016\ WDEFv - 0.008\ Rm$ $R^2 = 0.89$, F-Test = 0.027
	Katete	$Y = 21.98-0.009\ Rm - 0.247\ Txm - 0.841\ Tna$; $R^2 = 0.78$, F-Test = 0.047
	Chipata	$Y = -29.214 - 0.045\ WDEFi + 0.212\ INDX - 0.086\ ETAf$; $R^2 = 0.97$, F-Test = 0.010
	Chadiza	$Y = -1.505 + 0.006\ WEXr - 0.008\ WEXt - 0.380\ Tnn$; $R^2 = 0.94$, F-Test = 0.037
	Lundazi	$Y= -0.502 + 0.135\ Txm - 0.169\ Tnm - 0.145\ Tnn$; $R^2 = 0.58$, F-Test = 0.159

The model best representing de-trended maize yields are influenced largely by climatic variables in most of the districts and less often by WBPs. For example, the yields in Mumbwa, Chibombo, Serenje, Katete and Lundazi are functions of climate variables entirely. Yields in Mumbwa for instance are increasing as a response to average rainfall increasing in combination with minimum rainfall and lowest minimum temperature decreasing. In the same district Mumbwa, minimum temperature has much higher influence in the equation (5 times more) than the average and minimum rainfall. Yield anomalies in Kapiri Mposhi, Kabwe, Mkushi, Petauke and Chadiza are functions of a combination of climatic and WBPs. Only the yield anomalies in Chipata are entirely defined as a function of WBPs. In Chipata, yields are increasing as a response to initial stage water deficit and flowering stage actual evapotranspiration decreasing and water satisfaction index increasing.

It is also noticed that some independent variables are more important in the yield functions than other variables. For example, in Kapiri Mposhi, average maximum temperature is over 50 times more important than the water deficit at vegetation stage and the minimum rainfall. Similarly, in Mkushi, avarege maximum temperature has a much higher influence on yield anomalies than water satisfaction index (17 times more) and the water deficit at vegetation stage (70 times more). In Chadiza, the lowest minimum temperature is over 47 times more important in influencing the yield anomalies than excess water at ripening stage and water excess for the total growing period. This shows that temperature is more important in influencing crop yields than other independent variables.

For all districts except Mumbwa, Serenje and Lundazi, the yield functions have R^2 values greater than 0.7 indicating that the regression models are capturing much of the variations in observed data, with low F-test insuring significance. In Mumbwa, Serenje and Lundazi, R^2 values are smaller and F-test larger denoting low capacity to capture variability in the data and non-significance. Therefore, we have relatively less confidence in those latest district's functions.

Table 4.2 is showing the adopted regression functions computed for soybean yields in each district.

Table 4.2: Adopted regression functions for predicting soybean yields.

Province	**Districts**	**Yield Function**
Central	Mumbwa	Y= -48.186 + 0.684 Txm - 0.352 Tnm + 0.799 Tnn; R^2 = 0.814, F-Test = 0.026
	Kapiri Mposhi	Y=-53.214 - 0.060 INDX + 0.0307 WDEFi + 0.028 WDEFv; R^2 = 0.99, F-Test = 0.006
	Kabwe	Y= 0.006 + 0.031 Ra - 0.010 Rm - 0.099 Rn; R^2 = 0.24, F-Test = 0.207
	Chibombo	Y=-29.080 + 0.063 Ra - 0.495 Txn - 0.011 WDEFv; R^2 = 0.981, F-Test = 0.033
	Mkushi	Y = 31.047 + 0.243 INDX + 0.908 Txm - 4.902 Tna; R^2 = 0.865, F-Test = 0.044
	Serenje	Y= -42.682 + 1.872 Txa - 0.283 Txn - 0.388 Tnn; R^2 = 0.785, F-Test = 0.044
Eastern	Petauke	Y= 28.545 + 0.029 Rm -1.861 Tna + 0.767 Tnm; R^2 = 0.925, F-Test = 0.021
	Katete	Y= -0.893 - 0.037 INDX + 0.253 Tnn + 0.033 Ra; R^2 = 0.567, F-Test = 0.054
	Chipata	Y= -68.799 + 0.242 INDX + 0.017 WEXv + 4.053 Txa; R^2 = 0.926, F-Test = 0.054
	Chadiza	Y= 2.568 + 0.002 WEXt - 0.178 Tnm + 0.163 Tnn; R^2 = 0.124, F-Test = 0.301
	Lundazi	Y= -21.249 - 0.019 WEXr + 0.046 Rn + 1.179 Txa; R^2 = 0.997, F-Test = 0.016

Similar to the pattern in maize yield functions, the regression models for soybean are showing that climate variables play a greater role in influencing the yields of soybean compared to the WBPs. Yield anomalies in Mumbwa, Kabwe, Serenje and Petauke are functions of climate variables exclusively. Except for Kapiri Mposhi where the yield anomaly is functions of WBPs only, yield anomalies in the remaining districts are functions of a mixture of climatic and WBPs.

Like in maize yield functions, in soybean yield functions, we notice that some independent variables are important in influencing yields than other variables. For example, in Chibombo, lowest maximum temperature is 8 times more important than average rainfall and 45 times important than water deficit at flowering stage. In Lundazi district, average maximum temperature is 62 times more important than water excess at ripening stage and 26 times more important than minimum rainfall. Similarly, temperature is more important in influencing soybean yields than other independent variables.

Soybean yield functions in most districts are characterised by R^2 values greater than 0.7 showing their high capacity to model observed variability with low F-test values also showing significance. For Kabwe, Katete and Chadiza on the other hand, R^2 values are lower than 0.7, i.e., low capacity to model observed variability and are non-significant. Therefore, we have relatively less confidence in those latter district's yield functions.

4.3 Projected impact of future climate on crop yields

The yield functions built in the previous section were used to simulate historical (1981 to 2000) yields per crop and per district under three GCMs. Future mean yield anomalies were also simulated for two future time periods, the near future (2020 to 2039) and the far future (2050 to 2069) as projected from each of the three GCMs under two RCPs. The standard deviation of the historical yields is used as a representation of the natural extent of variations. In accordance with this historical variation, future yield changes (future mean minus historical mean) for each GCM, each RCP, each crop in each district are classified either as large negative (brown), moderate negative (orange), marginal (grey), moderate positive (blue) and large positive (green) accordingly.

4.3.1 Historical and future maize yield changes under RCP 4.5 and RCP 8.5

4.3.1.1 CAN-ESM2

The mean yield changes in Central province for the near future period (2020 to 2039) range from -10.167 tonnes per hectare (t/ha) (Mkushi) to 6.692 t/ha (Chibombo) under RCP 4.5 and -12.123 t/ha (Mkushi) to 7.628 t/ha (Chibombo) under RCP 8.5. For the far future period (2050 to 2069), the mean yield changes range from -14.069 t/ha to 10.878 t/ha under RCP 4.5 and -21.720 t/ha to 16.011 t/ha under RCP 8.5 in Mkushi and

Chibombo respectively. In Eastern province, mean yield changes in the near future are range from -1.717 t/ha (Katete) to 0.397 t/ha (Chipata) under RCP 4.5 and - 1.831 t/ha (Katete) to -0.032 t/ha (Lundazi) under RCP 8.5. For the far future period, changes range from -2.620 t/ha (Katete) to -0.026 t/ha (Petauke) under RCP 4.5 and - 4.139 t/ha (Katete) to 1.688 t/ha (Chipata) under RCP 8.5.

Table 4.3: Historical yield standard deviations (σ) and future mean yield changes simulated under CAN-ESM2

Province	**District**	**Historical sd (σ)**	**Projected mean yield changes (y)**			
			RCP4.5		**RCP8.5**	
		1981-2000	**2020-2039**	**2050-2069**	**2020-2039**	**2050-2069**
Central	Mumbwa	0.415	-0.333	-0.451	-0.320	-0.765
	Kapiri Mposhi	1.362	-3.299	-4.243	-3.660	-7.891
	Kabwe	1.745	-0.422	0.292	-0.076	-1.682
	Chibombo	2.496	6.692	10.878	7.628	16.011
	Mkushi	3.672	-10.167	-14.069	-12.123	-21.720
	Serenje	0.389	-0.456	-0.731	-0.797	-1.810
Eastern	Petauke	0.779	-0.120	-0.026	-0.065	-0.943
	Katete	0.522	-1.717	-2.620	-1.831	-4.139
	Chipata	2.345	0.397	-1.799	-0.295	1.688
	Chadiza	0.278	-0.390	-0.519	-0.427	-0.968
	Lundazi	0.223	-0.022	-0.138	-0.032	-0.210

Legend	$y < -3\sigma$	$-3\sigma \leq y < -\sigma$	$-\sigma \leq y \leq \sigma$	$\sigma < y \leq 3\sigma$	$3\sigma < y$
	Large decrease	Moderate decrease	Marginal (decrease or increase)	Moderate increase	Large increase

Central province

In the case of Central province, mean yield changes generally decrease except for Chibombo district where there are moderate to large increases under both RCPs. Across all RCPs and time periods, moderate to large mean yield reductions are projected in Kapiri Mposhi, Mkushi and Serenje. The yield changes in Mumbwa district range from marginal to moderate decreases. Marginal changes falling within the first absolute historical standard deviation in mean yield are projected in Kabwe district under both RCPs and time periods.

Eastern province

The projected mean yield changes are consistently decreasing especially in Katete district where there are large yield decreases across both RCPs and time periods. Moderate yield decreases are seen in Chadiza under both RCPs except RCP 8.5 which has a large yield decrease. In the remaining districts, the yield changes are mostly within historical deviation, and are mostly decreasing. No positive mean yield change is seen in the province.

4.3.1.2 CNRM-CM5

CNRM-CM5 projected mean maize yield changes are exhibiting a similar pattern to that of CAN-ESM2 (Table 4.4). The mean yield changes in Central province are ranging from -4.085 t/ha (Mkushi) to 4.506 t/ha (Chibombo) in the near future under RCP 4.5. In the near future under RCP 8.5, the changes range between -4.669 t/ha (Mkushi) and 5.233 t/ha (Chibombo). With regards to the far future period, the mean changes range from -9.190 t/ha to 7.599 t/ha under RCP 4.5 and from - 12.606 t/ha to 10.718t/ha under RCP 8.5 in Mkushi and Chibombo respectively. In Eastern province, the near future mean yield changes range from -1.015 t/ha (Katete) to - 0.011 t/ha (Lundazi) and from - 1.146 t/ha (Katete) to -1.660 t/ha (Chipata) under RCP 4.5 and RCP 8.5 respectively. For the far future period, the yield changes range from -1.737 t/ha (Katete) to - 0.103 t/ha (Lundazi) under RCP 4.5 and from -2.609 t/ha (Katete) to 2.284 t/ha (Chipata) under RCP 8.5.

Table 4.4: Historical yield standard deviations (σ) and future mean yield changes simulated under CNRM- CM5

Province	**District**	**Historical sd (σ)**	**Projected mean yield changes (y)**			
			RCP4.5		**RCP8.5**	
		1980-2000	**2020-2039**	**2050-2069**	**2020-2039**	**2050-2069**
Central	Mumbwa	0.433	-0.117	-0.333	-0.185	-0.388
	Kapiri Mposhi	1.218	-1.849	-3.942	-1.733	-5.219
	Kabwe	1.938	-0.088	-1.266	-1.067	-0.515
	Chibombo	1.434	4.506	7.599	5.233	10.718
	Mkushi	2.755	-4.085	-9.190	-4.669	-12.606
	Serenje	0.450	-0.252	-0.626	-0.383	-0.913
Eastern	Petauke	0.663	-0.222	-0.147	0.091	-0.598
	Katete	0.304	-1.015	-1.737	-1.146	-2.609
	Chipata	2.746	-0.733	-1.171	1.660	2.284
	Chadiza	0.311	-0.159	-0.283	-0.140	-0.500
	Lundazi	0.214	-0.011	-0.103	-0.069	-0.110

Legend	$y < -3\sigma$	$-3\sigma \le y < -\sigma$	$-\sigma \le y \le \sigma$	$\sigma < y \le 3\sigma$	$3\sigma < y$
	Large decrease	Moderate decrease	Marginal (decrease or increase)	Moderate increase	Large increase

Central province

Large increases in yield changes are projected in Chibombo under both RCPs and time periods. In all other districts, varying levels of yield decreases are projected. In Kapiri Mposhi and Mkushi in particular, moderate decrease occurs in the near future under both RCPs, then a large decrease in the far future under both RCPs, emphasising the temporal evolution of the projected change (the further in time, the worst effect). Despite being negative, the marginal changes in Mumbwa and Kabwe remain within historical deviation.

Eastern province

The projected mean yield changes in Eastern province largely remain within historical deviations except for Katete district which has large yield decreases across both RCPs and time periods. Although the mean yield changes remain within the historical standard deviations, maize yield in Petauke, Chipata, Chadiza and Lundazi are generally declining through both RCPs and time periods.

4.3.1.3 MPI-ESM-MR

MPI-ESM-MR projected mean maize yield changes (Table 4.5) show a consistent decline across both RCPs and time periods. District yield changes in Central province range from - 14.539 t/ha (Mkushi) to 4.974 t/ha (Chibombo) under RCP 4.5 and -9.077 t/ha (Mkushi) to 6.804 t/ha (Chibombo) under RCP 8.5 in the near future horizon. In the far future period, the mean yield changes range from -20.820 t/ha (Mkushi) to 9.952 t/ha (Chibombo) under RCP 4.5 and from -21.864 t/ha (Mkushi) to 13.837 t/ha (Chibombo) under RCP 8.5. In Eastern province, the near future changes range from -1.456 t/ha (Katete) to 2.340 t/ha (Chipata) and from -1.635 t/ha (Katete) to 5.951 t/ha (Chipata) under RCP 4.5 and RCP 8.5 respectively. Under far future conditions, the mean yield changes range from -2.666 t/ha (Katete) to 2.755 t/ha (Chipata) and -3.653 t/ha (Katete) to 6.536 t/ha (Chipata) under RCP 4.5 and RCP 8.5 respectively.

Table 4.5: Historical yield standard deviations (σ) and future mean yield changes simulated under MPI-ESM-MR

Province	**District**	**Historical sd (σ)**	**Projected mean yield changes (y)**			
			RCP4.5		**RCP8.5**	
		1980-2000	**2020-2039**	**2050-2069**	**2020-2039**	**2050-2069**
Central	Mumbwa	0.371	-0.219	-0.395	-0.131	-0.729
	Kapiri Mposhi	1.150	-2.483	-5.117	-2.687	-7.591
	Kabwe	4.575	0.283	0.176	0.148	-0.310
	Chibombo	2.162	4.974	9.952	6.804	13.837
	Mkushi	3.277	-14.539	-20.820	-9.077	-21.864
	Serenje	0.457	-0.721	-1.046	-0.514	-1.741
Eastern	Petauke	0.372	0.341	0.588	0.263	0.317
	Katete	0.566	-1.456	-2.666	-1.635	-3.653
	Chipata	2.861	2.340	2.755	5.951	6.536
	Chadiza	0.295	-0.406	-0.603	-0.318	-1.056
	Lundazi	0.200	-0.028	-0.127	-0.060	-0.255

Legend	$y < -3\sigma$	$-3\sigma \le y < -\sigma$	$-\sigma \le y \le \sigma$	$\sigma < y \le 3\sigma$	$3\sigma < y$
	Large decrease	Moderate decrease	Marginal (decrease or increase)	Moderate increase	Large increase

Central province

Projected mean maize yield changes are generally negative except for Chibombo district which has moderate to large yield increases. Varying levels of decrease are seen in districts, with Kapiri Mposhi, Mkushi and Serenje showing moderate to large decrease in yield changes across both RCPs and time periods. Marginal yield changes in Kabwe remain within the historical deviations.

Eastern province

Katete and Chadiza districts display moderate to large yield decreases under both RCPs and time periods. In contrast, moderate yield increases are observed in Chipata under RCP 8.5 in both time periods and in Petauke under RCP 4.5 in the far future. The remaining yield changes for Chipata and Petauke districts are marginal and fall within the positive historical deviations. Yield changes in Lundazi are largely marginal except for the far future under RCP 8.5 showing moderate decrease.

4.3.2 Historical and future soybean yield changes under RCP4.5 and RCP8.5

4.3.2.1 CAN-ESM2

CAN-ESM2 projection of mean soybean yields is showing changes of varying decreases and increases levels across both RCPs and time periods (Table 4.6). Yield changes in Central province in the near future range from -6.363 t/ha to 3.088 t/ha and from -6.441 t/ha to 3.476 t/ha under RCP 4.5 and RCP 8.5 respectively. In the far future period, the mean yield changes range from -10.276 t/ha to 4.539 t/ha under RCP 4.5 and from -12.344 t/ha to 6.581 t/ha under RCP 8.5. For both RCPs and time periods described above, Mkushi and Serenje districts have the highest decrease and increase respectively.

In Eastern province, the near future changes range from -1.326 t/ha to 6.964 t/ha and from - 1.132t/ha to 7.903 t/ha under RCP 4.5 and RCP 8.5 respectively. As for the far future, the mean yield changes range from - 1.117 t/ha to 10.491 t/ha and from -1.626 t/ha to 19.797 t/ha under RCP 4.5 and RCP 8.5 respectively. Under all both RCPs and future time period conditions, the largest decrease is affecting Petauke district and the largest increase occurs in Chipata district.

Table 4.6: Historical yield standard deviations (σ) and future mean yield changes simulated under CAN-ESM2

Province	**District**	**Historical sd (σ)**	**Projected mean yield changes (y)**			
			RCP4.5		**RCP8.5**	
		1980-2000	**2020-2039**	**2050-2069**	**2020-2039**	**2050-2069**
Central	Mumbwa	1.176	2.496	4.203	2.879	6.193
	Kapiri Mposhi	0.952	-0.008	-0.916	-0.553	-0.083
	Kabwe	0.466	-0.094	0.009	-0.017	-0.330
	Chibombo	0.993	-0.530	-0.820	-0.766	-1.793
	Mkushi	3.773	-6.363	-10.276	-6.441	-12.344
	Serenje	1.090	3.088	4.539	3.476	6.581
Eastern	Petauke	1.072	-1.326	-1.117	-1.132	-1.626
	Katete	0.470	0.387	0.542	0.276	0.711
	Chipata	3.046	6.964	10.491	7.903	19.797
	Chadiza	0.193	-0.101	-0.192	-0.096	-0.211
	Lundazi	1.347	2.398	4.223	3.273	6.313

Legend	$y < -3\sigma$	$-3\sigma \leq y < -\sigma$	$-\sigma \leq y \leq \sigma$	$\sigma < y \leq 3\sigma$	$3\sigma < y$
	Large decrease	Moderate decrease	Marginal (decrease or increase)	Moderate increase	Large increase

Central province

The projected soybean yield changes consist of a mixture of reductions and improvements. Mkushi experiences moderate to large mean yield decreases under both RCPs and time periods. On the other hand, Mumbwa and Serenje districts experience moderate (near future) to large (far future) yield increase, across RCPs. Finally, all other districts experience largely marginal yield changes, although changes are mostly marginal decreases.

Eastern province

Moderate yield decreases are projected in Petauke districts under both RCPs and time periods. Chipata and Lundazi districts are projected to experience moderate yield increases in the near future and large increases in the far future time period. Marginal positive yield changes are projected in Katete in the near future under both RCPs and moderate yield increases in the far future under both RCPs.

4.3.2.2 CNRM-CM5

The mean yield changes in Central province for the near future period range from - 2.319 t/ha (Mkushi) to 1.771 t/ha (Mumbwa) under RCP 4.5 and from - 2.464 t/ha (Mkushi) to 1.786 t/ha (Mumbwa) under RCP 8.5. For the far future period, mean changes are ranging from - 6.840 t/ha (Mkushi) to 3.025 t/ha (Mumbwa) under RCP 4.5 and from - 6.427 t/ha (Mkushi) to 4.353 t/ha (Mumbwa) under RCP 8.5. In Eastern province, the near future mean yields changes range from - 0.389 t/ha (Petauke) to 5.127 t/ha (Chipata) under RCP 4.5 and from - 0.723 t/ha (Petauke) to 5.138 t/ha (Chipata) under RCP 8.5. For the far future period, the changes range from - 1.648 t/ha (petauke) to 9.040 t/ha (Chipata) under RCP 4.5 and from - 1.369 t/ha (Petauke) to 14.249 t/ha (Chipata) under RCP 8.5.

Table 4.7: Historical yield standard deviations (σ) and future mean yield changes simulated under CNRM- CM5

Province	District	Historical sd (σ)	Projected mean yield changes (y)			
			RCP4.5		RCP8.5	
		1980-2000	2020-2039	2050-2069	2020-2039	2050-2069
Central	Mumbwa	0.663	1.771	3.025	1.786	4.353
	Kapiri Mposhi	0.910	-0.512	-0.203	-0.139	-0.222
	Kabwe	0.517	0.080	-0.335	-0.261	0.024
	Chibombo	0.829	-0.031	-0.880	-0.048	-0.830
	Mkushi	2.786	-2.319	-6.840	-2.464	-6.427
	Serenje	0.646	1.637	2.829	1.755	4.163
Eastern	Petauke	0.792	-0.389	-1.648	-0.723	-1.369
	Katete	0.483	0.051	0.149	0.046	0.160
	Chipata	3.013	5.127	9.040	5.138	14.249
	Chadiza	0.145	-0.101	-0.138	-0.089	-0.146
	Lundazi	0.812	1.631	2.967	2.110	4.033

Legend	$y < -3\sigma$	$-3\sigma \le y < -\sigma$	$-\sigma \le y \le \sigma$	$\sigma < y \le 3\sigma$	$3\sigma < y$
	Large decrease	Moderate decrease	Marginal (decrease or increase)	Moderate increase	Large increase

Central province

In Central province, while Mumbwa and Serenje experience moderate (near future) to large (far future) positive mean yield changes, all other districts experience marginally positive or negative yield changes under both RCPs and future periods. Kapiri Mposhi, Kabwe, Chibombo and Mkushi experience marginal change into near future conditions, and marginal to moderate decreases into far future conditions under both RCPs.

Eastern province

The projected mean yield changes in Eastern province show a similar pattern with mean yield changes in Chipata and Lundazi increasing moderately in the near future and largely in the far future under both RCPs. Yield changes in the remaining districts are largely marginal except for Petauke which has moderate decreases in the far future for under both RCPs.

4.3.2.3 MPI-ESM-MR

The mean yield near future changes in Central province range from - 4.856 t/ha (Mkushi) to 2.498 t/ha (Mumbwa) and from - 5.693 t/ha (Mkushi) to 2.958 t/ha (Mumbwa) under RCP 4.5 and RCP 8.5, respectively. Into the far future period, the yield changes are ranging from - 8.518 t/ha (Mkushi) to 4.471 t/ha (Serenje) under RCP 4.5 and from - 14.942 t/ha (Mkushi) to 5.765 t/ha (Mumbwa) under RCP 8.5. In Eastern province, the near future mean yield changes range from - 1.150 t/ha (Petauke) to 6.143 t/ha (Chipata) and from - 1.287 t/ha (Petauke) to 7.946 t/ha (Chipata) under RCP 4.5 and RCP 8.5 respectively. For the far future period, the pattern is the same with Petauke having largest yield decreases and Chipata recording the highest yield improvements under both RCPs.

Table 4.8: Historical yield standard deviations (σ) and future mean yield changes simulated under MPI-ESM-MR

Province	District	Historical sd(σ)	Projected mean yield changes (y)			
			RCP4.5		RCP8.5	
		1980-2000	2020-2039	2050-2069	2020-2039	2050-2069
Central	Mumbwa	1.419	2.498	4.348	2.958	5.765
	Kapiri Mposhi	1.015	-0.847	-0.491	-0.313	-0.279
	Kabwe	0.787	0.305	0.190	0.365	0.187
	Chibombo	0.605	-0.435	-1.417	-0.765	-1.960
	Mkushi	2.914	-4.856	-8.518	-5.693	-14.942
	Serenje	1.002	2.214	4.471	2.853	5.667
Eastern	Petauke	0.722	-1.150	-2.159	-1.287	-2.654
	Katete	0.493	0.381	0.765	0.813	1.658
	Chipata	2.696	6.143	9.106	7.946	14.919

	Chadiza	0.383	0.022	-0.063	-0.070	-0.075
	Lundazi	1.064	2.048	4.176	2.567	5.456

Legend	$y < -3\sigma$	$-3\sigma \le y < -\sigma$	$-\sigma \le y \le \sigma$	$\sigma < y \le 3\sigma$	$3\sigma < y$
	Large decrease	Moderate decrease	Marginal (decrease or increase)	Moderate increase	Large increase

Central province

In Central province, Mumbwa and Serenje districts are exhibiting mean yield changes ranging from moderate increases in the near future to large increases in the far future under both RCPs. On the other hand, Chibombo and Mkushi exhibit moderate to large yield reductions under RCP 4.5 to RCP 8.5 and from near to far future. Kapiri Mposhi and Kabwe only experience marginal changes, although negative and positive, respectively.

Eastern province

MPI-ESM-MR projections show varying levels of soybean yield decreases and increases. Increases in Katete, Chipata and Lundazi are mostly moderate in the near future and large into the far future. Petauke is projected to have moderate reductions under both RCPs for near future, and moderate (RCP 4.5) or large (RCP 8.5) reductions into far future conditions. Mean yield changes in Chadiza remain within historical deviation under both RCPs and time periods.

4.4 Spatial analysis of the mean yields projected changes

Maps are used to visualise the future spatial variability of crop yield changes as in the face of climate change.

4.4.1 Maize yields spatial changes under RCP 4.5

The mean yield changes, from historical into the two future periods are presented in Figure 4.3. The colour code used above remains; orange and brown (blue and green) denoting moderate and large decrease (increase) as compared to historical standard deviation. Grey denotes a marginal change contained within historical deviation. White denotes districts not studied. The thick and thin black lines denote provincial and district boundaries, respectively.

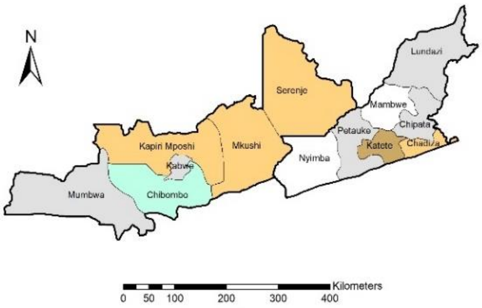
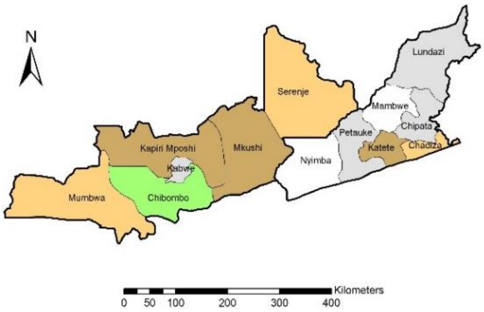
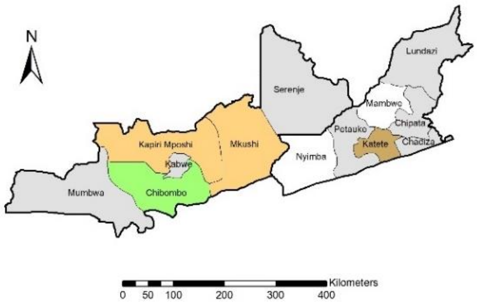
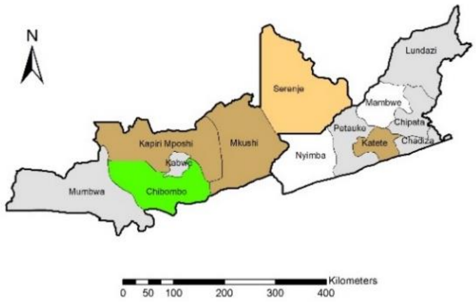
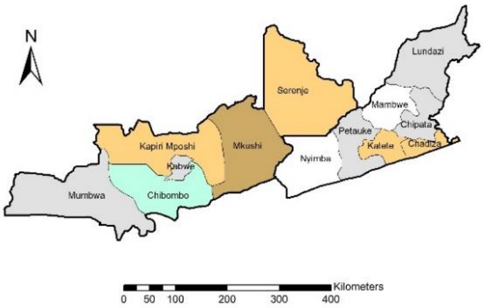
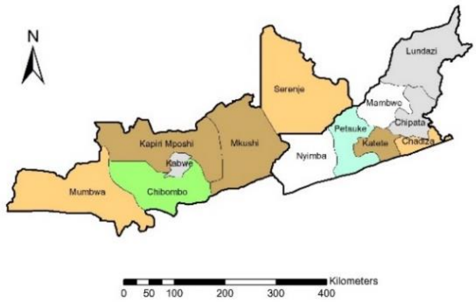
GCM	**Near future (2020-2039)**	**Far future (2050-2069)**
CAN-ESM2		
CNRM-ESM2		
MPR-ESM-MR		

Figure 4.3: Maize yields change amplitudes as a response to future climate under RCP 4.5.

Legend	$y < -3\sigma$	$-3\sigma \le y < -\sigma$	$-\sigma \le y \le \sigma$	No data	$\sigma < y \le 3\sigma$	$3\sigma < y$
	Large decrease	Moderate decrease	Marginal (decrease or increase)	Not studied	Moderate increase	Large increase

Near and future time horizons show relatively consistent spatial yield projections across the GCMs.

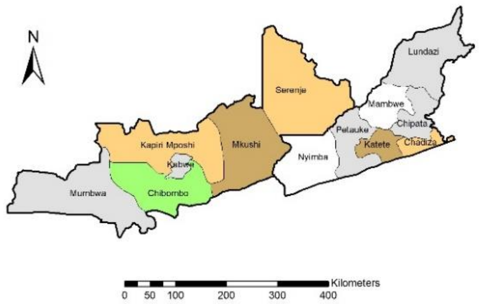
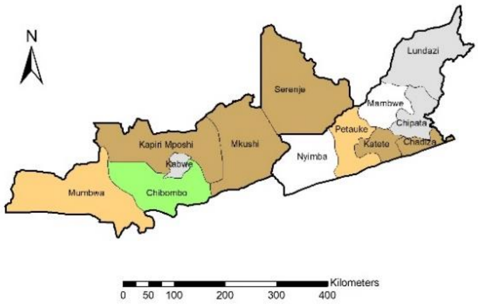
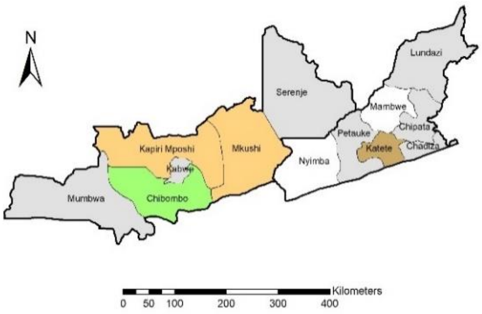
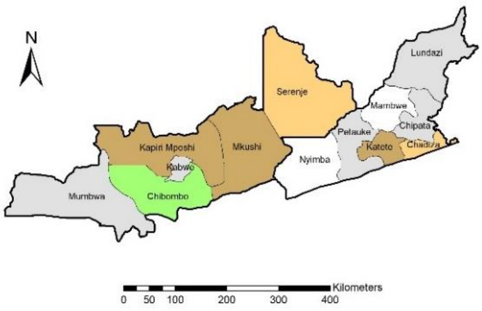
Central province

Kapiri Mposhi, Mkushi and Serenje exhibits moderate yield decreases into the near future. In the far future, yield decreases expand spatially into Mumbwa and amplify in Kapiri Mposhi and Mkushi districts from moderate to large. Unlike other districts, Chibombo is projected to experience a moderate yield increase in the near future and a large increase in the far future period. Marginal yield changes are projected in Kabwe district across GCMs.

Eastern province

The near and far future yield changes are mostly large (moderate) decreases in Katete (Chadiza) districts. In the remaining districts, the yield changes are marginal except for Petauke district which is experiencing a moderate yield increase in the far future under the MPI-ESM GCM.

4.4.2 Maize yields spatial changes under RCP 8.5

<table>
<tr><th>GCM</th><th>Near future (2020-2039)</th><th>Far future (2050-2069)</th></tr>
<tr><td>CAN-ESM2</td><td>
</td><td>
</td></tr>
<tr><td>CNRM-ESM2</td><td>
</td><td>
</td></tr>
</table>

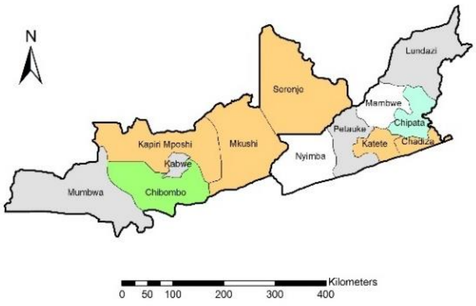
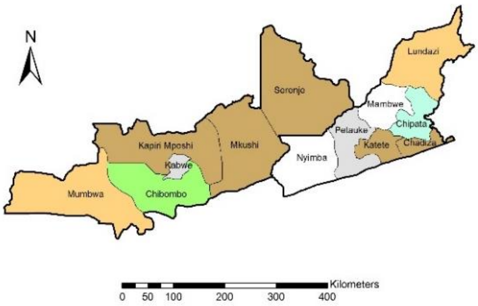
MPR-ESM-MR		

Figure 4.4: Maize yields change amplitudes as a response to future climate under RCP 8.5.

Legend	$y < -3\sigma$	$-3\sigma \leq y < -\sigma$	$-\sigma \leq y \leq \sigma$	No data	$\sigma < y \leq 3\sigma$	$3\sigma < y$
	Large decrease	Moderate decrease	Marginal (decrease or increase)	Not studied	Moderate increase	Large increase

Central province

Across GCMs, moderate yield reductions are projected mostly in Kapiri Mposhi, Mkushi and Serenje districts in the near future. In the far future these reductions expand to Mumbwa district and become more pronounced (large) in the districts that show moderate changes in the near future. A large yield increase in Chibombo is projected across GCMs and time periods. In Kabwe, only marginal changes are projected across GCMs and time periods.

Eastern province

CAN-ESM2 and MPI-ESM-MR projections are showing mostly moderate yield decrease in Katete and Chadiza districts in the near future and are amplifying to large changes into the far future. In the far future, the moderate yield decreases are expanding to Petauke under CAN-ESM2 GCM and to Lundazi under MPI-ESM-MR GCMs. In Chipata maize yield changes are moderate increases in both time periods under MPI-ESM-MR, the remaining GCMs project marginal yield changes within the historical deviation.

4.4.3 Maize GCMs agreement maps

Maize yield changes from RCP 4.5 and RCP 8.5 are exhibiting quite similar patterns. Figure 4.5 is showing GCM's agreement maps for maize for two RCPs and two future periods.

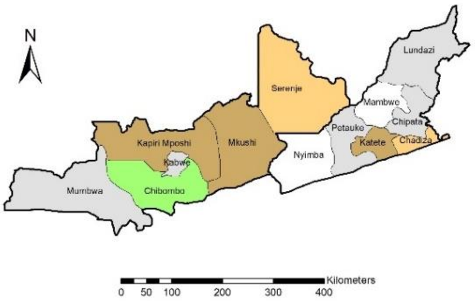
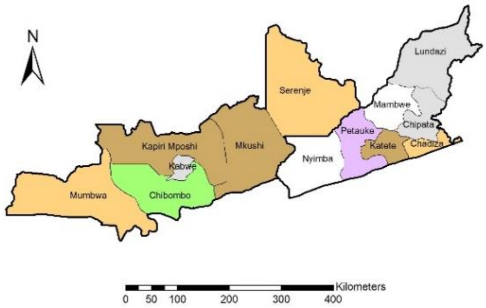
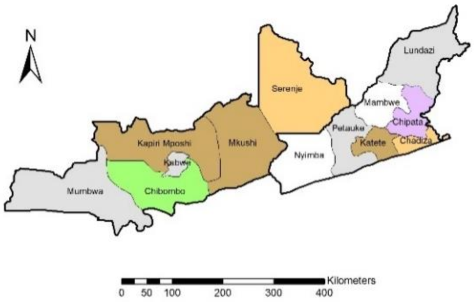
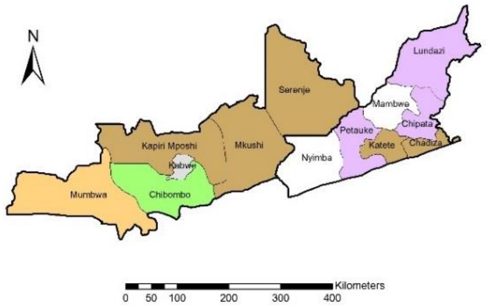
RCP	Near future (2020 – 2039)	Far future (2050 – 2069)
RCP 4.5		
RCP 8.5		

Figure 4.5: GCM's agreement maps for future maize yield changes.

Legend

FULL AGREEMENT - DECREASE	MODERATE AGREEMENT - DECREASE	FULL AGREEMENT – NO CHANGE	DISAGR-EEMENT	Not studied	MODERATE AGREEMENT - INCREASE	FULL AGREEMENT - INCREASE
All GCMs agree on a moderate to large decrease	All GCMs agree on a decrease, mostly characterised as non-marginal	All GCMs agree on a marginal change (increase or decrease)	GCMs disagree on change direction	No data	All GCMs agree on an increase, mostly characterised as non-marginal	All GCMs agree on a moderate to large increase

Central province

In the near future period, under both RCPs, GCMs are in full agreement regarding large yield decreases in Kapiri Mposhi and Mkushi and moderate decrease agreement regarding decreasing yields in Serenje. Similarly, GCMs are in full agreement of no change about marginal yield changes in Mumbwa and Kabwe districts, remaining within historical deviation. On the other hand, there is a full increase agreement among GCMs in mean maize yields changes in Chibombo district under both RCPs and time periods. In the far future, the GCMs are in full agreement on the large decrease in mean yields in Kapiri Mposhi and Mkushi, also including Serenje under RCP 8.5. The GCMs are in moderate decrease agreement in Mumbwa district. GCMs are in full no change agreement in Kabwe district and a full increase agreement in Chibombo districts in the far future.

Eastern province

In the near future, GCMs are in full and moderate agreement on the moderate to large yield decreases in Katete and Chadiza. The GCMs are in full marginal agreement on the changes in Petauke and Lundazi, and they disagree on amplitude and direction of change in Chipata under RCP 8.5. Into the far future, and except for Petauke were GCMs disagree, all other districts exhibit similar changes as for near term under RCP 4.5. Under RCP 8.5, the GCMs are in full agreement on the large and moderate yield decreases projected in Katete and Chadiza districts in the near future. However, under RCP 8.5, the GCMs are in disagreement on the yield changes in Petauke, Chipata and Lundazi districts in the far future period.

In summary, the results are suggesting that future climate change is likely to negatively affect future maize yields in Kapiri Mposhi, Mkushi, Mumbwa and Serenje districts in Central province in addition to Chadiza and Katete districts in Eastern province. Additionally, the GCMs are mostly in agreement of the yield changes in Central province under both RCPs and time periods while GCMs relatively disagree on the yields changes in some districts in Eastern province especially under RCP 8.5 in the far future.

4.4.4 Soybean yields spatial changes under RCP 4.5

Soybean yield response to future climate under RCP 4.5 are presented in Figure 4.6.

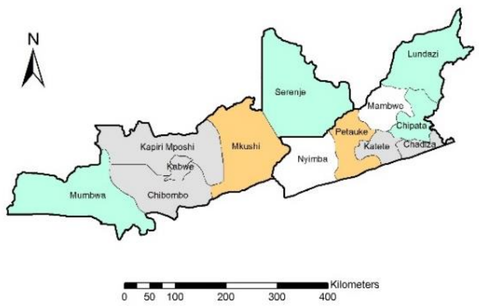
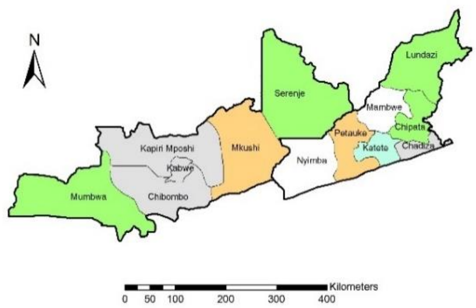
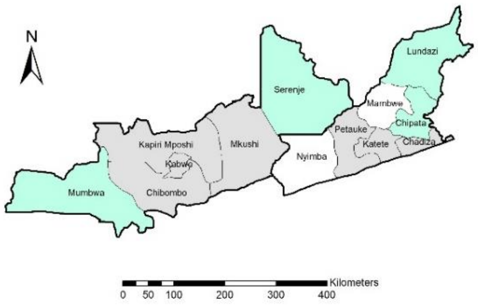
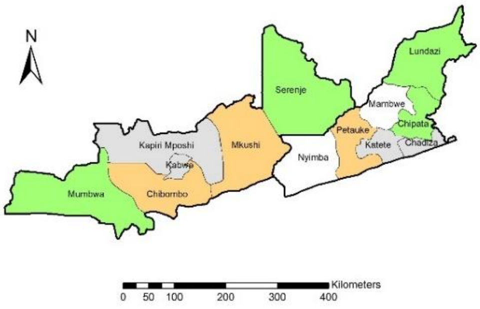
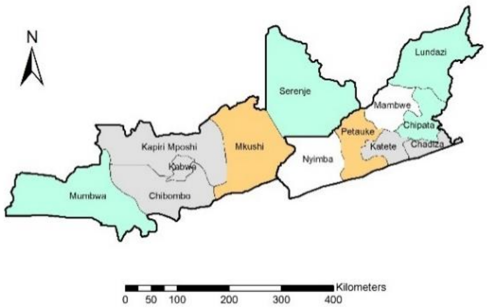
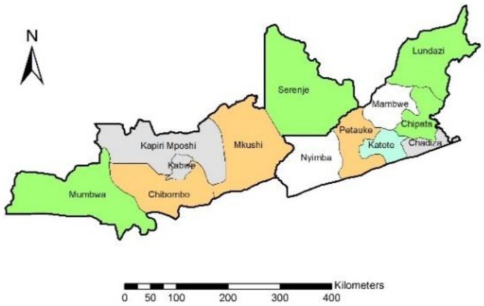
GCM	Near future (2020-2039)	Far future (2050-2069)
CAN-ESM2		
CNRM-ESM2		
MPR-ESM-MR		

Figure 4.6: Soybean yields change amplitudes as a response to future climate under RCP 4.5.

Legend	$y < -3\sigma$	$-3\sigma \leq y < -\sigma$	$-\sigma \leq y \leq \sigma$	No data	$\sigma < y \leq 3\sigma$	$3\sigma < y$
	Large decrease	Moderate decrease	Marginal (decrease or increase)	Not studied	Moderate increase	Large increase

Central province

Moderate changes of yield increases are projected in oppositely isolated districts of Mumbwa and Serenje in the near future. In the far future, there is a shift in these districts from moderate to large increases. CAN-ESM2 and MPI-ESM-MR are projecting a moderate yield decrease in Mkushi in both near and far futures. Yield changes for Kapiri Mposhi, Kabwe and Chibombo are marginal in the near future under both RCPs and time periods except CNRM-CM5 and MPI-ESM-MR GCMs having moderate decreases in Chibombo distrcit in the far future time period.

Eastern province

Moderate changes of soybean yield increases are projected in Chipata and Lundazi in the near future and the yield changes in these districts shifts to large increases in the far future. Yield changes in Katete and Chadiza districts are marginal in the near future under both RCPs and time periods. In the far future, marginal yield changes in Chadiza district remain unchanged while marginal yield changes in Katete district shifts to moderate increases under CAN-ESM2 and MPI-ESM-MR GCMs. Yield changes in Petauke district are moderate decreases under GCMs, RCPs and time periods except the near changes under CNRM-ESM2 which has marginal yield changes remaining within the historical deviations.

4.4.5 Soybean yields spatial changes under RCP 8.5

Soybean yield responses to future climate under RCP 8.5 are presented in Figure 4.7. The pattern of changes under RCP 8.5 is similar to that of RCP 4.5. The GCMs are showing a mixture of soybean yield increases and decreases across districts under both RCPs and time periods. The negative or positive yield changes are moderate in the near future and amplifying in the far future.

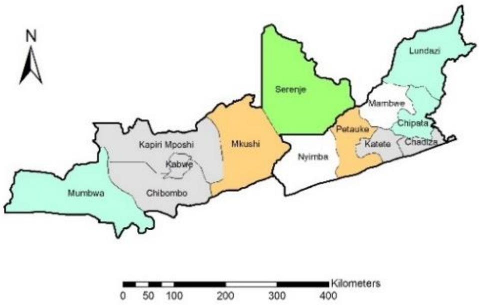
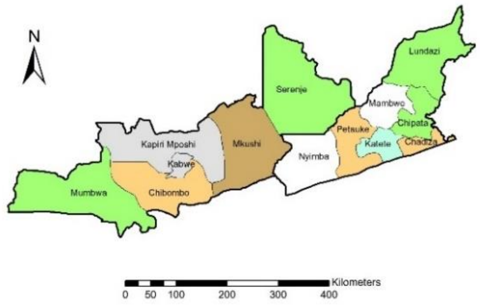
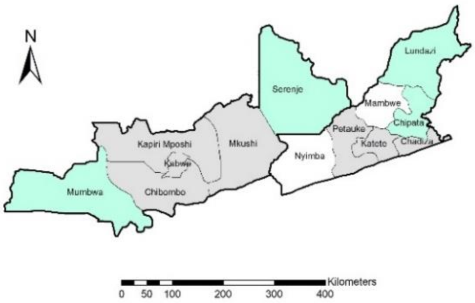
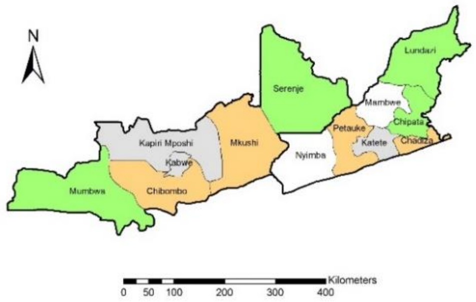
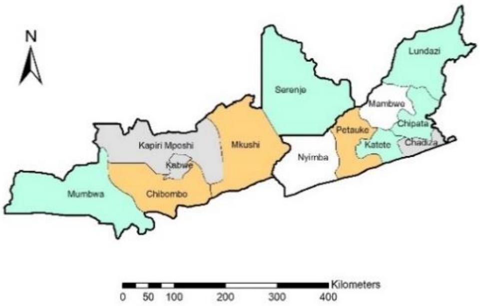
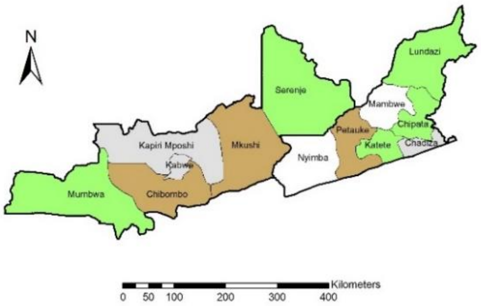
GCM	Near future (2020-2039)	Far future (2050-2069)
CAN-ESM2		
CNRM-ESM2		
MPR-ESM-MR		

Figure 4.7: Soybean yields change amplitudes as a response to future climate under RCP 8.5.

Legend	$y < -3\sigma$	$-3\sigma \leq y < -\sigma$	$-\sigma \leq y \leq \sigma$	No data	$\sigma < y \leq 3\sigma$	$3\sigma < y$
	Large decrease	Moderate decrease	Marginal (decrease or increase)	Not studied	Moderate increase	Large increase

Central province

Moderate changes of yield increases are projected mostly in Mumbwa and Serenje districts in the near future. This moderate change in these districts amplifies to large increase in the far future. CAN-ESM2 and MPI-ESM-MR GCMs are projecting a moderate yield decreases in Mkushi in near future which evolves into a large decrease in far future. Yield changes for Kapiri Mposhi, and Kabwe are marginal falling within the historical deviation under both RCPs and time periods.

Eastern province

Moderate soybean yield improvements are projected in Chipata and Lundazi districts including Katete under MPI-ESM-MR in the near future and shift to large increases in the far future. Petauke is projected to experience fluctuations of moderate to large yield reductions across the GCMs and time periods while yield changes in Chadiza are marginal in the near future and show mostly moderate reductions in the far future.

4.4.6 Soybean GCM's agreement maps

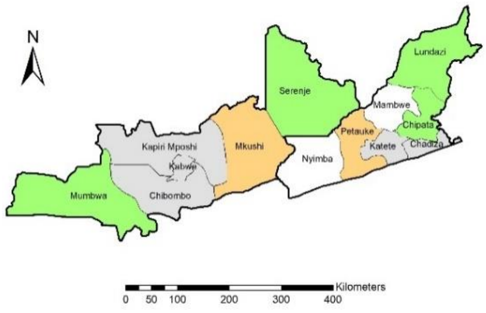
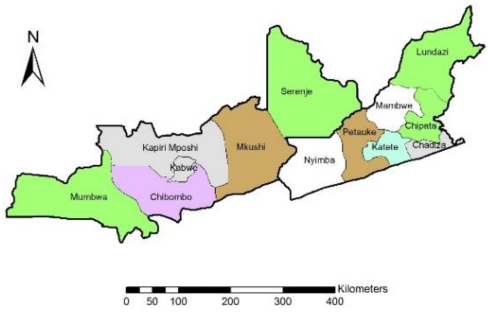
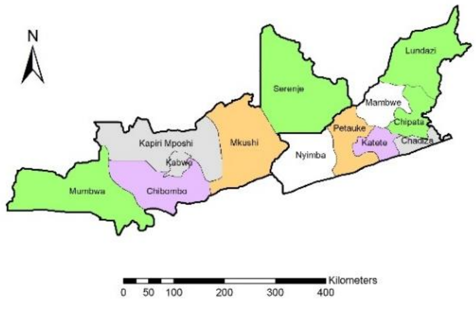
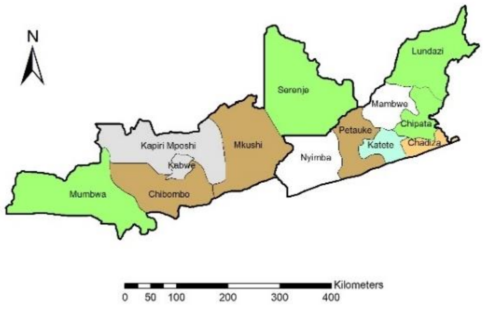
RCP	Near future (2020 – 2039)	Far future (2050 – 2069)
RCP 4.5		
RCP 8.5		

Figure 4.8: GCM's agreement maps for future soybean yield changes.

Legend

FULL AGREEMENT - DECREASE	MODERATE AGREEMENT - DECREASE	FULL AGREEMENT – NO CHANGE	DISAGR-EEMENT	Not studied	MODERATE AGREEMENT - INCREASE	FULL AGREEMENT - INCREASE
All GCMs agree on a moderate to large decrease	All GCMs agree on a decrease, mostly characterised as non-marginal	All GCMs agree on a marginal change (increase or decrease)	GCMs disagree on change direction	No data	All GCMs agree on an increase, mostly characterised as non-marginal	All GCMs agree on a moderate to large increase

Central province

As shown in Figure 4.8, the GCMs are in full agreement about soybean yields increasing largely in Mumbwa and Serenje districts under both RCPs and time periods. In addition, the GCMs are in full no change agreement on yields in Kapiri Mposhi and Kabwe districts under both RCPs and time periods. Further, the GCMs moderately agree on the yield decreases in Mkushi districts in the near future and this evolves into full agreement in the far future. GCMs are in disagreement on the direction of yield changes in Chibombo district under RCP 4.5 in the far future and RCP 8.5 in the near future.

Eastern province

The GCMs are in full agreement on the yield increases in Chipata and Lundazi districts under both RCPs and times periods. In addition, the GCMs are in full no change agreement on the yield changes Chadiza district under both RCPs and time periods. As for Petauke districts, the GCMs are in moderate and full agreements on the yields decreases in the near and far future, respectively. Yield changes in Katete district fluctuates among GCMs, RCPs and time periods from no change, disagreement to moderate increases.

5 CHAPTER FIVE: DISCUSSION

5.1 Factors influencing maize and soybean yields

The observed yields of maize (Figure 4.1) and soybean (Figure 4.2) showed increasing slopes of varying statistical strengths. Table 4.1 show that most of the maize yield functions built demonstrated the ability to capture variations in observed data and therefore simulated good estimates of mean maize yield. This was evident from R^2 values greater than 0.7 coupled with F-test values less than 0.05. This indicates towards the usefulness of the yield functions used in simulating modelled historical and future yields under GCMs downscaled data. In a few cases however, the yield functions did not perform as well, where R^2 values show limited capacity to model yields variations. In consequence, the study acknowledges the lesser confidence in these district's simulated yields, relatively to other districts and crops.

Similarly, soybean yield functions shown in Table 4.2 have R^2 values greater than 0.7 in most of the districts with Chibombo, Chipata, Kapiri Mposhi, Lundazi and Petauke districts having R^2 values greater than 0.90 and F-test values well below the 0.05 significance threshold. While these conditions offer a higher confidence in simulated yield outputs for those districts, the study recognise the relatively lower confidence in the yield functions built in other districts including Chadiza, Kabwe and Katete. Despite this limitation, the observation of mean yields and its change from multi-decadal historical to future periods remain highly relevant.

In addition, the study shows that climate variables play a larger role in influencing both maize and soybean yields as compared to water balance parameters (WBPs). In maize, yields in five out of eleven districts are entirely a function of climate variables. Only the yield anomalies in one district (Chipata) are entirely defined as a function of WBPs with the yields in the remaining districts being defined by a combination of climate and WBPs. Similarly, soybean yields in four out of eleven districts are functions of climate variables exclusively. Except for Kapiri Mposhi where the yield anomaly is functions of WBPs only, soybean yield in the remaining districts are functions of a mixture of climatic and WBPs. The study therefore suggest that maize and soybean crops should be subjected to optimal amounts of rainfall and temperatures for maximum productivity.

5.2 Sensitivity of maize and soybean yields to future climates

Maize yield projections from CAN-ESM2 (Table 4.3), CNRM-CM5 (Table 4.4) and MPI-ESM-MR (Table 4.5) show a similar pattern across GCMs, RCPs and time periods. Projection results from these GCMs suggest a large maize yield decrease in Mkushi and a large increase in Chibombo districts in Central province. While in the Eastern province, the GCMs agree that the largest decrease in maize yields will occur in Katete while the largest increase is occurring in Chipata mostly, in Lundazi and Petauke in some cases. Furthermore, the results suggest that the effect of climate change on maize mean yields will reduce maize yields in Mkushi and Katete districts whereas Chibombo and Chipata will experience yield increases. Similarly, soybean yield projections from CAN-ESM2 (Table 4.6), CNRM-CM5 (Table 4.7) and MPI-ESM-MR (Table 4.8) show a similar pattern across GCMs, RCPs and time periods. The GCMs agree that Mkushi will experience the largest soybean yield decrease in Central province whereas the largest increase will fluctuate between Mumbwa and Serenje districts. In Eastern province, the GCMs are consistent that Petauke will have the largest decrease while the largest increase will occur in Chipata district.

In addition to the above results, six out of the eleven districts studied (Figure 4.5) are projected to experience negative climate change impacts on maize yield including Kapiri Mposhi, Mkushi, Serenje, Katete, Chadiza, extending to Mumbwa in the far future under both RCPs. On the contrary, five out of eleven districts studied are projected to see soybean yield improvements, three districts to experience marginal yield changes with only two districts projected to experience yield reductions due to climate change (Figure 4.8). This implies that maize is more sensitive to climate change when compared to soybean and future climate change will favour soybean production. In addition, Figure 4.8 shows substantial positive changes in soybean yields likely occurring including in Mumbwa, Serenje, Chipata, Lundazi districts extending moderately to Katete in the far future period. Unlike the other districts, soybean crop in these districts is thus expected to benefit from climate change.

Equally, comparing GCMs projections for maize (Figure 4.5) and soybean (Figure 4.8), it is noticeable that maize is more sensitive to future climates. For maize, only Chibombo district is projected to have positive yield change in response to future climates whereas soybean has four to five districts that will have a positive response to climate change. Negative yield changes are projected for both maize and soybean in Mkushi and marginal yield changes are projected for both crops in Kabwe district. Libanda and Ngonga (2018) highlights Mkushi as one of the areas projected to be vulnerable to the negative impacts of climate change by the end of the 21st century, making this a major concern since the district is one of the major producers of maize in Zambia.

These negative impacts of climate change on maize yields are consistent with the findings of both large-scale studies in the region and local scale studies performed in Zambia. Large scale studies such as Jones and Thornton (2003) and Thornton et al. (2011) projected respectively a 10% and 16% decline in maize yields in most countries globally by 2050. Likewise, Schlenkler and Lobell (2010) projected a 22% decline in maize yields by the end of the 21st century. Zipper et al. (2016) found a greater relationship between a drought index, SPEI, and maize compared to the relationship it has with soybean production. Comparably, results obtained under present study are consistent with local previous studies (Wang et al., 2014; Adhikari, 2015; Winemana and Crawfordb 2017) that have indicated maize to be among the most negatively affected crop with significant yield reductions due to projected future climate compared to other crops. Winemana and Crawfordb (2017) found that smallholder farmers are shifting production from maize towards other crops like sweet potatoes and cotton that are offering more resilience to climate change than maize.

Furthermore, in line with results from this study, a recent study by Mulungu and Ng'ombe (2019) describes maize as highly sensitive crop especially to high temperatures even though it is considered as a warm season crop. At a high temperature of 35°C, maize yield declines by 9% with about 25.4 mm reduction in rainfall. Mulungu and Ng'ombe (2019) further contend that maize crop is highly susceptible to climate change such that 70 – 80% maize losses in SSA region is attributed to climate change extremes such as droughts and floods. Hamadudu and Ngoma (2020) suggested a 13% decline in water availability in Zambia by the end of the century due to climate change and this will pose a great risk to most field crops especially maize.

Further confidence in the results of this present study emanates from Lubinga et al. (2019) which showed that the provision of supplementary irrigation under high input farming system lessens the impact of climatic variability and change on crop productivity. The negative impacts of climate on maize yields may in consequence reduce the availability of the crop within the local and national markets. In addition, low supply of maize may lead to an increase in the price of this staple food and as a result, becoming unaffordable for low-income households. This will likely worsen the level of food insecurity within the country. A global study by Zhao et al. (2017) showed that without effective adaptation, each degree Celsius increase of global mean temperature will reduce maize by 7.4% and soybean by 3.1% signifying maize to be a more vulnerable to climate change impacts than soybean.

Since all the GCMs and both RCPs are agreeing that there will be soybean yield improvements in a number of districts in both time periods, this study suggest that the soybean crop will therefore most likely benefit from climate change and offer an alternative crop to maize production.

Agriculture is the mainstay of the Zambian economy, contributing to food security and employment of rural households. Drastic reductions in maize yields compared to soybean will cause major implications in the agricultural system since maize is a staple crop in these provinces and the whole country. Maize in Zambia is grown at a larger scale and receives so many incentives from government than soybean crop. In line with Ngoma (2008), the findings of this study suggest that although maize is one the crops grown mostly by farmers in Zambia and being the staple food, its production is largely dependent on climatic factors. This means that some changes in climatic condition may affect its production negatively. This finding is a vital consideration amidst Zambia's more maize-centric agricultural policies. Policy programs that support smallholder rain-fed farmers should extend to other crops like soybean that are anticipated to be less affected by future climate change. Additionally, as suggested by Mulenga et al. (2015), future climate change adaptation plans will require smallholder farmers to move away from the current pattern of growing more land with maize to growing more climate resilient crops like soybean, among others.

5.3 Spatial sensitivity of maize and soybean to future climates

As shown in Figure 4.5, more districts in Central province are projected to experience maize yield reductions than the districts in Eastern province where the changes are mostly within the historical deviations as a result of climate change. However, unlike the present study result where maize yields are projected to decrease mostly in Central province, Wang et al. (2014) projected Central province to be one of the potentially suitable regions for future maize production whereas Syampaku et al. (2019) projected maize yields to reduce significantly in Eastern province especially towards the end of the 21st century. The maize yield projections obtained in Wang et al. (2014) for Central province are reflected in the present study in Chibombo district only where yields will likely increase. As for soybean (Figure 4.8), there is an equal balance in yield changes between the districts in Central and Eastern provinces. These results therefore suggest soybean to less sensitive to climate change and both the study areas will be suitable for soybean growing. Occasionally, soybean yields within a province are projected to increase in districts adjacent to districts where yields are projected to decline, sometimes drastically. Hence this study suggests that the substantial spatial variability in direction and amplitude of yield changes could be a result of local physical characteristics (water table depth, soil texture, soil water holding capacity topography), farming systems and agricultural management which have not been explored in this study.

5.4 Uncertainty, agreement and confidence

In climate change impact assessments, it is vital to consider several sources of limitations arising from crop yield simulations. Decision making based on results from such studies need to be interpreted accordingly. In this study, the model used, AMS only considers soil water holding capacity as the representative of the soil general properties, leaving out many other soil characteristics that also play a role in crop growth. Moreover, this study considered only the impacts of climate change on maize and soybean yields leaving out other sources of crop yield losses such as management practices, pests and diseases and environmental conditionals which may necessitate further investigation. Nevertheless, this study has shown the direction of change for maize and soybean yields in relation to future climates.

To build confidence in the yield changes, this study utilized three GCMs, two RCPs and two future time periods to project future yields. In most cases, the GCMs are in full agreement on the direction and amplitude of crop yield changes. As seen from Figure 4.5, the GCMs are in full agreement on the direction and amplitude of maize yield changes in at least six districts. As for soybean, the GCMs are in full agreement on the direction and amplitude of yield changes in at least seven districts. Similarly, for both maize and soybean, the RCPs are showing the same direction of yield changes. Furthermore, the results of the present study highlight that when the change in crop yields is marginal or moderate in the near future (2020 to 2039), it amplifies into large changes in the far future term (2050 to 2069). This suggests that the effects of climate change on crop yields intensify over time and urges to take adaptation steps earlier rather than later. In both Central and Eastern province districts, for both maize and soybean, larger yield changes (negative or positive) are projected under RCP 8.5 than RCP 4.5. From a climate perspective, RCP 8.5 translates into higher atmospheric GHG concentrations and a higher increase in temperatures which increases over time. This builds confidence in the projection results of this study.

Moreover, the use of downscaled climate data for each district has helped to determine variations of climate change impacts across districts despite being in the same agro-ecological region. For example, in soybean yields, Serenje district is benefiting from climate change while the adjacent district Mkushi has negative impacts of climate change. Downscaled climate data is useful for generating local climate information and in designing adaptation strategies at local scales such as district or province as opposed to coarse grid resolutions. Coarse grid resolutions lead to generalizations of different districts thereby providing fewer insights to both policy makers and farmers. Furthermore, coarse resolution data limit the results' utility for stakeholders and policy makers in developing goals and strategies aimed at withstanding climate change impacts. This understanding is critical in Zambia where generalisations of impacts of climate change projections are made using large-scale climate data, hence giving broad recommendations of adaptation measures.

6 CHAPTER SIX: CONCLUSION

6.1 Study key results

As part of the efforts toward reducing the negative impacts of climate variability and change on crop production, this study sought to understand how future climate change will affect the yields of maize and soybean in Central and Eastern provinces of Zambia. Maize and soybean yields play important roles as a staple food crop (maize) and for economical purposes as a foreign exchange earner (soybean) in Zambia.

The results of this study suggest that climate variables play a larger role influencing maize and soybean yields compared to water balance parameters (WBP). For example, maize yields in Mumbwa, Chibombo, Serenje, Katete and Lundazi districts are entirely functions of climate variables while the yields in the remaining districts are a mixture of climate and WBPs. Similarly, soybean yields in Mumbwa, Kabwe, Serenje and Petauke districts are functions of climate variables only while soybean yields in remaining districts are functions of a combination of climate and WBPs.

Additionally, there is considerable agreement amongst the three GCMs and representative concentration pathways (RCPs) on the direction of crop yield changes as a response to climate change in each district. This suggest that the projected yield changes, whether positive or negative, are consistent and robust. The amplitude of those changes however varies across crops and districts. The GCMs are in agreement that the largest decrease in maize yields will potentially be in Mkushi, Central province and Katete district in Eastern province. Our projections suggest that future maize yield will largely decline whereas soybean yields may likely increase. Of the 11 districts studied, only Chibombo is projected to see future maize yields increase. For soybean yields, positive changes are projected in four (near future) and five (far future) districts. In the remaining soybean growing districts, changes remain frequently marginally within the historical deviations.

The results of the present study align with large regional and local scale studies that have shown maize to be the most vulnerable to climate change as compared to other crops. Our results suggest that maize respond well under current climate conditions, but the projected increase in temperature, particularly so combined with decrease or shift in rainfall would negatively affect its production.

Further, the districts in Central province are projected to have more maize yield declines than the districts in Eastern province where the changes are mostly within the historical deviations. As for soybean, there is an equal balance in the yield changes between the districts in Central and in Eastern provinces. Also, the results of this study highlight that when the crop yield change (decrease or increase) is marginal or moderate in the near future (2020 to 2039) it amplifies into large changes in the far future term (2050 to 2069). This suggests that the effects of climate change on crop yields amplify over time and urges to take adaptation steps earlier rather than later.

6.2 Implication of study results

The decline of maize yields will have adverse consequences for food security in the two provinces studied and generally in Zambia where maize yields are a common determining factor of food security. This is especially amongst rainfall dependant smallholder farmers. Therefore, the suggestion of this study aligns with Siamabele (2019), that poverty reduction in line with the Zambian vision 2030 and the 7NDP (2017) through agriculture crop diversification will require a comprehensive understanding and investments in cash crops, like soybean which are less sensitive to climate change impacts. Governmental bodies and policymakers are major actors of design and implementation of adaptation strategies in response to the detrimental effect of climate change. In fulfilling this mandate, it is important that they acknowledge the spatial, crop and temporal variability of the crop yield changes projected. Knowing of district scale climate-crop yield relationships, or how specific crops are impacted by climate change at different scales, allows for the design of tailored policies, with better chances to become efficient tools of adaptation and sustained food security. In addition, farmers need to diversify their crop production as advised by policy makers through extension services to effectively lessen extreme effects of climate variability and change thereby promoting future food security.

6.3 Contribution of the study

While results from this study agree with regional and local scale studies, it draws out conclusions relating to location and crop specific impacts. The use of downscaled climate data for each district has helped to determine variations of climate change impacts across districts despite being in the same agro-ecological region. This understanding is critical in Zambia where generalisations of impacts of climate change projections are made using large-scale climate data, hence giving broad recommendations of adaptation measures. The use of locally downscaled climate data is a vital step towards capturing of site-specific crop responses, yield variations and towards the development of adaptation measures best suited for each district. This can be achieved through the consideration of bio-physical and socio-economic conditions under which local smallholder farmers in the area operate.

Climate change impacts and crop sensitivity such as performed in this study can support already existing self-sufficient efforts of smallholder farmers through providing insights into useful and accessible on-farm adaptation options. Such research can also help governments, policy makers and developmental organisations to better target adaptation investments to the needs of local farmers and to avoid unnecessary collapsing of already scanty resources. Building on existing coping strategies in efforts to support adaptation, may contribute to overcoming prevailing food security challenges in resource constrained farming districts and the country at large, while supporting sustainable future crop production.

Whilst the study acknowledges adaptation efforts already in place, this study suggests that taking a step further at improving adapting measures may reduce the negative effects of climate change on crop production. For example, strengthening investments in small scale adaptation measures such as investing in more proficient water harvesting methods, irrigation technologies, early warning systems to large scale adaptation measures which includes the use of heat-tolerant seed varieties, agricultural investment in research and extension, and strengthen policies that support reduction of smallholder farmer's risks and enhance their adaptive capacities such as weather index-based insurance and access to credit. Since agriculture in Zambia has the potential to pull many people in both urban and rural areas out of poverty, good performance in the sector translates into overall improvement of the country’s GDP, job creation and consequently tax base expansion.

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