Vulnerability and Adaptation to Climate Variability and Change in Smallholder Farming Systems in Zimbabwe

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Dedication

To my parents, who died just before and soon after I started my PhD, whose aspirations and lessons of life gave me the strength to finish this work.

Abstract

Climate change and increased climate variability are currently seen as the major constraints to the already stressed smallholder farming livelihood system in southern Africa. The main objectives of this study were first to understand the nature and sources of vulnerability of smallholder farmers to climate variability and change, and second to use this knowledge to evaluate possible farm-level management options that can enhance the adaptive capacity of smallholder farmers in the face of increased climate variability and long-term change in climate. The study was conducted in Makoni and Hwedza districts in eastern Zimbabwe. Local famers' and expert empirical knowledge were combined using research tools that mainly included detailed field observations and surveys, systems analysis and field experimentation, and simulation modelling (the Agricultural Production Systems Simulator (APSIM)). To understand the nature and sources of vulnerability, long term climate data were analysed and farmers were interviewed individually and in groups. On-farm experimentation and simulation modelling were conducted to evaluate the impacts and interactions of adaptation options namely maize cultivar choice, staggered planting dates, and variable fertilizer rates, on maize yield under both short-term climate variability and long-term climate change. Another on-farm experiment was conducted to assess whether small grains (finger millet and sorghum) perform as well as maize under variable soil and rainfall conditions.

The long-term rainfall and temperature analyses closely supports farmers' perceptions that the total annual rainfall has so far not changed, but variability in the rainfall distribution within seasons has increased. The number of rain days has decreased, and the frequency of dry spells within season increased. The mean daily minimum temperature increased by 0.2°C per decade in Makoni, and by 0.5°C per decade in Hwedza, over the period from 1962 to 2000. The surface air temperature is further projected to increase significantly in Makoni and Hwedza, by 2100. The impacts of rising temperatures and increased rainfall variability among smallholder households were highly differentiated because different households depend on varied farming livelihood sub-systems, which were exposed uniquely to aspects of climatic risk. For example, livestock production was sensitive to drought due to lack of feed, affecting resource-endowed farmers, who often own relatively large herds of cattle. Crop production was more sensitive to increased rainfall variability, affecting especially farmers with intermediate resource endowment. Availability of wild fruits and social safety nets were affected directly and indirectly by extreme temperatures and increased rainfall variability, impacting the livelihoods of poorer farmers. Farmers have also access to different biophysical and socioeconomic resources such as fertilizer and farm labour inputs, and as a result they respond variedly to impacts of a changing climate. Thus, alongside climate variability and change, farmers also faced biophysical and socioeconomic challenges, and these challenges had strong interactions with adaptation options to climate change.

Experimentation in this study demonstrated that the maize cultivars currently on the market in Zimbabwe, and in many parts of southern Africa, exhibit narrow differences in maturity time such that they do not respond differently to prolonged dry spells. The yield performance for all three cultivars is projected to be similar in future change in climates, consistent with results from the experiments. In the current cropping system farmers can select any cultivar available on the market without a yield penalty. However, with climate change none of the available cultivars will be able to compensate for the decline in yield. Greater maize grain yields were obtained with both the early (25 October – 20 November) and normal (21 November – 15 December) plantings, with no significant differences between these planting windows (e.g. on average 5 t ha^{-1} in Makoni, and 3 t ha^{-1} in Hwedza for the high fertilization rate). Contrary to previous research findings, there is a reasonably wide planting window in which good yields can be obtained if the rains start on time, but if the start of the rains is delayed until after the beginning of December planting should be done as soon as possible. Regardless of the amount of fertilizer applied, yields were reduced strongly when planting was substantially delayed by four weeks after the start of the rainy season. Maize yielded more than finger millet and sorghum even when rainfall was poor in the 2010/2011 season. For example, maize yielded 2.4 t ha^{-1} compared with 1.6 t ha^{-1} for finger millet and 0.4 t ha^{-1} for sorghum in the 2010/2011 rainfall season in Makoni. Finger millet and sorghum failed to emerge unless fertilizer was applied. Application of manure alone failed to address this challenge of poor emergence until fertilizer was added. Sorghum suffered critical yield losses due to bird damage. The better performance of maize over finger millet and sorghum suggested that the recommendation to substitute small grains for maize as a viable adaptation option to a changing climate, will neither be the best option for robust adaptation nor attractive for farmers in southern Africa. Alternatively spreading crops across the farm and in time can be a viable strategy to spread climatic risk as well as improve human nutrition. Poor soil fertility constrained yield more strongly than rainfall and late planting, as demonstrated by the large yield gap (> 1.2 t ha^{-1}) between the unfertilized and fertilized cultivars even in the poor rainfall season (2010/2011).

Fertilization increased yield significantly under both the baseline and future climates particularly when planting before mid-December. The maize response to mineral nitrogen is, however, projected to decline as climate changes, although effects only become substantial towards the end of the 21st Century. Soil fertility management is therefore likely to be a major entry point for increasing the adaptive capacity of smallholder farmers to climate change and increased climate variability. However, management of factors related to both nutrient resource access and farmers decisions to enhance resource use efficiencies are critical if agriculture is to be used as robust adaptation options to climate change by smallholder in Southern Africa.

Keywords: Climate change; Increased climate variability; Vulnerability; Smallholder farmers; Adaptation

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Chapter 1

General introduction

1. Background

Climate change and increased climate variability present a new set of realities, to which society needs to adjust. Intervention is obviously of utmost importance in agriculture, which has a direct consequence on food security. This global climate crisis, if not taken into account in decision making, will hamper efforts at various levels (e.g. the proposed Sustainable Developmental Goals), to alleviate poverty and hunger while sustaining ecosystem services (Vermeulen et al., 2012). Achieving food security will be a huge challenge particularly in sub-Saharan Africa where about two hundred and eighty million people still suffer from poverty and hunger (FAO, 2011), and the environment has been degrading (Frost et al., 2007). To worsen the situation, food demand is anticipated to increase as nine billion people are projected to inhabit the Earth by 2050 and many people will change their diets as their income increases (van Ittersum et al., 2013). The human population is projected to increase particularly in Africa given the current population growth rate of between 1.5% and 3% per year (United Nations, 2011).

The recent IPCC (2013) report has further provided evidence that the climate on earth is changing: temperatures are increasing in many regions of the world while precipitation patterns and intensity are changing. The change in climate has largely been driven by anthropogenic greenhouse gases, from which the most important is carbon dioxide (IPCC, 2013). Global surface air temperatures have increased by values between 0.55°C and 0.67°C, over the period from 1951 to 2010 (IPCC, 2013). If stringent mitigation policy measures are not put in place in time, temperatures will further increase beyond 2°C by 2100, a threshold for dangerous global warming (Peters et al., 2013). Such temperature increases will cause irreversible consequences for humanity and the environment (Peters et al., 2013) although the scientific basis for the 2°C endpoint target is controversial (Anderson and Bows, 2008). The changes in the patterns of rainfall are less clear but it is anticipated that dry regions will become drier, of which there is already some evidence in some regions (Dai, 2013; IPCC, 2013). In many parts of southern Africa, the rainy season starts later and the length of intra-season droughts has increased (Shongwe et al., 2009; Tadross et al., 2009). However, in other regions such as east Africa and eastern Europe climate change will bring new opportunities such as increased rainfall (Van der Linden and Mitchell, 2009; Thornton et al., 2011). The changing climate will intensify natural climate variability and extreme weather events such as flooding and droughts (Coumou and Rahmstorf, 2012). Given that emissions of greenhouse gases and the associated radiative forcing have been increasing (IPCC, 2013; Peters et al., 2013), the rate and magnitude of climate variability and change are likely to increase as well.

1.1. Vulnerability of smallholder farming systems to climate variability and change

There is scientific consensus that global impacts of the changing climate will have great consequences on agriculture-based livelihoods in sub-Saharan Africa, although the impacts will differ in effect and magnitude depending on the region and sector (IPCC, 2007). Projections show that the adverse impacts of the changing and increasingly variable climate will be felt strongly in southern Africa, and Zimbabwe is one of the 'hotspot' countries (Lobell et al., 2008; Knox et al., 2012). Smallholder farmers will be especially vulnerable to the impacts of climate variability and change (IPCC, 2007). Their susceptibility is driven by all three elements of vulnerability: exposure, sensitivity and adaptive capacity (IPCC, 2007).

First, due to its geographic location, many areas of southern Africa are prone to climatic risk, particularly erratic rainfall and droughts, which have been associated with natural climate variability (Usman and Reason, 2004). The changing climate is likely to increase the intensity of climate variability and extreme events, and to change variables that are critical for crop production such as air temperature. Rainfall has traditionally been the major driver of crop production in southern Africa, including Zimbabwe, and temperature has not been considered a limiting factor (Hussein, 1987). Given that surface air temperature has increased by 0.1°C per decade between 1933 and 1993 and is projected to further increase by between 2°C and 5°C by 2100 in Zimbabwe (Unganai, 1996), similar to global projections (Fig. 1.1), temperature will play a key role in crop production. A combination of elevated temperatures and droughts are predicted to dramatically reduce crop yields in southern Africa (Lobell et al., 2011). There is already evidence that yields of major staple cereal food crops of the region such as maize, sorghum and millets will decline due to increased temperatures and change in rainfall patterns (Zinyengere et al., 2013). Because of the uncertainties in processes underpinning the changing climate, however, more research is needed to understand the impacts on crop production. Overall, the changing climate will increase the exposure of smallholder farming systems to harsh climate conditions.

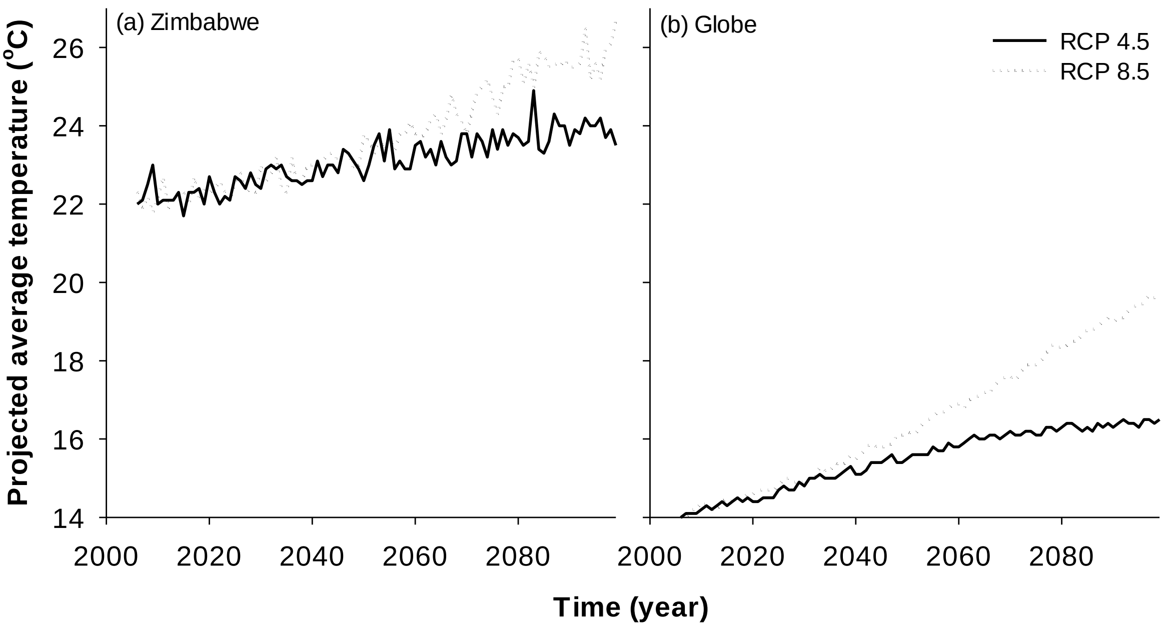

Fig. 1.1. Projected average temperatures for (a) Zimbabwe and (b) the Globe, for two emission scenarios: radiative forcing of 4.5 W m^{-2} and 8.5 W m^{-2} (data was generated from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (http://pcmdi3.llnl.gov/esgcet/home.htm, last accessed 4 January 2014).

Second, smallholder farmers in sub-Saharan Africa (SSA) faced many biophysical and socioeconomic challenges, most notably degrading land resource bases and poorly functioning markets (Nyikahadzoi et al., 2012; Mapfumo et al., 2013). The adverse effects of the changing climate will interact or combine with existing and emerging biophysical and socioeconomic challenges to add an extra burden on smallholder farms (Vermeulen et al., 2012). Thus, apart from climatic risk, the extent of yield decrease will also depend on other factors, particularly on soil fertility management and market access (Chipanshi et al., 2003; Mapfumo et al., 2013). It is clear that smallholder farmers are sensitive to possible adverse changes in climate.

Third, the capacity of smallholder farmers to adapt to the changing circumstances, and in particular to climate variability and change, is constrained by poverty and a limited capacity to switch to alternative livelihood options (Mapfumo et al., 2013). These circumstances have been exacerbated by lack of supporting policies and institutions (Nyagumbo and Rurinda, 2012). The fact that the constraints emanate from all three elements of vulnerability, suggest interacting and multiple stresses on farmers' vulnerability. Thus, there is a critical need to understand these interactions and multiple stresses to identify the major sources of vulnerability as an entry point for exploring appropriate adaptation measures to enhance the resilience of smallholder farmers.

Although smallholder farmers are generally vulnerable to a changing climate, the degree to which they are vulnerable varies from farmer to farmer because smallholder farms are widely diverse (Giller et al., 2011). This diversity is mainly linked to differential endowments among households (Mtambanengwe and Mapfumo, 2005). The differences in vulnerability among smallholder farmers to changing climate is not only because farmers respond uniquely due to their varied endowments, but also because their varied livelihood strategies are impacted differently by the unique aspects of climate risk (Adger, 2006). Assessing the specific vulnerability of different types of smallholder farmers is central to targeting adaptation to increase resource use efficiency. It is also essential to be able to target interventions to the poorest and most vulnerable groups such as the women-headed households.

1.2. Adaptation of smallholder farmers to a changing climate

To minimize the consequences of climate change on livelihoods and the environment, two complementary approaches have been emphasized: mitigation and adaptation (IPCC, 2007). Mitigation is required to reduce emissions of greenhouse gases in the atmosphere before the concentrations reach levels that will cause irreversible consequences for humanity and the environment (IPCC, 2013). While mitigation policies are important, adaptation is unavoidable because the impacts of the changing climate are inevitable for several decades to come, given that we are faced with significant degree of anthropogenic climate change due to past and current greenhouse emissions (IPCC, 2013). Even at higher policy levels, i.e. under Articles 4.1 and 10, of the United Nations Framework Convention on Climate Change and the Kyoto Protocol, respectively, national governments are required to formulate and promote adequate adaptation to climate change. Adaptation is particularly critical in sub-Saharan Africa not only because of the existing poverty, but also because of the large uncertainty about the effects and the magnitude of climate change due to the scarcity of measured data (IPCC, 2013). Thus, in the region, adaptation should be an important part of any meaningful response to climate variability and change.

Given that in southern Africa more than 70% of rural people depend on agriculture for their food and income, and that agriculture is highly sensitive to climate variability and change, there is need to explore how smallholder farmers can adapt to pressures of the changing climate. Adaptation is defined as adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2007). Adjustments can be spontaneous in which a system can implement existing knowledge and technology as climate changes, or planned in which appropriate response mechanisms are well designed (Dixon et al., 2003). In southern Africa, farmers have always been adjusting their cropping patterns to better manage agricultural risk associated with rainfall variability and droughts (Shumba et al., 1992), and other stresses such as farm labour constraints (Dorward, 2013). Given the accelerated rate of climate change and climate variability (IPCC, 2013), the major question is whether farmers can change their farming systems fast enough to keep pace with the changing climate. Farmers might need technical and institutional support to speed up their adaptation processes (Vermeulen et al., 2012). Because smallholder farming systems are diverse, adaptation needs to be tailored to farmers with different biophysical and socioeconomic circumstances.

Several options that can increase the capacity of smallholder farmers to adapt to the changing climate have been suggested. Farmers can adapt tactically to the changing climate by staggering planting dates (Stringer et al., 2009) and fertilizer applications (Piha, 1993). Strategically, farmers can also adapt by managing soil fertility, which has been identified as the main biophysical factor constraining crop production in southern Africa (Mapfumo and Giller, 2001). Further, they can diversify their cropping systems by strategically integrating multiple crops and crop cultivars in the farm. Diversifying crops on farms can be an option not only to increase production, but also to increase human nutrition and the overall resilience of agro-ecosystems (Lin, 2011).

Many of these adaptation options have remained untested under farmer conditions, especially in southern Africa, and Zimbabwe specifically. Thus, there is need to evaluate the useful of potential adaptation options in farmers' fields with the participation of farmers to provide locally adapted practical solutions. Involving farmers in the adaptation process is important to link knowledge with action. Furthermore, participation by farmers and local policy makers promote experiential co-learning that can strengthen the capacity of local farming communities and their institutions to be able to continuously adapt to an increasingly broad range of climatic conditions (Mapfumo et al., 2013). As the changing climate will not operate in isolation from other constraints, adaptation should also address existing and emerging biophysical and socioeconomic challenges such as land degradation and market risk (Howden et al., 2007).

1.3. Problem statement

Climate change and increased climate variability are currently seen as major threats to agricultural production in Zimbabwe and other parts of Southern Africa, coming on top of the long lasting challenges of land degradation and poor market access. Smallholder farmers depend on rain-fed agriculture for their livelihoods in such a way that any change in climate will have direct impacts on food production. Smallholder farmers may have little capacity to adapt to adverse impacts of the changing and increasingly variable climate due to their limited resources, but knowledge is lacking on how responses of farmers vary from farm to farm. Given the predicted rate and magnitude of climate change in Zimbabwe, identification of suitable adaptation options for smallholder farmers is urgent, because on their own they may not be able to adjust their farming systems fast enough to match with the rate of climate change.

1.4. Research objectives

The main objectives of this study are first to understand the nature of, and to identify the sources of vulnerability among smallholder farming households to impacts of climate variability and change. Second to use this knowledge to evaluate possible farm-level management options that can enhance the adaptive capacity of smallholder farmers in the face of climate change and increased climate variability.

The specific objectives were:

1. To determine whether there is a relationship between farmer resource endowments and the vulnerability of smallholder farmers households to climate variability and climate change;
2. To test adaptation options identified by farmers, namely improved soil fertility management, improved time of planting and shorter duration maize cultivars, on crop productivity, to identify options that reduce the risk of crop failure and increase crop yields under variable rainfall;
3. To assess whether small grains (finger millet and sorghum) perform as well as maize under variable soil and rainfall conditions, to inform farmers on cropping systems that can increase their food and nutritional security;
4. To evaluate the response of maize production to projected changes in future climates, to evaluate possible adaptations in crop management that can help smallholder households to reduce the risk of declining crop production with progressive climate change;
5. To evaluate the suitability of selected adaptation options to increase food production at farm level for households differing in their vulnerability to climate variability and climate change.

1.5. Research Approach

The study combined local famers' and expert empirical knowledge using research tools that mainly included detailed field observations and surveys, systems analysis and field experimentation, and simulation modelling, to identify the sources of vulnerability to a changing climate, and evaluate possible adaptation options for supporting smallholder farmers in Zimbabwe and in similar conditions in Southern Africa (Fig. 1.2).

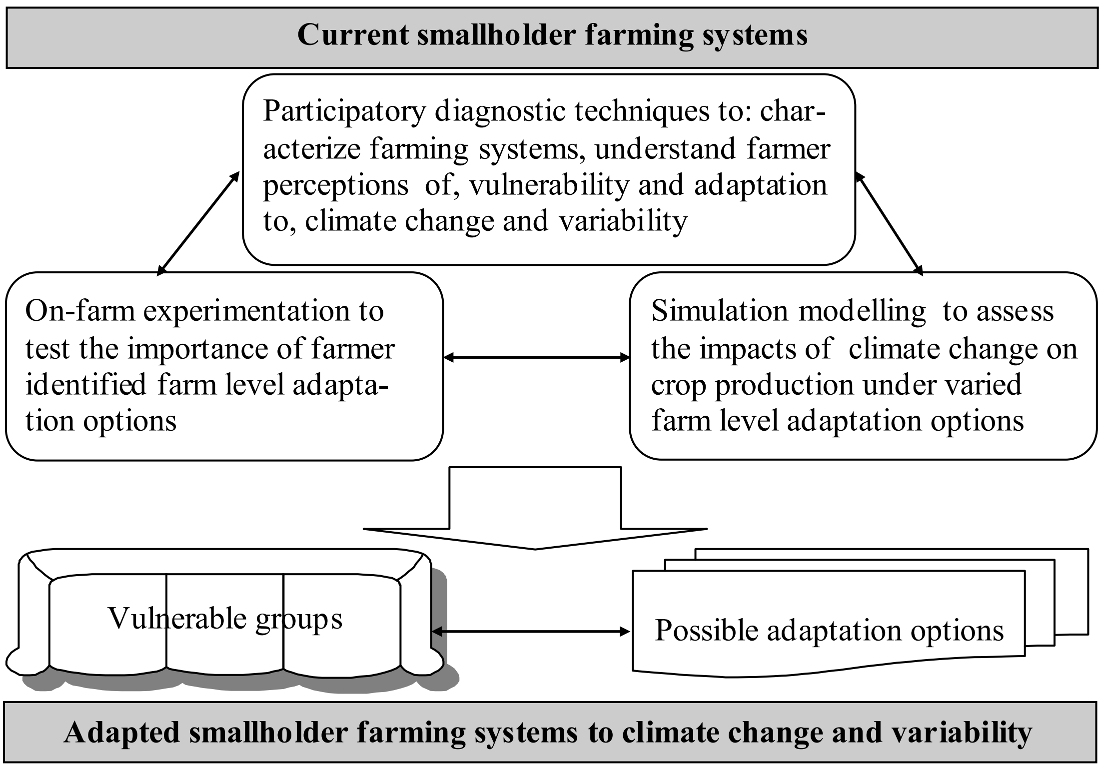

Fig. 1.2. A schematic representation of the research approach and major outputs.

1.5.1. A brief description of the study sites

This study was conducted in Makoni and Hwedza smallholder farming areas in eastern Zimbabwe (Fig. 1.3), which is a hotspot for increased risk due to climate change, particularly drought and increased rainfall variability (Thow and de Blois, 2008). Zimbabwe is characterized by unimodal rainfall season from October to April, and about 90% of the total rainfall is associated with thunderstorm activity producing falls of short duration and high intensity (Anderson et al., 1993). Annual rainfall ranges between 750 mm and 1000 mm in Makoni, and between 650 mm and 800 mm in Hwedza (Anderson et al., 1993). Both sites have soils of poor fertility, Lixisols and Arenosols, which are representative for large areas in sub-Saharan Africa (World Soil Resource Base, 1998). For example, Arenosols cover about 13% of sub-Saharan Africa and more than 6.5 million ha of cropland in southern Africa (Hartemink and Huting, 2008).

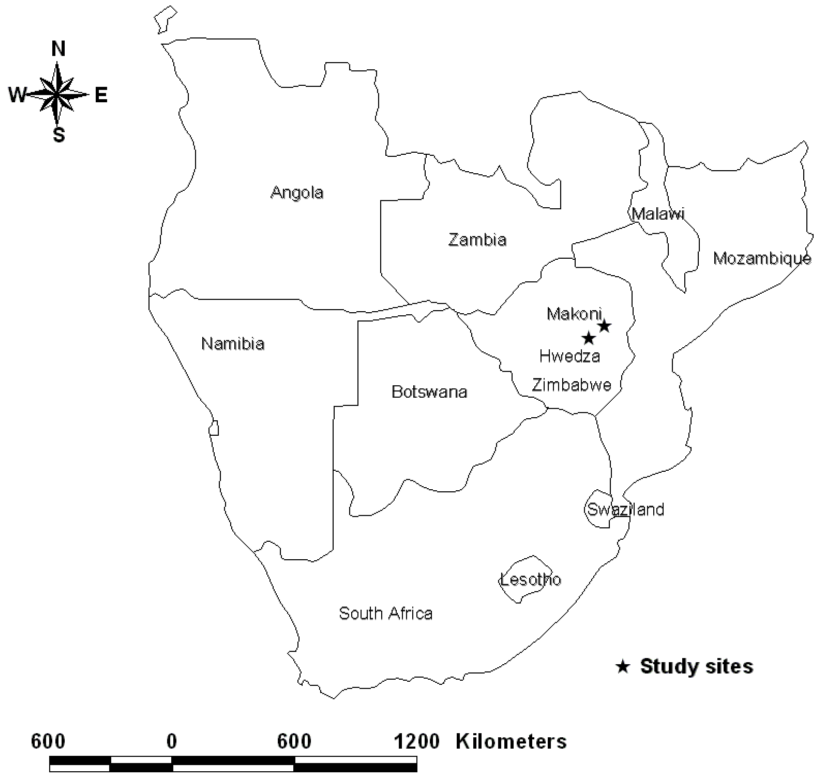

Fig. 1.3. A map of southern Africa showing Makoni and Hwedza districts in eastern Zimbabwe.

1.6. Thesis outline

In brief, chapter two focused on understanding the nature and identify the major sources of vulnerability of smallholder households to impacts of climate change and increased climate variability. Through on-farm experimentation, Chapter three evaluated the importance of farmer identified adaptation options namely staggered planting dates, varied fertilization rates and multiple cultivars, in response to increased climate variability. Chapter four assessed whether small grains i.e. finger millet and sorghum perform as well as maize under variable soil and rainfall conditions, to inform farmers on cropping system that can increase their food and nutrition security in a changing climate. The adaptation options tested in farmers' fields in chapter three were used to inform model simulations to understand the importance of these adaptation options to reduce the risk of maize production under climate scenarios of increasing temperatures and change in rainfall patterns. The final chapter distilled key findings from these four chapters, and discussed them in the context of biophysical and socioeconomic circumstances of smallholder farmers in Zimbabwe and in similar environments in Southern Africa, to reduce vulnerability to climate variability and change.

Chapter 2

Sources of vulnerability to a variable and changing climate among smallholder households in Zimbabwe: A participatory analysis

This chapter has been accepted for publication as:

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Abstract

Vulnerability analysis is essential for targeting adaptation options to impacts of climate variability and change, particularly in diverse systems with limited resources such as smallholder farms in sub-Saharan Africa. To investigate the nature and sources of vulnerability of smallholder farmers to climate variability and change, we analysed long term climate data and interviewed farmers individually and in groups in Makoni and Hwedza districts in eastern Zimbabwe. Farmers' perceptions of changes in climate characteristics matched the recorded data. Total seasonal rainfall has not changed, but variability in the rainfall distribution within seasons has increased. The mean daily minimum temperature increased by 0.2°C per decade in Makoni and by 0.5°C per decade in Hwedza. The number of days with temperatures >30°C increased in Hwedza. Farmers indicated that livestock production was sensitive to drought due to lack of feed, affecting resource-endowed farmers, who own relatively large herds of cattle. Crop production was more sensitive to increased rainfall variability, affecting especially farmers with intermediate resource endowment. Availability of wild fruits and social safety nets were affected directly and indirectly by extreme temperatures and increased rainfall variability, impacting the livelihoods of resource-constrained farmers. There was no simple one-to-one relationship between vulnerability and farmer resource endowment, suggesting that vulnerability to climate variability and change is complex and not simply related to assets. Alongside climate variability and change, farmers were also faced with biophysical and socioeconomic challenges such as lack of fertilizers, and these challenges had strong interactions with adaptation options to climate change. Diversifying crops and cultivars, staggering planting date and managing soil fertility were identified as the major adaptation options to stabilize yields against increased rainfall variability. There is need to test the identified adaptation options on farm and with the participation of farmers to provide empirical evidence on the best options for different households.

Keywords: Adaptation options; Extreme temperatures; Increased droughts; Increased rainfall variability; Farmer resource endowment; Vulnerability

2. Introduction

While climate variability and change are global phenomena, vulnerability differs by location. Sub-Saharan Africa (SSA) has been identified as the most vulnerable region to climate variability and change because many areas inherently receive unpredictable rainfall (Sivakumar, 2006). Zimbabwe is one of the ‘hotspots’ for climate change, with predicted increases in temperatures and rainfall variability, combined with reduced rainfall (Unganai, 1996; Lobell et al., 2011), and increased probability of extreme events such as droughts (Shongwe et al., 2009). In particular, smallholder farmers are vulnerable to impacts of the changing climate because of multiple interacting stresses, such as soil degradation (Mapfumo and Giller, 2001), lack of lucrative output markets (Nyikahadzoi et al., 2012), a declining natural resource base linked to population pressure (Frost et al., 2007), and deterioration of societal ‘safety nets’ related to extreme poverty (Mapfumo et al., 2013). Climate variability and change are therefore an extra burden that exacerbates existing challenges.

Patterns of vulnerability vary among smallholder households, even within the same community (Westerhoff and Smit, 2009). Smallholder farmers are often classified into different categories largely based on resource endowments in different regions in SSA (Mtambanengwe and Mapfumo, 2005; Tittonell et al., 2005). First, these distinct endowments and livelihood options among smallholders would be impacted differently by either single or multiple climatic variables leading to differential vulnerability. Farmers practicing improved soil fertility management were less vulnerable to increased temperatures than non-practicing farmers with respect to wheat production (Luers, 2005). Second, the variation in endowments among smallholder households is associated with different responses to hazards (Adger, 2006). Larger farm size has been found to increase adaptive capacity of farmers and hence reduce vulnerability (Reidsma et al., 2009). However, in another study smallholder farmers with relatively small farms were found to be less vulnerable to droughts than privately owned large farms due to a range of livelihoods options (Toni and Holanda Jr, 2008). These findings suggest that even the perceived marginalized households can use a range of options to reduce vulnerability. However, being resource-endowed does not necessarily mean one is less vulnerable. Furthermore, institutions and social networks within a local community can play a key role in decreasing vulnerability (Mapfumo et al., 2013).

Detailed vulnerability analyses not only require context specificity, but also involvement of the target communities at local level (Cutter, 1996). Given that the determinants of vulnerability, whether climatic, or biophysical and social conditions, change over time, the target communities would play a key role in identifying indicators and thresholds for vulnerability (Cutter, 1996). In addition, the uncertainties in climate change research due to both lack of knowledge and the stochastic nature of processes underpinning climate change, prompt for bottom-up approaches to enable continual co-learning to respond to future climatic surprises (Dessai and van der Sluijs, 2007). Participatory analysis helps to integrate knowledge from both local farmers and science, particularly when comparing local farmers’ perceptions of climatic exposure characteristics and measured data.

Despite the reported differences in endowment and management between farm types in SSA, there is little knowledge available to understand the relationship between smallholder households of different endowments and vulnerability to climate change and increased climate variability relative to other stresses such as soil fertility depletion. Yet, understanding vulnerability of different households is essential to identify ‘best fit’ adaptation options particularly in diverse environments with limited resources. In Addition, vulnerability analysis helps to target and reach the most vulnerable households (Luers, 2005). Although research on vulnerability analysis has increased (Janssen, 2007), efforts have been focused more on building theoretical concepts and how they can be applied to systems in general (e.g. Turner et al., 2003). Such frameworks are important to understand the concept of vulnerability, but they lack practical relevance for intervention (Luers, 2005) as their usefulness has not been tested in real situations. Given that the impacts of climate variability and change are context specific, there is a need for local vulnerability analyses (e.g. Cutter, 1996) to derive lessons on the how the relationship between farmer resource endowment and vulnerability to climate variability and change is mediated by the environmental and socioeconomic resources present in the system. As a result, lessons could be learnt to share with other communities and other regions. Some analyses of vulnerability have focused on the impact of single climate variables such as drought (Eriksen et al., 2005) or temperature (Luers, 2005), which may conceal impacts of other climatic factors (O'Brien et al., 2009). Thus, analysis of vulnerability requires a holistic systems approach recognising multiple climatic exposure as well as social and biophysical constraints. Recent definitions of vulnerability recognise the interaction between external and internal forces characterised by exposure, sensitivity and adaptive capacity of a system, sub-system or system components (Cutter, 1996; IPCC, 2007).

The focus of this study was to understand the nature of, and to identify the sources of vulnerability among smallholder farming households to impacts of climate variability and change in two distinct communities representing similar smallholder environments in Zimbabwe. The objectives were (i) to analyse the relationship between vulnerability and farmer resource endowments; (ii) to identify adaptation options used by different households in response to sources of vulnerability and to link them to the socioeconomic and environmental resources available in the region; (iii) to identify opportunities for enhancing the capacity of farming households to adapt to climate variability and change for informed policy decisions.

2.1. Research approach

2.1.1. Study site

The study was carried out in two communities; namely Nyahava in Makoni district and Ushe in Hwedza district, in Zimbabwe, between 2009 and 2012. The two communities were selected because they are located in regions with high climate variability: particularly in terms of droughts and start and length of the growing season (Houghton, 1997; Thow and de Blois, 2008). Both communities largely depend on agriculture for their livelihoods. Makoni is a resettlement area with an average farm size of 6 ha per household. Hwedza is a communal area with farm sizes range from 2 to 5 ha per household. Makoni receives annual rainfall ranging between 750 mm and 1000 mm and Hwedza between 650 mm and 800 mm. The soils are generally granite-derived sands with inherently poor soil fertility (Nyamapfene, 1989). In these smallholder farming systems, the livelihoods of farmers are strongly dependent on the interactions between crop and livestock production and common natural resource pools. Crop production provides feed for livestock, while livestock provide draught power and manure for crop production. Common natural resources provide feed for livestock and organic material for crop production. In times of crop harvest failure, communities in these districts depend on non-timber forest products, mainly fruits of *Parinari curatellifolia* and *Uapaca kirkiana* as food (Woittiez et al., 2013). Some households mostly wealthier ones also maximize production during favourable rainfall and store surplus grain in granaries to compensate for drought years (Milgroom and Giller, 2013).

2.1.2. Analysis of vulnerability of smallholder households

This study draws on both qualitative and quantitative research approaches. Participatory diagnostic techniques, monitoring of farming livelihoods systems using farm diaries, a household questionnaire survey, and analysis of long term climate data were used to understand the nature of vulnerability of households, and to identify adaptation options.

The analysis of vulnerability was performed across households belonging to three farmer resource endowments, based on an existing classification developed in a similar environment (Mtambanengwe and Mapfumo, 2005). Farm size and cattle ownership were the main assets used for classification of farmers into different resource groups. The proportion of households in each resource group was determined together with local extension officers using a list of households in each community compiled by the Department of Agriculture and Extension Services (AGRITEX) (Table 2.1).

Table 2.1. Proportion (%) of household and household heads in each farmer resource category in Makoni and Hwedza in Zimbabwe

Site/ Farmer category	Male-headed household	[a]Defacto female-headed household	Widowed female-headed household	Child-headed household	Overall proportion
Makoni					
Resource-endowed: *n*=36	14	1	3	0	18
Intermediate: *n*=84	32	7	3	0	42
Resource-constrained: *n*=80	25	5	9	1	40
Hwedza					
Resource-endowed: *n*=34	12	3	2	0	17
Intermediate: *n*=54	19	4	3	1	27
Resource-constrained: *n*=112	31	9	15	1	56

[a]Defacto female-headed household is a household headed by a woman because her husband is away most of the time.

2.1.3. Qualitative data collection approaches

2.1.3.1. Characterisation of smallholder farming livelihood systems in relation to climate variability and change

A series of community meetings were organised at each site to (i) to record farmers perceptions of climate variability and change; (ii) identify issues and problems affecting farmers in the face of climate variability and change; (iii) describe who is vulnerable and establish the causes; (iv) identify adaptation options used by different farmers during drought and flood years. These participatory diagnostic meetings were also helpful to design relevant and clear questions for the farm diaries and for the household questionnaire survey that were implemented to study in more detail the above mentioned key issues. The number of farmers that participated in these meetings was 350 in Makoni and 400 in Hwedza, and each community comprised a total of about 1500 households.

At the first meeting at each community, farmers were grouped into three categories based on endowments: resource-endowed, intermediate and resource-constrained, matching the existing farm typology (Mtambanengwe and Mapfumo, 2005). Separation of farmers into the appropriate resource group was done with the assistance of local extension officers at each site performed using cards coded with letters A, B and C, representing the three resource groups. Care was taken to ensure that the group participants had no knowledge of the actual significance of the letters. A fourth group comprising key informants, including chiefs, headmen, village heads, and councillors, was strategically formed to avoid bias and dominance likely to occur as a result of their presence during the group discussions. Researchers equipped with participatory action research (PAR) skills (German et al., 2008) facilitated and documented both the process and the technical information emerging from each of the four groups.

2.1.3.2. Vulnerability to climate variability and change

Another meeting was organised specifically to understand the nature of exposure to climate variability and change, and how households would respond. A total of 49 farmers (23 women and 26 men) in Makoni, and 68 farmers (39 women and 29 men) in Hwedza were present at the meetings. Three groups were formed, a mix of young and older, and men and women. Focus group discussions within each group were guided by such questions as: (i) what were the main climatic variables impacting the farming livelihood system?; (ii) what were the frequency / magnitude / duration of identified climatic hazards?; (iii) if there was a drought for instance, what sub-systems and components of the farming livelihood system would be affected?; and (iv) which were the most vulnerable households and to what particular climatic hazard were they vulnerable?

In plenary discussion, consensus was reached about the main climatic exposure characteristics and the affected sub-systems. Farmers were asked to rank how each sub-system would be impacted by each of the identified climatic exposure characteristics. Each group was allocated a different climatic exposure characteristic, and was asked to analyse it for the same sub-systems. In each group circles were drawn on the ground to represent each sub-system. Each farmer was given maize seeds and asked to place them in the circles to rank the most affected sub-systems. The sub-system with the largest number of seeds was the most affected by a defined particular climatic exposure characteristic. Then the circle for this sub-system was removed and the ranking exercise started again for the remaining sub-systems until each of the sub-systems was ranked against each of the defined climatic hazards. The extent of loss and time needed of recovery of indicators of household well-being (food, income, social value, draught power, manure, stover for livestock) were the main attributes defined by the community that were used for ranking.

Household food insufficiency and loss of cattle were identified as the main indicators of vulnerability. Farmers considered a household with enough food to last for one agricultural season (12 months) to be food self-sufficient, which was about 1 tonne of maize (or 0.5 tonnes of small grains) for a family of six. The number of cattle considered sufficient to deal with drought events was 7 for wealthier farmers and 3 for poorer farmers.

2.1.4. Quantitative approaches

2.1.4.1. Detailed characterisation of farming livelihood systems

Informed by the participatory work and initial surveys, a sample of 10 households for each farmer resource group was selected for in-depth understanding of the sources of vulnerability. These households were selected to represent the diversity within the group (Mtambanengwe and Mapfumo, 2005). Farming activities were monitored for two agricultural seasons (2009/2010 and 2010/2011) using farm diaries with the assistance of extension personnel. Data on cropping patterns, types and amounts of fertilizer used, and crop yields were recorded in diaries. To determine grain yield, three farms were selected from each of the sub-sample of 10 under each farmer resource category. The yields were measured at each field allocated to maize on each farm. Maize grain yield was determined at physiological maturity from a net-plot of 2 rows × 5 m replicated twice.

2.1.4.2. Farmer perceived climatic exposure and adaptation options

A household questionnaire was administered to complement information gathered during the focus group discussions. The questions mainly focused on: (i) the perceptions of farmers to climate variability and change, (ii) factors constraining crop production, and (iii) existing and possible adaptation options. Stratified random sampling was used to select 100 households in each community. Each community was divided into strata based on villages sharing common pool resources (e.g. grazing area, dip tanks). As a result, in Hwedza the villages were divided into 6 strata and 17 households were randomly selected from each. In Makoni 20 households were selected from each of the 5 strata. A number of variables such as farmers' perceptions of climate variability and change and factors constraining crop production were analysed and frequency tables were produced.

2.1.5. Analysis of long-term climatic data

Daily rainfall and temperature data collected by the Meteorological Services Department of Zimbabwe over a 48 year period (1962 – 2009) for Hwedza were analysed for trends. Variables analysed included total seasonal rainfall, date for the start of rain season, frequency of dry spells, seasonal means of maximum and minimum daily temperatures, and the number of days with temperatures >30°C. This latter indicator was chosen because analyses have shown that each degree day spent above 30°C reduces maize grain yield by 1% under optimal rain-fed conditions, and by 1.7% under drought conditions in Africa (Lobell et al., 2011). Rainfall data for Makoni was incomplete and hence could not be used. Date of the beginning of the rain season was analysed using a threshold of 48 mm of rainfall in at least two rainy days out of ten consecutive days (Unganai, 1990). The starting date to search for the beginning of the rain season was mid-October. The analyses were done in Instat Plus 3.36 (Stern et al., 2006), and the frequency of dry spells was analysed using the Markov chain modelling option in Instat.

2.2. Results

2.2.1. Farmer derived conceptual framework for vulnerability analysis in smallholder farming livelihood systems

A conceptual framework to define vulnerability among smallholders to climate variability and change was developed combining local farmers' knowledge and empirical data (Fig. 2.1). Three components of vulnerability: exposure, sensitivity, and adaptation were at the core of the framework. Cropping, livestock production, availability of natural resources such as wild fruits and social safety nets were identified as the main sub-systems of a broader farming livelihood system exposed to different climatic exposure characteristics. The indicators for the perceived impacts of climatic exposure characteristics on these sub-systems and their components were household food self-sufficiency and cattle ownership. Increased rainfall variability, occurrences of droughts and extreme temperatures were identified as the major climatic exposure characteristics. Farmer suggested adaptation options were classified after de Koeijer et al. (2003) into operational (short-term e.g. staggering planting date), tactical (medium-term e.g. diversifying crop cultivar/type) and strategic (relatively long-term e.g. strengthening social safety nets). The extent to which households adopt these adaptation options depends on the availability of and access to both biophysical and socioeconomic resources, and also the support they receive from different institutions operating at different levels (Fig. 2.1).

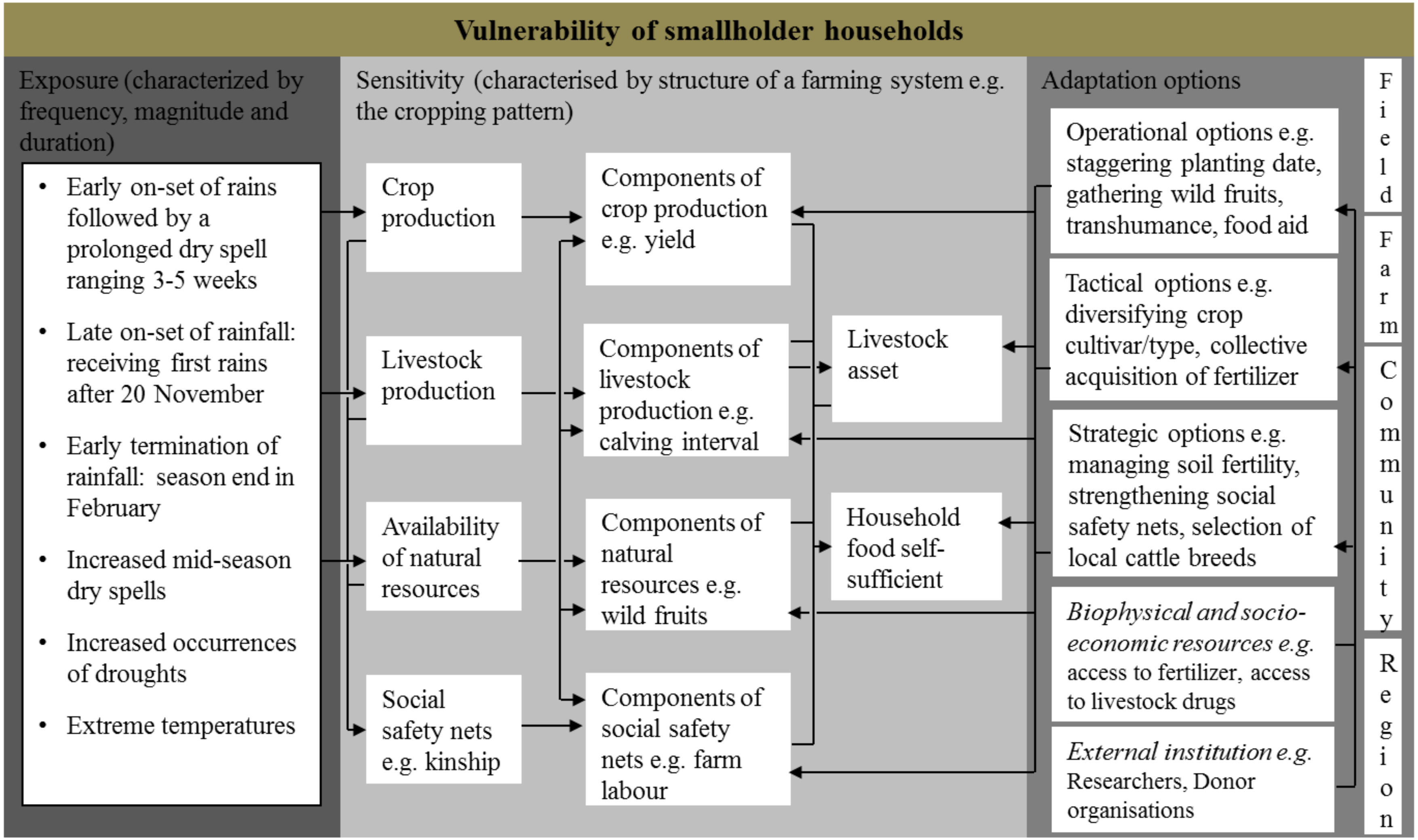

Fig. 2.1. Operational conceptual framework for vulnerability analysis in smallholder farming communities

2.2.2. Climatic exposure in smallholder livelihood systems

Farmers perceived increased rainfall variability, extreme temperatures and increased occurrences of droughts as the main climatic exposure characteristics impacting their farming livelihood systems (Table 2.2). The results of the survey showed no significant difference in how households of different endowments perceive climate exposure characteristics (Table 2.2). Analysis of long-term rainfall indicated that the total seasonal rainfall has not changed, but there was increased variability in the rainfall distribution within seasons (Fig. 2.2). Although there was a large variability in the date for the start of the growing season, a delay of a week was observed for the period, 1990-2010 compared with the period, 1962 to 1989 (Fig. 2.2b). Similarly, the probability of dry spells between the end of January and early February has also increased in the last two decades (Fig. 2.2(c and d)). The mean maximum temperature has not changed, but the mean minimum temperature has increased by 0.2°C per decade in Makoni (Fig. 2.3a). The mean minimum temperature has increased by 0.2°C per decade, while the mean maximum has increased by 0.5°C per decade in Hwedza (Fig. 2.3b). The number of days with temperatures >30°C have also increased in Hwedza but not in Makoni (Fig. 2.3(c and d)).

Table 2.2. Farmers' perceptions of climatic exposure characteristics in Makoni and Hwedza in Zimbabwe (based on a household survey conducted in 2009)

Site / Climate exposure characteristic	Resource-endowed	Intermediate	Resource-constrained
		%	
Makoni	*n* = 25	*n* = 35	*n* = 40
Increased rainfall variability	56	68	57
Late on-set of rainfall	33	35	32
Prolonged dry spells	11	5	11
Increased drought incidences	5	10	12
Extreme temperatures	9	10	8
Other (reduced rainfall, cyclones)	5	10	5
Hwedza	*n* = 18	*n* = 30	*n* = 52
Increased rainfall variability	78	61	64
Late on-set of rainfall	33	35	32
Prolonged dry spells	11	23	14
Increased drought incidences	6	21	13
Extreme temperatures	28	17	15
Other (reduced rainfall, cyclones)	7	5	4

Note: the overall percentage exceeds 100 due to multiple responses.

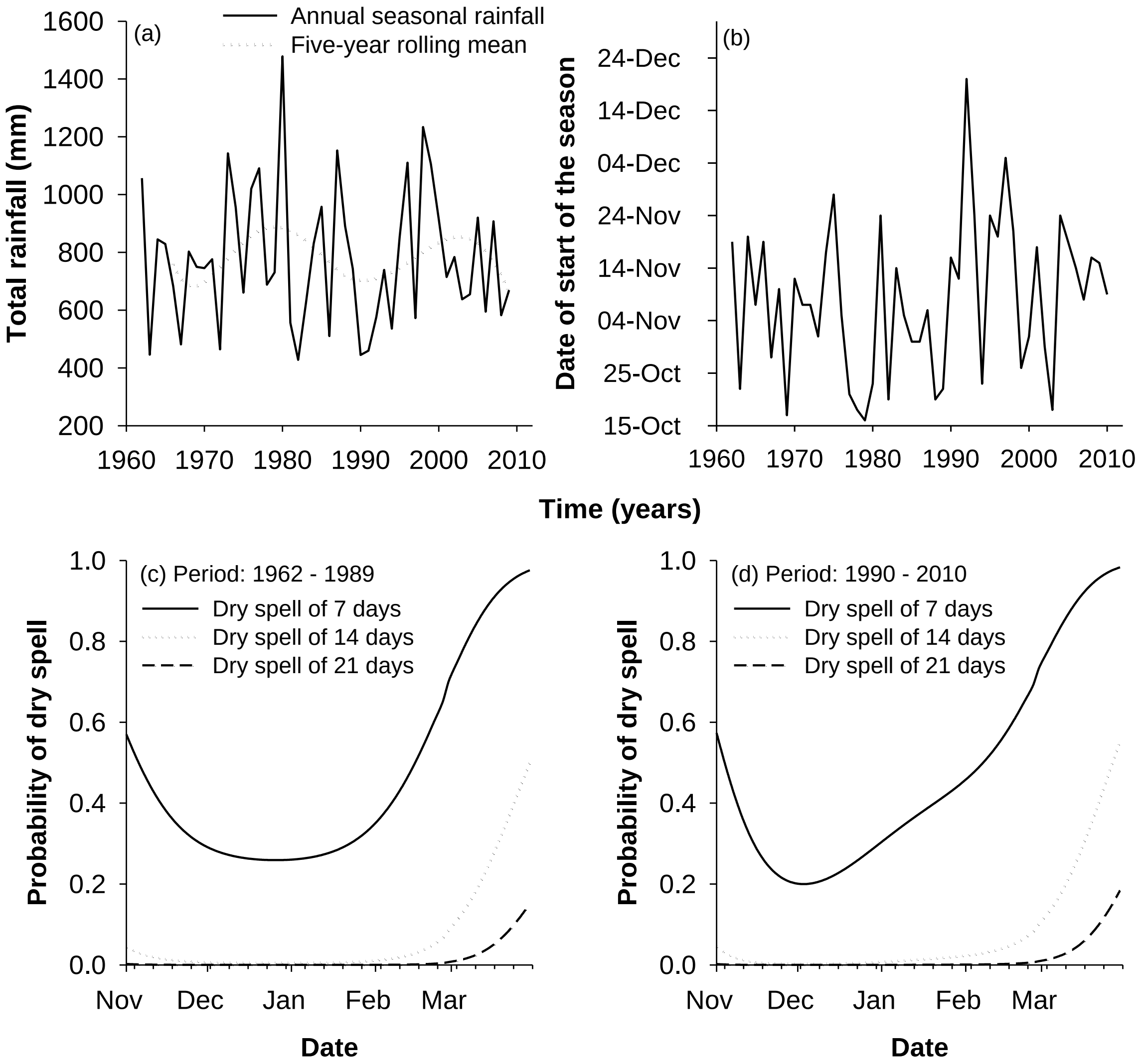

Fig. 2.2. Rainfall analysis outputs in Hwedza: (a) variation in annual seasonal rainfall (tau-b = -0.021, *P* = 0.831), (b) date of start of rainy season (using 48 mm in at least two rainy days out of ten consecutive days) (tau-b = 0.104, *P* = 0.296), (d) Probability of dry spells of different lengths for period 1962-1989, and (d) Probability of dry spells of different lengths for period 1990–2010.

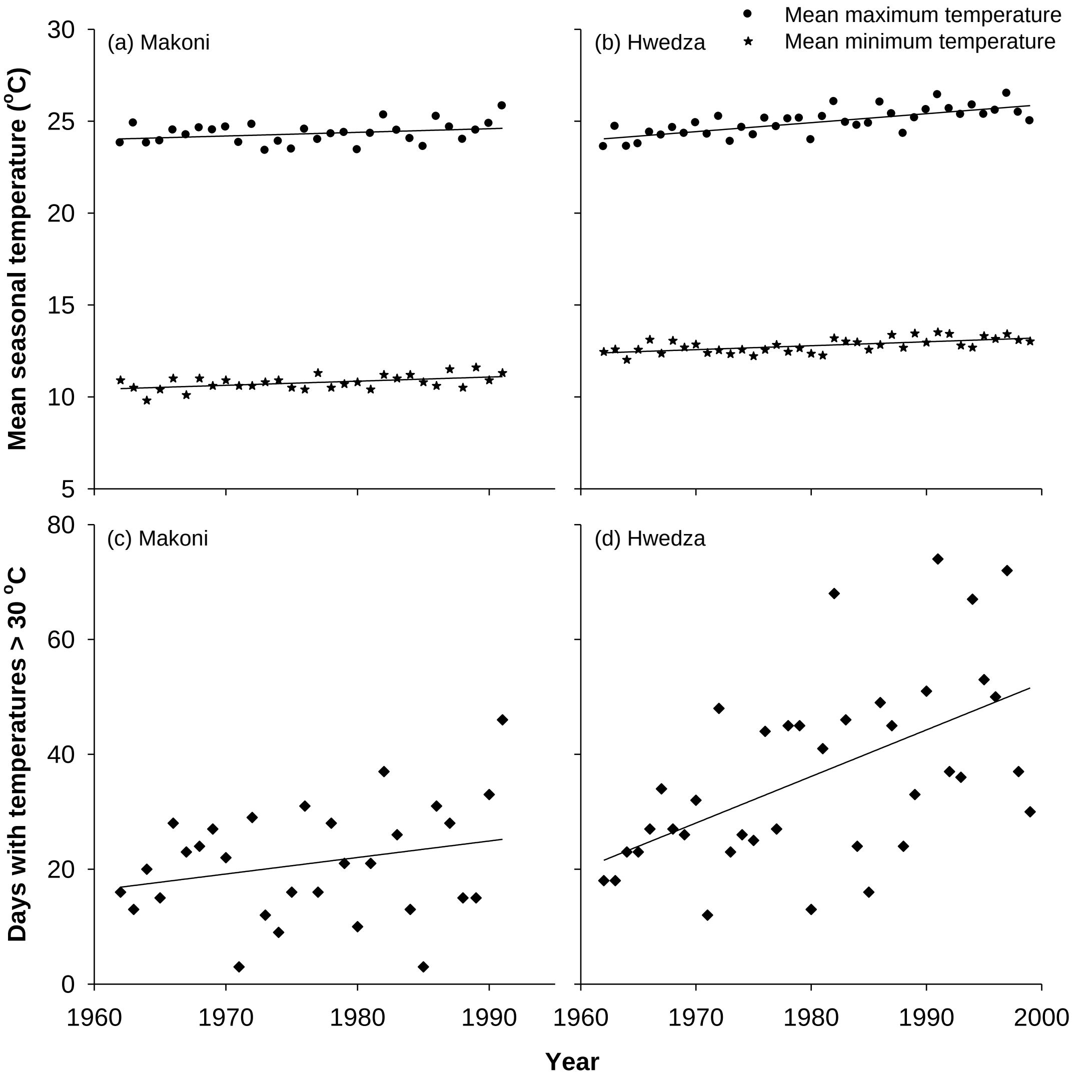

Fig. 2.3. Time series trend for (a) mean maximum (n = 30, tau-b = 0.191, P = 0.139) and mean minimum (n = 30, tau-b = 0.300, P = 0.024) daily temperatures in Makoni; (b) mean maximum (n =38, tau-b = 0.556, P = 0.000) and mean minimum (n =38, tau-b = 0.391, P = 0.001) daily temperatures in Hwedza; and (c) number of days with temperatures > 30 °C in Makoni (n =30, tau-b = 0.163, P = 0.211) and (d) Hwedza (n =38, tau-b = 0.414, P = 0.000), Zimbabwe.

2.2.3. Vulnerability of different farmer groups to climate variability and change

Farmers perceived that the four sub-systems of a farming livelihood system namely cropping, livestock production, natural resources and social safety nets were impacted differently by different climatic exposure characteristics (Table 2.3). Farmers revealed that crop production was affected most by increased rainfall variability, whereas livestock production was threatened most by droughts (Table 2.3). Availability of rangeland and non-timber forest products collected from natural environments were affected most by extreme temperatures (Table 2.3). Social safety nets were affected indirectly by both increased rainfall variability and droughts due to decreasing crop and livestock productivity (Table 2.3).

The livelihoods of resource-endowed households were most vulnerable to droughts as a result of cattle loss due to lack of feed. As resource-endowed farmers own relatively large cattle herds, they often find it difficult to feed these large herds in times of drought. This can result in substantial cattle losses, unless farmers have access to capital to buy supplementary feed. Resource-endowed households normally have enough food (see Table 2.4) because of timely access to farm inputs such as draught power, manure and fertilizers for crop production. Farmers of intermediate resources, which depend most upon crop production, were vulnerable to increased rainfall variability within a season coupled with rising temperatures (Table 2.3).

The resource-constrained households, who depend on social safety nets and common natural resource pools, were threatened by both extreme temperatures and increased rainfall variability (Table 2.3). This group depended on social safety nets to hire out labour, for a substantial part of their food and cash availability. Weakening of social safety nets was driven by both biophysical and social variables. Declining crop and livestock productivity due to increased rainfall variability and droughts forced resource-endowed and resource-intermediate households to compete with resource-constrained for scarce natural resources such as wild fruits, thereby creating conflicts between households. Declining crop production also reduced the amount of farm work available for resource-constrained farmers on resource-endowed farms. Maize grain yields of resource-constrained households were poor (< 1 t / farm) even in the good 2009/10 rainfall season in Hwedza resulting in low food self-sufficiency (Table 2.4). The low food self-sufficiency demonstrated that poor households fail to produce enough food for the household. Consequently, they supplement household food with other livelihood options particularly hiring out labour and gathering wild fruits.

Table 2.3. Farmer ranking of sub-systems of a farming livelihood system impacted by different climatic exposure characteristics in Makoni and Hwedza, Zimbabwe (Rank 1 is the most affected sub-system and 4 is the least)

Climatic exposure characteristic	Rank of a sub-system	Main system component impacted	Impact	
			Positive	Negative
Increased rainfall variability: prolonged mid-season dry spells ranging from 3 -5 weeks, and late on-set of rainfall	1. Crop production	Yield	Increased crop yield in wetland fields	Decreased crop yield in dry land fields due to soil moisture deficits
	2. Social safety nets	Hired labour	-	Reduced hiring of farm labour Reduced sharing of draught power
	3. Livestock production	Yield of milk	Reduced livestock diseases	Reduced milk yield due to lack of quality pastures
	4. Natural resources	Fruits		Reduced availability of fruits
Droughts	1. Livestock production	Weight of cattle Calving interval Yield of milk	-	Poor livestock condition and death Reduced reproduction potential Drastic reduction in milk yield Increased incidences of diseases
	2. Crop production	Yield	-	Crop failure
	3. Social safety nets e.g. kinship	Hired labour		Reduced hiring of farm labour Reduced sharing of draught power
	4. Natural resources	Fruits	-	Decreased availability of wild fruits Increased extraction of natural resources for sale e.g. firewood Reduced availability of pastures
Extreme temperatures	1. Natural resources	Fruits	-	Reduced availability of fruits
	2. Social safety nets	Human health	-	Increased outbreak of diseases
	3. Livestock production	Weight of cattle	-	Poor livestock condition
	4. Crop production	Yield	-	Reduced production due to frost

Table 2.4. Maize grain yield and energy produced and food self-sufficiency ratio (FSSR) for each farmer resource category in Makoni and Hwedza for the 2009/2010 and 2010/2011 seasons. Data in parentheses indicate range

Site / Farmer category	2009/10 season			2010/11 season		
	Maize yield t ha^{-1}	Total energy $\times 10^6$ kcal/household/year	FSSR %	Maize yield t ha^{-1}	Total energy $\times 10^6$ kcal/household/year	FSSR %
Makoni						
Resource-endowed	7.0 (3.1- 11.5)	25.1 (11.1 - 41.2)	583	2.0 (2.0-2.5)	7.2 (7.2 - 9.0)	167
Intermediate	5.4 (2.5-6.3)	19.3 (9.0 - 22.6)	450	1.5 (1.0-2.0)	5.4 (3.6 - 7.2)	125
Resource-constrained	3.4 (2.3-4.5)	12.2 (8.2 - 16.1)	283	1.3 (0.8-1.3)	4.7 (2.9 - 3.7)	108
Hwedza						
Resource-endowed	2.6 (2.1-3.1)	9.3 (7.5 - 11.1)	217	1.7 (1.5-2.0)	6.1 (5.4 - 7.2)	142
Intermediate	1.6 (1.0-2.8)	5.7 (3.6 - 10.0)	133	1.2 (0.8 - 1.5)	4.3 (3.2 - 5.4)	100
Resource-constrained	0.6 (0.5-0.7)	2.5 (1.8 - 2.5)	58	0.5 (0.2-0.8)	1.8 (0.7 - 2.9)	42

Notes: 100g of grain maize, 12% moisture content provide 358 kcal of energy (FAO).
Minimum dietary energy requirement (MDER) is 1790 kcal/person/day (FAO, 2009) $=3.9\times10^6$ kcal/6 persons/year.
Average dietary energy requirement (ADER) is 2260 kcal/person/day (FAO, 2009) $= 4.9\times10^6$kcal/6 persons/year.
Food self-sufficiency rate (FSSR) = Household production / sufficient quantity required for household consumption x 100

2.2.4. Vulnerability to climate variability and change and to other drivers

Limited access to fertilizer in Makoni and limited access to fertilizer and draught power in Hwedza were the main economic factors constraining crop production (Fig. 2.4). Farmers' ranking of factors constraining crop production in Hwedza had the following order: increased rainfall variability (64% of the respondents) > Lack of access to draught power (20%) > Lack of access to fertilizer (18%). In Makoni, 64% of farmers ranked increased rainfall variability first followed by lack of access to fertilizer (30%) (Fig. 2.4). Timely access to affordable fertilizers, improved access to draught power and improved soil fertility management were also given high priority by farmers of different endowments as options to reduce vulnerability to climate variability and change (Table 2.5).

Lack of quality pastures and increased incidence of pests and diseases were the main biophysical and economic factors affecting livestock production worsening the impacts of droughts (Table 2.6). Availability of natural resources such as wild fruits was also impacted by deteriorating social safety nets and land use change. Local community by-laws that govern conservation of natural resources strictly depend on community social cohesion. Lack of involvement of the local community in better identifying and helping the most vulnerable households was also seen at each site as a major issue threatening social safety nets.

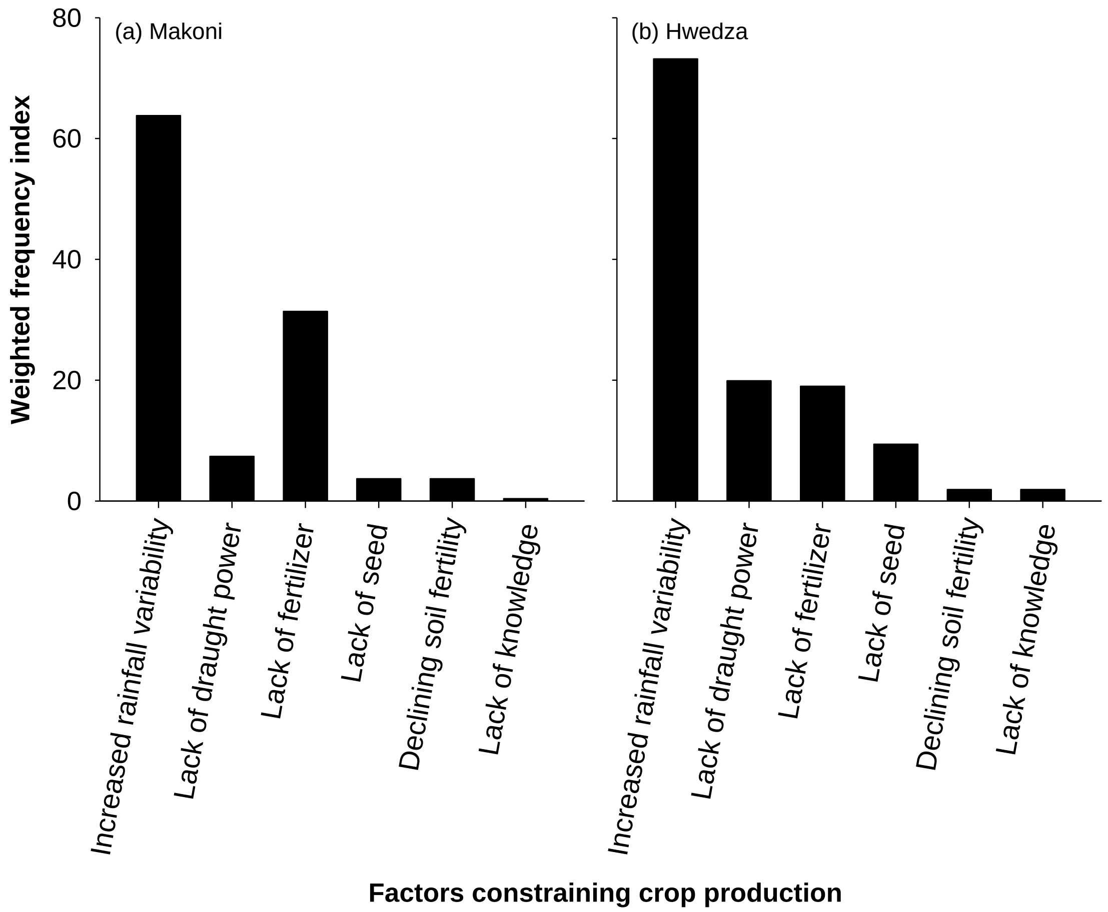

Fig. 2.4. Farmer ranking of main factors constraining crop production in (a) Makoni and (b) Hwedza, in Zimbabwe. Weighted index was calculated from frequency divided by rank, n = 100 in each site.

Table 2.5. Farmer ranking of prioritized issues to reduce vulnerability to climate variability and change in Makoni and Hwedza in Zimbabwe (Rank +++++ is the most important and + is the least important per farmer resource category)

Site / Farmer resource category	Prioritised issues to reduce vulnerability to climate variability and change							
	Timely access to affordable fertilizers	Develop local input and out markets	Improved access to draught power	Improved management of poor soils	Need for appropriate production technologies e.g. crop cultivar/type	Enhance performance of learning and knowledge sharing platforms e.g. [a]LC	Need for local criteria to better target the most vulnerable households	Conservation of natural resources e.g. wild fruit trees
Makoni								
Resource-endowed	+++++	++++				+++	++	+
Intermediate	++++	+				+++	++	+++++
Resource-constrained	+++++	+++				++	+	++++
Hwedza								
Resource-endowed	+++++			++++	+++	++	+	
Intermediate	++++			+++	+	+++++	++	
Resource-constrained	+++++		++		+++		+	++++

[a]A learning centre (LC) is defined as a field-based, interactive platform for practical integration of local, conventional and emerging knowledge on superior agricultural innovations requiring promotion or farm-level adaptive testing to address complex problems by alliances of farmers, research and extension agencies, agro-service providers and other stakeholders (Mapfumo, 2009).

2.2.5. Risk management: Adaptation options for different farm types to climate variability and change

Diversifying crop cultivar/type, staggering planting date and managing soil fertility were identified as the major adaptation options to stabilize yields in the face of increased variable rainfall (Fig. 2.5). Collective farming action (i.e. working in groups) was suggested as a potential tactical adaptation option not only to access draught power, but also to acquire fertilizer in time and at a reduced cost (Table 2.6). Collective acquisition of fertilizers reduces transaction costs because farmers share the cost of transport and buy fertilizer at wholesale price. Selecting local cattle breeds that are adapted to local conditions would sustain cattle production in response to increased droughts (Table 2.6). Establishing community woodlots and planting indigenous fruit trees at homesteads was seen to be important to increase production of declining common woodlands (Table 2.6). Involvement of the community in better targeting the most vulnerable households was identified as critical to strengthen social safety nets.

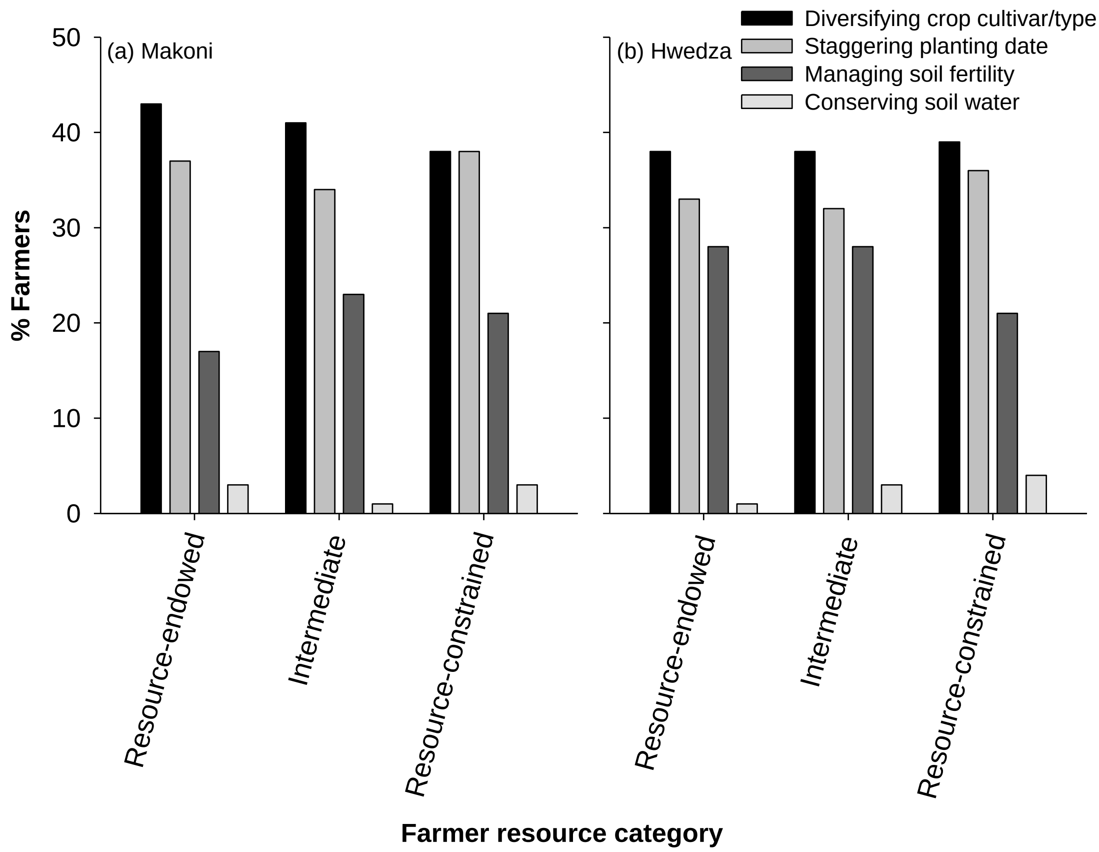

Fig. 2.5. Adaptation options suggested by farmers of different endowments, to stabilize yields in the face of climate variability and change in (a) Makoni and (b) Hwedza, in Zimbabwe.

Table 2.6. Farmer identified adaptation options to climate variability and change and other stresses in Makoni and Hwedza

Climate exposure characteristic	Impacted sub-system	Other factors affecting sub system	Adaptation options	Suggested key players
Increased rainfall variability	Crop production	Lack of access to fertilizers	Collective acquisition of fertilizers e.g. through farmer groups	Farmers, Agritex, Fertilizer companies
			Develop local input and output market channels	Farmers, researchers, agro-dealers, Agritex
		Lack of access to draught power	Revive the *humwe* concept to assist farmers with limited access to draught power	Local leaders, farmers
		Lack of knowledge on climate change	Improve performance of learning and knowledge sharing platforms such as learning centres	Researchers, Agritex, farmers
Increased droughts	Livestock production	Lack of quality pastures	Selection of local cattle breeds that are adapted to local conditions	Researchers, extension and farmers
			Increased production of small ruminants that are more resistant to droughts than cattle e.g. goats	Livestock unit, extension, farmers
			Government facilitated collective acquisition of pastures from distant areas	
		Increased incidences of pests and diseases	Integrating locally available resources, medicinal herbs and synthetic vaccines	Veterinary services, extension, farmers
Extreme temperatures	Natural resources provisions	Deteriorating social safety nets	Reviving local institutions to strengthen social cohesion	Local leaders, farmers
			Involvement of the community to better target the most vulnerable households	Local leaders, farmers, food aid organisations, Rural District Council
		Land use change	Establish community woodlots and plant valuable indigenous trees at homesteads	Farmers, Environmental Management Agents, Rural District Council

2.3. Discussion

2.3.1. Exposure to climate variability and change of smallholder farming livelihood systems and its implications

Farmers' recall of weather and climate closely matched climatic records. Increased rainfall variability characterised by delayed seasonal rainfall and prolonged dry spells, droughts, and increased temperatures were the most important climate indicators identified by farmers during the study. These findings are consistent with Houghton (1997) who projected increased rainfall variability and extreme events such as droughts in southern Africa. Unganai (1996) also found that temperature has increased by up to 0.8°C in Zimbabwe and further projected temperature increase in the range 2°C – 4°C in Zimbabwe and other parts of southern Africa.

Increased frequency of within season dry spells combined with increased temperatures could cause serious soil moisture deficits that can increase risk of crop failure. The impact of these dry spells on crop production could be large because the probability of dry spells seems to have increased around the critical flowering period of crops, i.e. between end of January and early February (see Fig. 2.2(c and d)). The change in temperature characteristics was greater in Hwedza than in Makoni, because not only the minimum and maximum temperatures have increased, but also days with temperatures >30°C, affecting crop production (Lobell et al., 2011). This indicated high temperature variability in otherwise proximal areas. Similar to crops, changes in temperatures will affect livestock production. At temperatures above 30°C most livestock species reduce their feed intake by between 3% and 5% each 1°C increase (NRC, 1981).

2.3.2. Vulnerability for different farmer resource categories to climate variability and change

Although vulnerability differed between households of the same community, there was no one-to-one relationship between vulnerability and farmer resource endowments. Households of different endowments were distinctively affected by the varied impacts of the changing climate.

The resource-endowed households, who relied more on cattle, were most vulnerable to droughts because cattle production was most sensitive to droughts. For example about 1.03 million (> 23% of the Zimbabwean national herd) cattle died during the 1991/92 drought (Tobaiwa, 1993). Many farmers who lost cattle during this drought have not yet recovered and their herds will not be able to do so without external support. Thus, the impact of drought can be long term not only because the reproductive rate of cattle is slow (Campbell et al., 2000) but also because huge investments are required to restock the herd. Given on the one hand the importance of cattle and on the other hand the increased occurrences of droughts, occur roughly 1-2 times per decade in Zimbabwe (Rockström, 2004), several approaches have been proposed to buffer livestock production against droughts. Scoones (1992) recommended sale of cattle during droughts and restocking during favourable conditions. Lack of insurance and price differences between the drought period and the period of restocking, however, would complicate the implementation of this strategy (Campbell et al., 2000). Normally prices of cattle fall during droughts due to poor cattle condition and increased supply. The value of money may also depreciate so that cattle can only be purchased at a much higher price.

Resource-intermediate households, which depended most upon crop production, are most vulnerable to increased rainfall variability within a season combined with increased temperatures. Such households have relatively few cattle, so farmers are reluctant to sell cattle in times of food deficits unless the impact of drought on household food is strong. Instead, resource-intermediate households prefer to change their consumption patterns - rationing their food as a coping strategy (Eldridge, 2002) rather than selling their productive assets with the objective of enhancing their future entitlements. The impacts of increased rainfall variability on household food availability can be huge, but generally short-term and can be addressed in a shorter time period compared with the impacts of drought on livestock production. However, if poor rainfall events occur frequently for consecutive seasons, farmers would not only experience food shortages for a longer period, but would also be forced to sell the few cattle they have, which would lead to long term impacts on their livelihood.

The resource-constrained households, who depended on social safety nets were vulnerable to both extreme temperatures and increased rainfall variability. These households largely depend on off-farm activities, especially exchange of labour for food and income with the wealthier households (Zingore et al., 2007), and use of natural resources such as wild fruits (Woittiez et al., 2013). Climate variability affects both of these activities. Woittiez (2013) reported an increased energy intake from wild fruits by wealthier households in times of crop failure in Zimbabwe. The increased competition for scarce natural resources such as wild fruits can also create conflicts between households thereby weakening community social safety nets. Declines in crop productivity would also reduce the amount of farm work available to poor households on resource-endowed farms. Eldridge (2002) showed that food (or cash) obtained in exchange for work on richer farmers dropped in parallel with the reduction in harvest in Zimbabwe. Wealthier farmers prefer to hire relatively cheap labour outside their community creating local tension with the poor households.

The analysis of household vulnerability to climate variability and change shows a complex picture, and cannot be related simply to poverty. Both poor and wealthier households are vulnerable depending on the specific climatic exposure. In a related study, it was shown that because of diversified livelihood strategies, farmers who were using common pastureland for livestock production and were regarded as poor, were less vulnerable to droughts than private farms that were regarded as rich (Toni and Holanda Jr, 2008). Furthermore, as also discussed earlier, the vulnerabilities for the different households are intertwined because farmers depend on each other (see Table 2.7).

Table 2.7. Farmer suggested options to assist the most vulnerable households in Makoni and Hwedza in Zimbabwe

Resource-endowed	Intermediate	Resource-constrained
The most vulnerable households should organize themselves to work in groups	Collective ploughing, weeding and harvesting through *humwe*[a]	Exchange labour for food (or cash) with wealthier households *(maricho)*
Every vulnerable household should have a Learning Centre	Mutual arrangements: households with no draught power should arrange with those with cattle to access draught power in time	Provision of food to the most vulnerable households
Resource-endowed farmers should ensure that the vulnerable households plant early by assisting them with draught power	Farmers without access to draught power should exchange labour for draught power	Resource-endowed farmers should ensure that the most vulnerable households plant early by assisting them with draught power
The local leaders should organize a *Zunde raMambo*[b] field for the most vulnerable households	The community leaders should tighten rules to reduce incidences of crop damage by straying animals	

[a]*Humwe* refers to a local custom in which a community collectively provides labour to a fellow farming household irrespective of wealth and social status, to hasten critical and time-bound farming operations such as ploughing, weeding and harvesting. The humwe can be as a result of a distress call by the beneficiary member or a local leadership initiative within the context of a local social safety net systems. The host farmer provides food and beverages for energy to keep the moral, and as a token of appreciation to fellow farmers.

[b]*Zunde raMambo* is a traditional practice whereby the traditional leader, usually the chief, kept a strategic grain reserve that was intended to support the needy and vulnerable within the community such as orphans, the elderly, widows and the disabled. This food would also be used for village ceremonies and functions. The community provided labour and worked on a piece

2.3.3. Vulnerability to climate variability and change relative to other problems

Alongside climate variability and possible climate change, farmers are also faced with other biophysical and social-economic problems. The vulnerability of households also varied depending on the capacity of different households to address these other challenges.

Lack of access to fertilizers and draught power were identified as the main issues preventing farmers from stabilizing their yields against increased rainfall variability. Because of lack of access to fertilizer, poor farmers failed to produce sufficient food for household consumption, even in a good rainfall year (see Table 2.4). The resource-endowed farmers, however, demonstrated that with fertilization household food self-sufficiency could be achieved even in a relatively bad rainfall season. Similarly, Fraser et al. (2008) reported that fertilizer input was important for stabilizing yields in low rainfall years. Despite the importance of fertilizer, farmers, particularly resource-constrained ones, often fail to access fertilizers due to prohibitive costs (Nyikahadzoi et al., 2012). Availability of cattle not only provides draught power, but was identified as a major source of diversified and improved livelihoods among smallholders (Scoones, 1992). Timely access to draught power would allow farmers to plant during the windows of favourable rainfall conditions. Draught power can be rented to other farmers and thereby provide household income. Livestock also provide manure, a key organic nutrient input for sustaining soil productivity. Livestock are a central means of concentrating nutrients within a farming system (Giller et al., 2006).

There is an apparent contradiction in that farmers perceived lack of fertilizer to be one of the major constraints to crop production (see Fig. 2.4), but ranked declining soil fertility as of relatively low importance. In fact these soils are inherently poor in nutrient content derived from granitic parent material (Nyamapfene, 1989) perhaps explaining why soil fertility decline was not perceived to be a major issue.

Lack of good quality pastures and increased incidence of livestock diseases were mentioned by farmers as factors that increase the sensitivity of cattle to droughts. Increased incidence of livestock diseases may have been caused by the dis-functioning of ectoparasites control dip tanks in the regions. This also led to increased prices of vaccines (Chatikobo et al., 2013). The dis-functioning was caused by the economic meltdown and associated hyper-inflation that affected many smallholder farmers in Zimbabwe. Also increasing temperatures (e.g. in Hwedza) will likely provide favourable climatic conditions for disease transmitting vectors (e.g. ticks and flies) to multiply and this will further increase the incidence of livestock diseases. Increased incidences of cattle diseases such as bovine dermatophilosis and inadequate grazing were also ranked as the major constraints to livestock production in north-western Zimbabwe (Chatikobo et al., 2013). Lack of quality pastures were caused by declining grazing areas due to land use change. Because of population pressure, new homesteads for young families have been established in areas traditionally designated for grazing. Reduced stover biomass, a key feed component at the end of the dry season, due to deteriorating crop production has exacerbated shortages of cattle feed.

Farmers revealed that social safety nets were also under threat because of donor and relief organisations. The criteria used by the donor agencies to target the most vulnerable households failed to recognise the role of local institutions. Tobaiwa (1993) reported that amounts of food aid received by the poorest households were considerably less than could be expected based on the amounts distributed, due to logistical and organisational constraints and inadequate targeting. Farmers perceived that inadequate targeting of the most vulnerable households would punish hard working farmers and reward the lazy ones, thereby creating conflicts between members of the same community. The weakening of social capital would affect the resilience of smallholder communities in the medium to long term because sharing of resources such as draught power and labour would also be affected.

2.3.4. Risk management and resilience of smallholder communities

To increase resilience of smallholder communities, adaptation options need to address both climatic risk, and other biophysical and socioeconomic problems. Farmers suggested various short, medium and long-term strategies, which we classified into tactical, operational and strategic adaptation options based of the concept of strategic farm management of de Koeijer et al. (2003). For example staggering planting date and diversifying crop cultivar/type were major options to minimize the impact of increased rainfall variability on crop yield. On the other hand, managing soil fertility and farmer collective action were the major biophysical and socioeconomic adaptation options for stabilizing crop yields. Similar adaptation options have also been suggested elsewhere in Africa (Eriksen et al., 2005; Milgroom and Giller, 2013) and other regions (e.g. Fraser et al., 2008). Luers (2005) reported that soil fertility management reduced vulnerability of farmers to droughts. Many farmers are not making use of these adaptation options yet, mainly due to the lack of resources such as fertilizers and draught power. Farmers suggested several key players that could strengthen their capacity to adopt these adaptation options (see Table 2.6).

Because many smallholder farmers in sub-Saharan Africa are still focused on ensuring their own survival, or ‘hanging in’ as Dorward (2009) calls it, it was not surprising that most of the identified adaptation options focused on changing farming management practices. Some literature suggests that stepping out of agriculture is actually the most robust adaptation option for farmers (Bryan et al., 2009), but because of limited opportunities elsewhere this venture might be difficult for farmers in the short to medium term. Also, poverty would constrain farmers to move out of agriculture as the trajectory for stepping out of agriculture requires that farmers should be out of poverty first before they move into other enterprises (Dorward, 2009). Overall, however, it is clear that because farmers are exposed to different climatic exposure characteristics and have access to different endowments, adaptation options should be tailored according to the socioeconomic and biophysical circumstances of farmers and their land.

2.4. Policy implications for vulnerability in smallholder farming systems

There was no simple one-to-one relationship between vulnerability and farmer resource endowments. Each sub-system of the farming livelihood system was sensitive to a unique climatic exposure characteristic leading to differential vulnerability between households of the same community. Better targeting of the most vulnerable to climate variability and change therefore requires understanding of the prevailing climatic conditions rather than focusing only on resource-constrained households to prevent other household types to fall into a poverty trap. Various adaptation options including diversifying crop cultivar/type, staggering planting date, using fertilizer, selecting local cattle breeds and establishing community woodlots were suggested to reduce the impacts of climate variability and change. Diversifying crop cultivar/type, staggering planting date and managing soil fertility, however, were identified as the major adaptation options to minimize the impacts of increased rainfall variability on crop production. To optimise and sustain the benefits that can be derived from such field, farm and landscape level adaptation options, they need to be integrated in the framework of sustainable intensification. Intensification of smallholder farming systems is key to enhancing and sustaining agricultural production as well as ecosystem services. Increasing production and adaptation go hand in hand and are not conflicting goals. Because each sub-system of the farming livelihood system was vulnerable to either single or multiple climatic variables, policy needs to target complementary adaptation options outside agriculture to build a robust and resilient food systems. Revamping the livestock herd and strengthening the social capital of the local communities, for example by facilitating formation of farmer learning groups, could strategically reduce the vulnerability and increase the resilience of smallholder communities to climate variability and change.

Chapter 3

Managing soil fertility to adapt to rainfall variability in smallholder cropping systems in Zimbabwe

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Abstract

Adaptation options that address short-term climate variability are likely to lead to short-term benefits and will help to deal with future changes in climate in smallholder cropping systems in Sub-Saharan Africa (SSA). In this study we combined field experimentation and long-term rainfall analyses in Makoni and Hwedza districts in eastern Zimbabwe to evaluate cropping adaptation options to climate variability. Analyses of long-term rainfall data closely supports farmers' perceptions that the mean annual total rainfall has not changed, but the pattern of rainfall within-season has changed: the number of rainfall days has decreased, and the frequency of dry spells has increased at the critical flowering stage of maize. On-farm experiments were conducted over two cropping seasons, 2009/10 and 2010/11 to assess the effects of planting date, fertilization and cultivar on maize production. Three maize cultivars were sown in each of the early, normal and late planting windows defined by farmers. Each of the nine cultivar-planting date combinations received N, P, K and manure combinations at either zero, low or high fertilization rates. Overall, there were no significant differences in maize development or grain yield among cultivars. Maize grain yield was increased by increasing the amount of nutrients applied. Average yield was 2.5 t ha^{-1} for the low rate and 5.0 t ha^{-1} for the high rate on early planted cultivars on relatively fertile soils in Makoni in 2009/10 season. Yields on poorer soils in Hwedza were small, averaging 1.5 t ha^{-1} for the low rate and 2.5 t ha^{-1} for the high rate. Maize grain yields for the early and normal planted cultivars were similar for each fertilization rate, suggesting there is a wide planting window for successful establishment of crops in response to increased rainfall variability. Yield reduction of >50% was observed when planting was delayed by 4 weeks (late planting) regardless of the amount of fertilizer applied. Soil nutrient management had an overriding effect on crop production, suggesting that although the quality of within-season rainfall is decreasing, nutrient management is the priority option for adaptation in rain-fed smallholder cropping systems.

Keywords: Climate variability; Adaptation options; Maize cultivar; Planting date; Soil fertility management

3. Introduction

Southern Africa is projected to face major risk of declining maize production because of a changing climate (Lobell et al., 2008). In Zimbabwe, maize yields will decline by between 10% and 57% by 2080 (Fischer et al., 2005; Lobell et al., 2008). Given that maize is the staple food, the impacts of the changing climate will expose millions of rural people to the risk of hunger. In the past, smallholder farmers have coped with erratic climatic conditions by adjusting their farming practices such as winter ploughing to allow early planting and replanting when crop establishment was poor (Shumba et al., 1992). The projected increase in climate variability, however, brings new risks that will require new adaptation options (Burke et al., 2009). Such adaptation options need to be designed jointly with farmers to increase local relevance (Giller, 2000). Poor distribution and lack of rainfall are key climatic constraints to rain-fed crop production in arid and semi-arid regions of southern Africa (Hussein, 1987; Tadross et al., 2009).

Adaptation options that focus on addressing short-term climate variability are likely to create benefits in the short-term as well as for future changes in climate (Easterling et al., 1992; Vermeulen et al., 2012). Adaptation can focus on shorter-term operational decisions (e.g. specific timing or sequencing of farming activities), on medium-term tactical options (e.g. changes in crop rotations, or allocation of crops across fields), or on longer-term strategic decisions (e.g. to change the major crops grown, or adopt completely new activities) (De Koeijer et al., 2003). Tactical adaptation options include staggered planting dates on the same farm (Makadho, 1996), to manage risk of drought at different times of the cropping season. The impact of planting date on crop production was evaluated in Zimbabwe with a focus on escaping dry spells that typically occur in January (e.g. Spear, 1968). Farmers were recommended to plant with the first effective rains to minimize reduction in maize grain yield of up to 32% associated with delayed planting (Shumba et al., 1992). Waddington and Hlatshwayo (1991) investigated the cause of reduced maize grain yield when planting is delayed, and concluded that yield reduction was mainly caused by shortening of day-length and delayed application of fertilizers. A diagnostic field survey in eastern Zimbabwe indicated that farmers use a range of planting dates because of lack of draught power or labour (Waddington and Hlatshwayo, 1991).

Diversification of crop cultivars and soil fertility management are also potential options for adaptation (IPCC, 2007). Use of cultivars that vary in time to maturity can increase the chance that one of the cultivars will escape dry spells particularly during critical crop development stages including silking and grain filling. Breeding in maize has focused on increasing tolerance to drought and poor soil fertility conditions in southern Africa (Bänziger et al., 2006). In the face of climate variability and change, it is not clear if current cultivars will be sufficiently resilient to sustain crop production (Thornton et al., 2011).

Soil nutrient depletion was identified as a fundamental bio-physical cause of declining per capita food production in sub-Saharan Africa (SSA) (Sanchez, 2002). The impacts of climate variability and change on crop production, are an extra pressure in addition to the existing problem of degrading soils due to continuous cropping without sufficient inputs. Integrated soil fertility management (ISFM) is therefore a potential entry point for adaptation. ISFM recognizes farming as a system that includes soil fertility management practices, improved and diversified crop cultivars, and the knowledge to select these according to local conditions and seasonal events, which should maximize fertilizer and organic resource use efficiency and crop productivity (Mapfumo, 2009; Vanlauwe et al., 2010). Organic resources can help to build-up soil organic carbon, a source of nutrients, and can improve soil moisture availability due to increased moisture retention (Nyamangara et al., 2001). Without soil fertility management, yields remain poor, averaging < 1 t ha^{-1} even when rainfall is sufficient (e.g. Mtambanengwe and Mapfumo, 2009). Rockström (2004) argued that soil and water management can mitigate the negative impacts of mid-season dry spells of up to 4 weeks on crop production.

While earlier agronomic studies investigated the production effects of some of the above-mentioned potential options for adaptation, most of such studies tested these agronomic management factors individually (Spear, 1968; Shumba et al., 1992). Recently, several modelling studies have assessed the combined effects of some of these suggested adaptation options. Crespo et al. (2011) investigated the effects of sowing time on maize production in southern Africa and concluded that planting time contributed strongly to maize yield variation. Phillips et al. (1998) modelled the effects of planting date and nitrogen input on maize yield using on-station data, and showed the importance of these factors in increasing yield under variable rainfall in Zimbabwe. However, increasing demand for empirical evidence to support decision making processes on climate change adaptation has led to increased realization that modelling provide useful information but cannot replace experimental and survey-based research (Stern and Cooper, 2011).

In this study we examined the interactions of planting date × nutrient input × genotype in experiments on smallholder farmers' fields. The experiments were conducted in two locations in eastern Zimbabwe, which is a hotspot for increased risk due to climate change, particularly drought and rainfall variability (Thow and de Blois, 2008). The two locations have dry sub-humid and semi-arid tropical contrasting climates and are representative of many areas of smallholder farming systems in SSA. For instance, more than 40% of agriculture in SSA is carried out in semi-arid regions and dominated by smallholder farmers (Rockström, 2004). Both sites have soils of poor fertility representative for large areas: arenosols cover about 13% of SSA and more than 6.5 million ha of cropland in southern Africa (Hartemink and Huting, 2008). The experiments tested potential adaptation options identified together with farmers. Our aim was to provide the quantitative knowledge needed for specific communities on suitable adaptation options to help them manage risk associated with climate variability (Vermeulen et al., 2012). The specific objectives of this study were: (i) to analyse long-term seasonal rainfall patterns on the basis of meteorological records and farmers' perceptions, (ii) to determine the impacts and interactions of adaptation options, namely cultivar, staggered planting dates, and fertilization on maize production under variable rainfall.

3.1. Materials and methods

3.1.1. Site description

The study was carried out at two sites: Nyahava community in Makoni district (18° 12' S 32° 24' E, 1400 m a.s.l) and Ushe community in Hwedza district (18° 37' S 31° 34' E, 1100 m a.s.l), both in eastern Zimbabwe. Makoni is a resettlement area opened in 1983 by the Government of Zimbabwe under the Land Resettlement Programme of 1980. The farm sizes range from 4 to 6 ha per household (Mtambanengwe and Mapfumo, 2005). Hwedza is a communal area with a long history of farming (>100 years); and the farm sizes range from 2 to 5 ha per household. Zimbabwe is characterized by unimodal rainfall season from October through April, and about 90% of the total rainfall is associated with thunderstorm activity producing falls of short duration and high intensity (Anderson et al., 1993). Rainfall ranges from 750 to 1000 mm per annum in Makoni, and 650 to 800 mm per annum in Hwedza (Anderson et al., 1993). The soils are granite-derived sands, Lixisols and Arenosols (WRB, 1998) with low organic carbon and low nutrients contents (Table 3.1) and poor water holding capacity (Nyamapfene, 1989).

3.1.2. Analysis of rainfall patterns in the study sites

Rainfall was analysed drawing on local farmers perceptions of changes in climate and daily rainfall data from the Meteorological Services Department of Zimbabwe. Diagnostic techniques that included a questionnaire survey of 100 households randomly selected in each community, focus group discussions and key informants were used to characterize rainfall patterns in the two sites (Mapfumo, 2009). Through focus group discussions farmers identified three seasonal rainfall patterns:

(i) Early rains (receiving first effective rains by mid-November) followed by a prolonged mid-season dry spell ranging from 3 to 5 weeks,
(ii) Late on-set of rains (receiving first effective rains after 20 November), and
(iii) Successive rains (rainfall for more than 10 consecutive days, often received around mid-December to early January).

Following from descriptions, three planting windows were identified: early (25 October – 20 November), normal (21 November – 15 December) and late (After 15 December) (Fig. 3.1). A diagnostic survey was conducted during the 2009/10 season to make an inventory of farmers' fields planted with maize at different planting dates. For this field survey, each community was divided into four areas with the assistance of local national extension officers, based on rainfall types and time of planting. Accordingly, 290 fields were randomly surveyed in Makoni, and 370 in Hwedza. Global Positioning System (GPS) was used to geo-reference the centre of each field. A Google Earth Image was then used to digitize the surveyed fields and then the area of each field was determined, in an Arcview GIS. The digitizing of fields was guided by coordinates recorded during the field survey. Farm diaries were allocated to 30 randomly selected farmers in each community to record time of planting, labour use, and nutrient inputs to maize plots. Nine farms characterized by different assets were purposefully selected in each site to measure maize yields. The yields were measured in each field allocated to maize on each farm. Maize grain yield was determined at physiological maturity from a net-plot of 2 rows × 5 m replicated two times. A questionnaire survey was also used to determine sources of draught power for different households in each site.

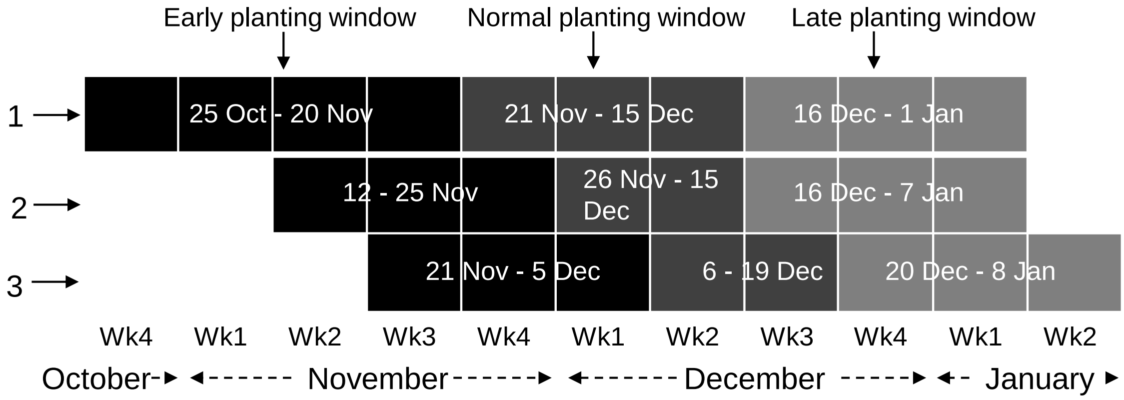

Fig. 3.1. Farmer defined crop planting windows based on perceived long-term seasonal rainfall types and season's rainfall quality in Makoni and Hwedza: (1) Planting windows based on long–term recall, (2) planting windows for the 2009/2010 season (3) planting windows for the 2010/2011 season.

Daily rainfall data for 48 years (1962 – 2009) in Hwedza was analysed to assess the possible trends in total annual rainfall, number of rain days per season, dates of the start and end of rainy season in Instat Plus 3.036 (Stern et al., 2006). Rainfall data for Makoni was incomplete and inconsistent and hence could not be used. A rain day was defined as a day with > 2 mm of rain, which corresponds to 0.5 × PET (potential evapotranspiration) on a daily basis for most of the regions in Zimbabwe (Chidhuza, 1993). The number of rain days was used to indicate the temporal distribution of rainfall throughout the rainy season. Date of the start of the rainy season was analysed using a threshold: 48 mm of rainfall in at least two rainy days out of ten consecutive days (Unganai, 1990). Since rainfall season lasts from October to April in Zimbabwe, the earliest possible start of the rainy season is often around October 15th. Accordingly, the potential starting date of the rainy season was defined as the first rainfall event from 15 October that has at least 48 mm in at least two out of ten consecutive rain days. The end of the rain season was defined as the first day of a dry spell exceeding 15 days during March (Stern et al., 1982).

The length of the dry spells of 7, 14 and 21days in 30 days during the growing season, was analysed by fitting a Markov chain probability model to daily rainfall occurrence data. The model assumes that the probability of rainfall on any day depends only on whether the previous day was wet or dry, i.e. whether rainfall did or did not occur. While the model is simple, it provides a rudimentary representation for the dry spells distribution, and it also fits well when relatively short daily rainfall records are available (Gabriel and Neumann, 1962). The usefulness of the Markov model to analyse daily rainfall data for dry spells length has been tested in many regions (Gabriel and Neumann, 1962) and southern Africa in particular (Stern and Cooper, 2011). In the analysis of dry spells the days were defined as wet when they had received at least 0.1 mm of rainfall (Gabriel and Neumann, 1962; Stern and Cooper, 2011). Both shorter and longer dry spell lengths were selected for analysis because certain crop growth stages are more sensitive to droughts and have a higher water requirement, and this is particularly critical for drought-sensitive crops such as maize (Sivakumar, 1992). Also, the number of rainy pentads, an indicator for rainfall distribution within a season was analysed for each season over 48 years. A rainy pentad is defined as the middle one of any three five day periods (pentads) which together have at least 40 mm of rain, provided that not more than one of the three periods has less than 8 mm (Lineham, 1983). Within-season rainfall distribution is generally considered good when the number of rainy pentads exceeds 15 (Lineham, 1983).

Table 3.1. Soil properties of experimental field sites in Makoni and Hwedza smallholder areas

Site	pH	Organic C	Total N	Available P	Ca	Mg	K	Clay	Sand
	(0.01 M $CaCl_2$)	(%)	(%)	(mg kg^{-1})		($cmol_c$ kg^{-1})		(%)	(%)
Makoni	4.8 (0.2)	0.76 (0.01)	0.08 (0.002)	9.4 (0.4)	1.6 (0.04)	0.8 (0.03)	0.4 (0.004)	7 (0.2)	88 (0.4)
Hwedza	4.1 (0.4)	0.32 (0.03)	0.04 (0.001)	3 (0.6)	0.6 (0.01)	0.2 (0.04)	0.1 (0.005)	6 (0.3)	91 (0.2)

Standard error of mean (SEM) in parentheses.

3.1.3. Potential agronomic adaptation options in response to rainfall patterns

Informed by participatory analysis of rainfall patterns, a researcher-managed field experiment was conducted in the 2009/10 and 2010/11 cropping seasons in Makoni and Hwedza to assess the effects of maize cultivar, planting date, and fertilization. In each study site, the field selected for the experiment was previously left fallow prior to the establishment. Three maize cultivars, three planting dates, and three fertilization rates were laid out in a split-plot block design with three replications per treatment. Planting date was assigned to the main plot, and fertilization rate × maize cultivar sub-plots were randomized within the main plot.

The three maize cultivars were: SC 403 (131 days to maturity), SC 513 (137 days to maturity) and SC 635 (142 days to maturity). The three planting dates were chosen based on farmers' planting windows as investigated in earlier studies (Mtambanengwe et al., 2012). In both seasons, however, the start of the rainy season was delayed, differing from farmers' long-term recall by two to four weeks (Fig. 3.1). Consequently, the planting windows were changed in each season in consultation with farmers so as to match each season's rainfall pattern (Fig. 3.1). In the 2009/10 season the early planting was delayed by three days, whereas in the 2010/11 season by about two weeks (Fig. 3.1). Although the rain started earlier during the 2010/11 season than in the 2009/10 season, it was characterised by very early season dry spells (false start to the season) (Fig. 3.2). In Makoni, the actual planting dates were 23 November for early planting date, 14 December for normal, and 7 January for late, in the 2009/10 season. In the 2010/11 season the planting dates were 5 December for early planting date, 18 December for normal, and 8 January for late. In Hwedza, the actual planting dates were 24 November for early planting date, 15 December for normal, and 6 January for late, in the 2009/10 season. In the 2010/11 season, the planting dates were 4 December, 17 December and 7 January.

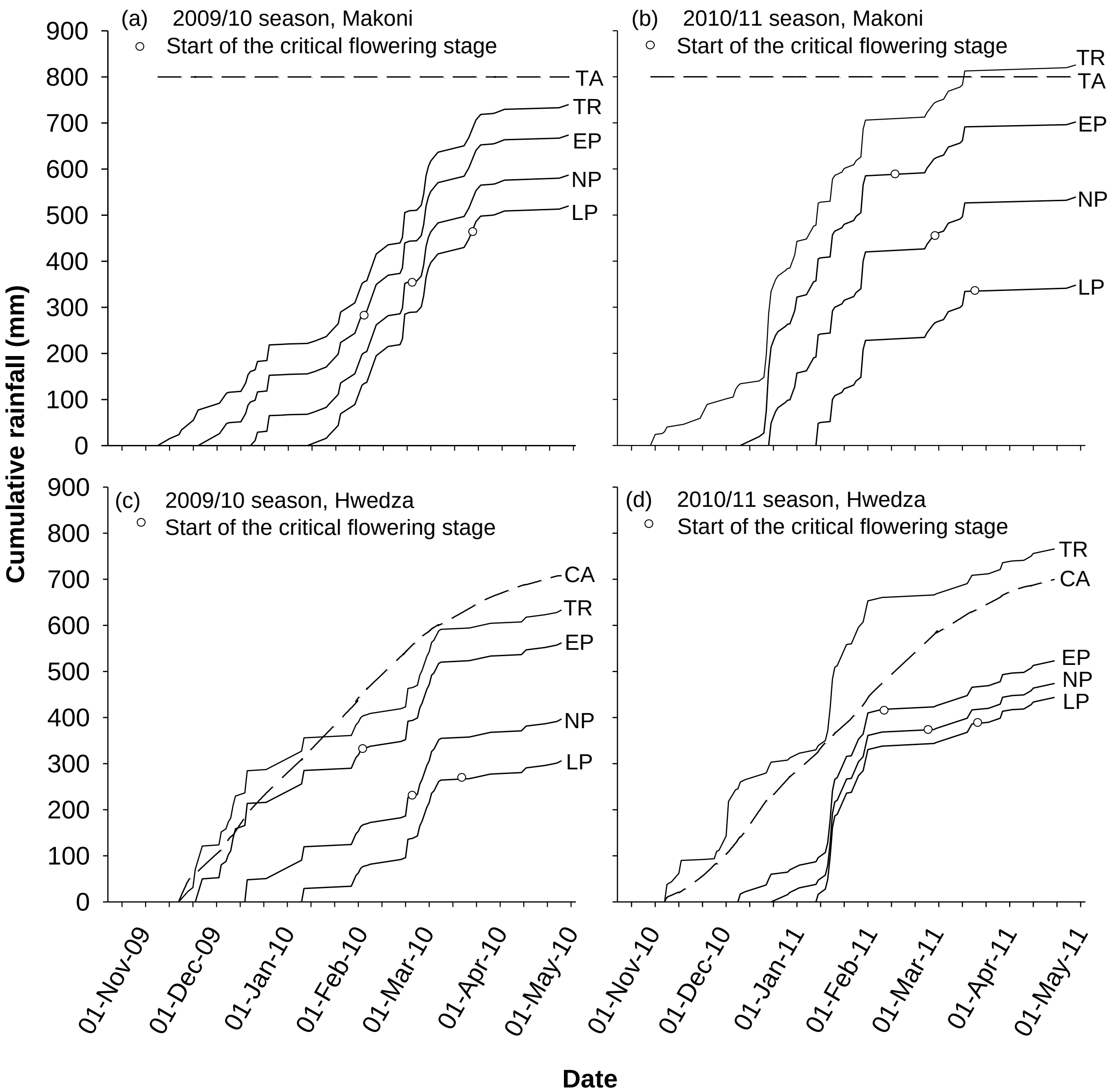

Fig. 3.2. Daily cumulative rainfall for total seasonal rainfall (TR), early planting (EP), normal planting (NP) and late planting (LP) in Makoni (a and b), and Hwedza (c and d) for the 2009/10 and 2010/11 seasons. TA: long-term mean rainfall, and CA: long-term mean cumulative rainfall. Empty circles indicate the start of the flowering stage for maize cultivars planted at different dates.

The three fertilization rates were: a control (unfertilized), low rate (35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure, on a dry weight basis) and high rate (90 kg N ha^{-1}, 26 kg P ha^{-1}, 7 t ha^{-1} manure, on a dry weight basis). Fertilization rates were derived based on crop demand for a target maize yield for farmers of different resource endowment (Mtambanengwe and Mapfumo, 2009). The lowest rate represents typical rates used by resource-constrained farmers, and highest rate is for yield maximization sometimes used by the better resource-endowed farmers.

Following farmers' common practices, the land was ploughed to a depth of 0.20 m and ridged using draught animals at the start of the rainy season for all planting windows. The experimental area was almost bare at ploughing in each site. Weeds were removed at normal and late plantings using a hand hoe. Each sub-plot had a gross area with dimensions measuring 4.5 m × 7 m and a plant spacing of 0.75 m × 0.30 m. Basal compound D fertilizer with composition: 7% N, 14% P_2O_5, 7% K_2O, was applied at planting. Nitrogen, topdressing was applied as ammonium nitrate (34.5% N) in two splits, at 4 weeks (40%) and 6 weeks (60%) after emergence. Weeding was done twice manually using a hand hoe. No major pests or diseases were observed throughout the experiment. Daily rainfall was recorded at each site using a rain gauge within a range of 300 m of field experiment in Makoni, and 100 m in Hwedza.

3.1.4. Laboratory and field measurements

3.1.4.1. Soil and manure analysis

Five soil samples (0-20 m) were randomly collected from the experimental area before the experiment was established. Soils were bulked to make a composite sample, air-dried, and sieved through a 2 mm sieve for analysis of soil texture (hydrometer method), pH (0.01M $CaCl_2$), organic carbon (Walkley Black), total nitrogen (micro-Kjeldahl), available phosphorus (modified Oslen) as described by Anderson and Ingram (1993) (Table 3.1). The total nitrogen in manure used in the experiment was 0.8% in Makoni, and 0.7% in Hwedza. The available P in manure was 0.3% in Makoni, and 0.26% in Hwedza.

3.1.4.2. Maize development, grain and stover yields

Leaf area index (LAI) was estimated at 3, 6, 9 and 12 weeks after crop emergence. Five plants were randomly selected and tagged from two rows in each of the sub-plots. Individual leaf area was estimated non-destructively from leaf length (*l*, cm), from the collar to the tip of fully expanded leaves, and from where a leaf could be seen in the whorl of expanding leaves to the tip; and leaf width (*w*, cm) at the widest point. Senesced leaves (50% or more of leaf having lost green colour) were not measured. Total plant leaf area was calculated by summing the products ($l \times w$) of each leaf from a plant and multiplying the total by 0.73 (leaf area = $\Sigma(l \times w)(0.73)$) (Mckee, 1964). Green LAI was then calculated as the sum of the areas of green leaves per unit area occupied by the plants (m^2 leaf m^{-2} of land).

Maize grain and stover yields were determined at physiological maturity from net-plots of 3 rows × 4.6 m. Grain yield was calculated at 12.5% moisture content. Stover samples were oven dried at 70 ^oC to constant weight before dry matter yield was determined.

3.1.5. Calculation of gross margins

Gross margins were calculated to assess the financial benefits of different adaptation options. Costs of production included in the analysis were inputs of fertilizers and maize seed, and labour for manure handling, land preparation, planting, weeding and harvesting. Costs of inputs and producer price of maize were determined using market prices for each season. The market value of maize stover was also included in the financial benefits because stover is an important livestock feed. Costs of labour were determined based on existing labour rates in each community using farm diaries and findings from informal interviews. Accordingly, the total labour was 61 labour days ha^{-1} (manure handling = 10 labour days ha^{-1}, land preparation = 4 labour days ha^{-1}, planting = 2 labour days ha^{-1}, weeding = 32 labour days ha^{-1}, fertilization = 3 labour days ha^{-1}, harvesting = 10 labour days ha^{-1}). The cost of each labour day was US$ 3.00 in each site for both seasons. The cost of a 50 kg bag of ammonium nitrate fertilizer (34.5% N) was US$ 30.00 in the 2009/2010 season and US$ 31.00 in the 2010/11 season. The cost of a 50 kg bag of Compound D (composition: 7% N, 14% P_2O_5, 7% K_2O) was US$ 27.00 in the 2009/10 season and US$ 28.00 in the 2010/2011 season. The cost of maize seed was US$ 2.2 kg^{-1}. The market price for maize grain was US$ 0.265 kg^{-1} in the 2009/10 season and US$ 0.3 kg^{-1} in the 2010/11 season. The ratio of market value of maize grain to maize stover was taken as 6 (Waddington et al., 2007). Since maize stover was not sold, the same ratio was used to derive the market price of maize stover. Accordingly, the market price of maize stover was US$ 0.04 kg^{-1} in the 2009/10 season and US$ 0.06 kg^{-1} in the 2010/2011 season.

3.1.6. Statistical analysis

A non-parametric Kendall tau-b correlation coefficient was used to analyse for the significance of time series trends in total annual seasonal rainfall, number of rain days per season and date of the beginning of the rainy season. The Mann-Kendall test has the capability to detect both linear and non-linear trends, and has been used in related studies in Zimbabwe and other parts of sub-Saharan Africa (Mazvimavi, 2010). The median was used to determine the date of the start of the rainy season. This median measure is relatively unaffected by extreme values. A generalized linear fixed model (GLFM) was used to test for significance of the effects of planting date (tested against main plot residuals), cultivar, fertility, season and the two-way, three-way and four-way interactions on leaf area, stover yield, harvest index and maize grain yield in GenStat version 14. All four factors (planting date, fertility, cultivar and season) were included as fixed factors.

3.1.7. Probability assessment of household food self-sufficiency and financial returns to fertilizer investment

To determine the probabilities of food self-sufficiency and financial returns to fertilizer investment, the relationship between rainfall and observed yield, per planting window for the two experimental seasons, was analysed. Regression analysis was used to determine the strength of the relationship between the variability in rainfall across seasons and planting dates and yield at each fertilization rate (Fig. 3.3). Because the cultivar yields were not significantly different, the best yield performing cultivar (SC635) was used in this analysis. In this analysis we assume that the differences in yield between the planting dates are caused by differences in rainfall amounts that the crop received. Water availability is generally seen as the most important factor explaining variations in maize yield, not only because of the relative low amount of rain that falls in a season but also because the water holding capacity of these granite-derived sandy soils is poor (Hussein, 1987; Nyamapfene, 1989). Using this rainfall – yield relationships (Fig. 3.3), yields were estimated for the 48 year rainfall dataset (1962-2009), and based on these yields the consequences for food self-sufficiency and financial returns to fertilizer investment were estimated. Food self-sufficiency was calculated as the ratio between farm production and the energy required for household consumption, expressed as a percentage. Sufficient dietary energy for a household of six is 3.9×10^6 kcal per year, equivalent to 1.2 t of maize (FAO, 2009). A regression statistical model was used in this analysis because it is robust and simple (Lobell and Burke, 2010). Although a similar analysis could be done using a crop simulation model such as APSIM (McCown et al., 1996), the large volume of data required for parameterisation limits the use of such models, particularly in Africa where data is scarce (Knox et al., 2012). Lobell and Burke (2010) investigated the usefulness of regression models against simulation models to predict crop yield response to weather and climate data and concluded that results from simple statistical models are consistent with studies that used process-based models.

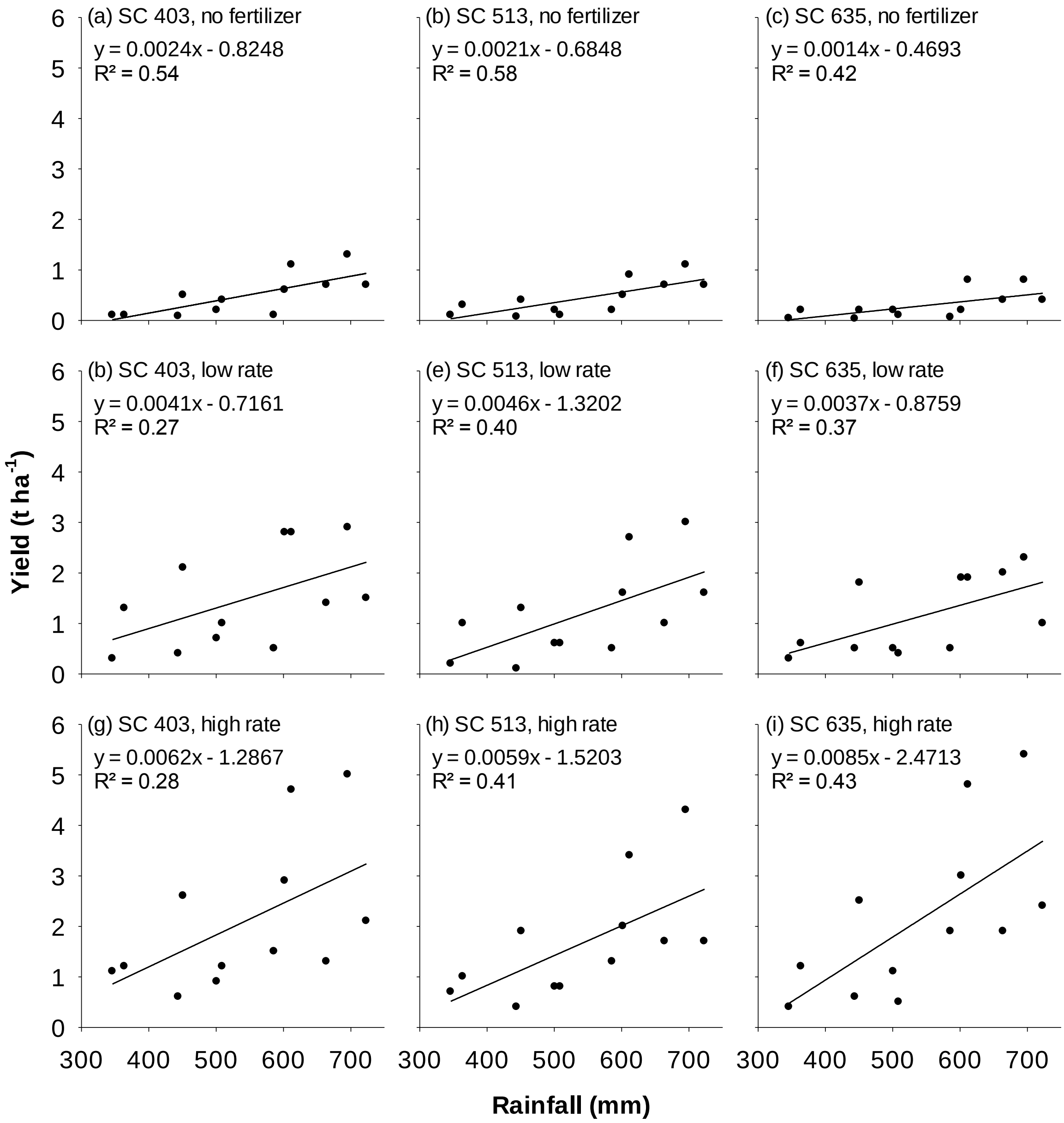

Fig. 3.3. Relation between rainfall and maize cultivar yield for different fertilization rates. Low rate: 35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure; and high rate: 90 kg N ha^{-1}, 26 kg P ha^{-1}, 7 t ha^{-1} manure.

3.2. Results

3.2.1. Seasonal rainfall patterns in the study sites

More than 90% of farmers perceived that the climate had changed with increased rainfall variability characterized mainly by late on-set of rainfall and prolonged season dry spells (Table 2.2). Less than 10% of farmers observed changes in the total amount of rainfall per season (Table 2.2). The number of rain days per season had decreased with time, $\tau = -.234$, $P < .05$, whereas the mean annual total rainfall had not changed, $\tau = -.021$, $P > .05$ (Fig. 3.4A(a and b)). The mean median value for the date of the start of the rainy season was 8 November (S.D. = ±14), and did not change significantly ($\tau = .104$, $P > .05$) for the period 1962 - 2009 (Fig. 3.4A(c)). However, the date of the start of the rainy season varied widely from the 16th October to 23rd December. The date of the start of the rainy season was negatively correlated with the length of rainy season ($\tau = -.365$, $P < 0.05$) (Fig. 3.4A(d)).

A Markov chain model fitted the daily rainfall data ($R^2 = 0.81$, F = 389.73, P = 0.0000), and the regression coefficients were significant (P < 0.001, ANOVA table not shown). This model showed that the probability of season dry spells of more than 7 days in the period between end of January to early February had increased to more than 0.4 for the period 1990 - 2009, compared with less than 0.3 for the period 1962 - 1989 (Fig. 3.4B(c and d)). The increase in dry spells during this period, which is the critical flowering stage of most of the crops in Zimbabwe, could have a profound impact on crop production. Compared with the long-term average of 16 rainy pentads per season in Hwedza, about 75% of the seasons between 1986 and 2010 had rainy pentads of < 16 (Fig. 3.4B (a)), suggesting deterioration of season quality due to poor intra-seasonal rainfall distribution.

Table 2.2. Farmer perceptions of rainfall patterns in Makoni and Hwedza with respect to climate variability and change in Zimbabwe

Site	Farmers' perceived changes in season rainfall patterns (*n* = 100 in each site)			
	Increased rainfall variability (%)	Late on-set of rains (%)	Prolonged season dry spells (%)	Reduced amount of total rainfall (%)
Makoni	62	34	17	12
Hwedza	73	37	11	8

Note: The overall percentage exceeds 100 due to multiple responses.

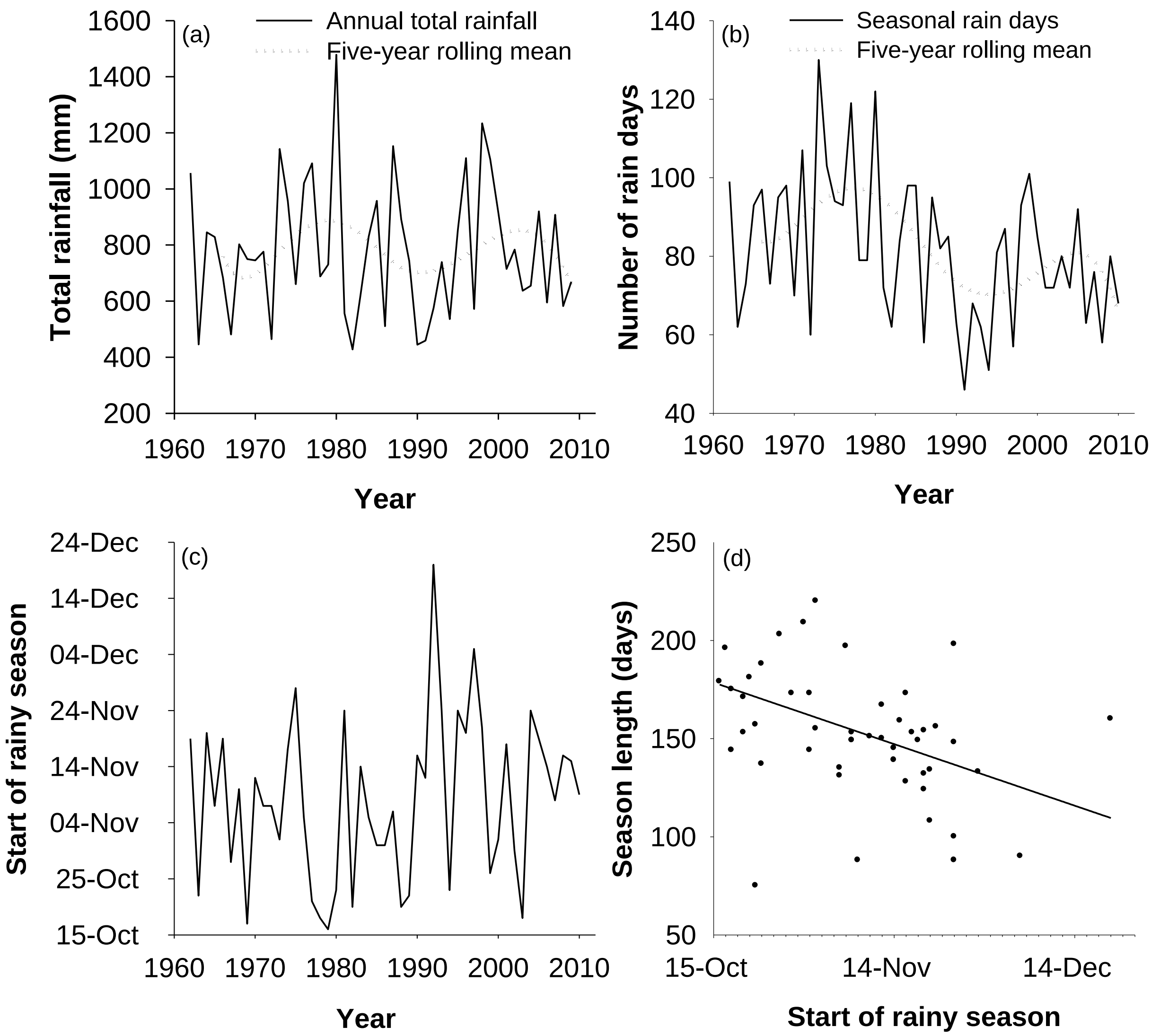

Fig. 3.4A. Rainfall analysis outputs for 48 years (1962 – 2009) in Hwedza: (a) variation in annual total rainfall (tau-b = -.021, P = .831), (b) number of rain days per season (tau-b = -.234, P = .017), (c) date of start of season (using 48 mm in at least two rainy days out of ten consecutive days) (tau-b = .107, P = .296), (d) Relationship between date of the start of rainy season and length of rainy season (tau-b = -.365, P = .003).

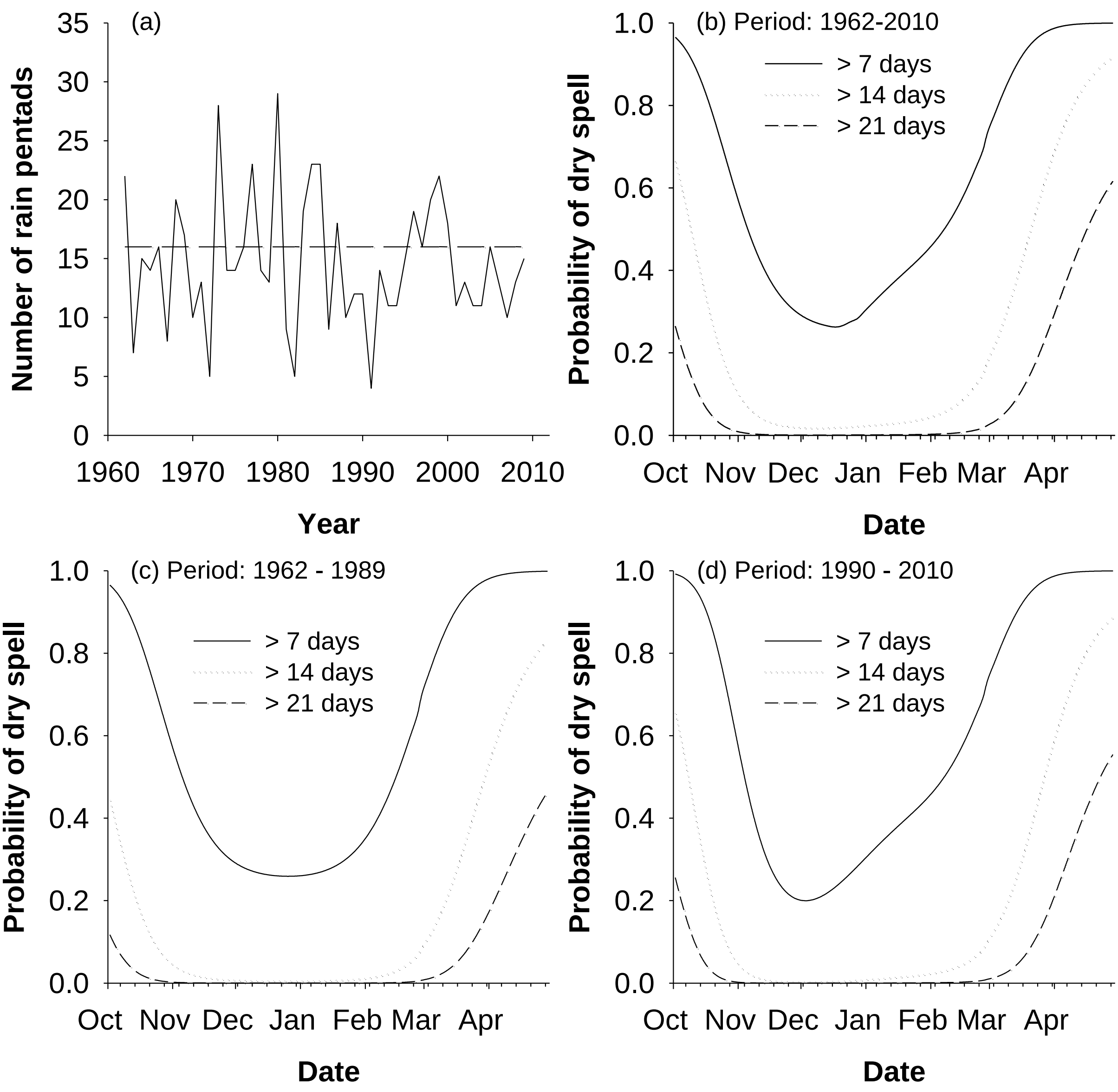

Fig. 3.4B. Rainfall analysis outputs for 48 years (1962 – 2009) in Hwedza: (a) number of rainy pentads per growing season (16 pentads indicated by the dashed line is the threshold for a good rainfall distribution within a season, and also is the long-term average for Hwedza), (b) probability of dry spells per growing season for period 1962 - 2009, (c) probability of dry spells per growing season for period 1962 - 1989, (d) probability of dry spells per growing season for period 1990 – 2009.

3.2.2. *Crop development influenced by cultivar*

The cultivars were similar in canopy development or grain yield for each planting date-fertilization combination. Leaf area indices (LAIs) for the low and high fertilization rates were similar, but larger than for the unfertilized maize in both study sites (Fig. 3.5). Overall, LAI did not exceed 2.0, regardless of the amount of fertilizer applied in both study sites (Fig. 3.5).

Although grain yields among cultivars were similar, grain yields for the early maturing cultivar (SC513) were relatively poor (e.g. < 2 t ha^{-1} in Hwedza) particularly for the high fertilization rate for early and normal plantings at both study sites (Fig. 3.6). The relatively poor performance of SC513 was attributed to poor crop emergence. There was no interaction between planting date and cultivar on maize grain yield. There was a significant interaction between cultivar and fertility in Makoni, the site with relatively fertile soils, whereas in Hwedza, the site with less fertile soils, the interaction was not significant (Table 3.3). The weak interaction in Hwedza was probably because the cultivars could not express their yield potential due to poor soil fertility conditions (see Table 3.1). This was demonstrated by the reduced yield differences between the low fertilization and high rates in Hwedza compared with Makoni.

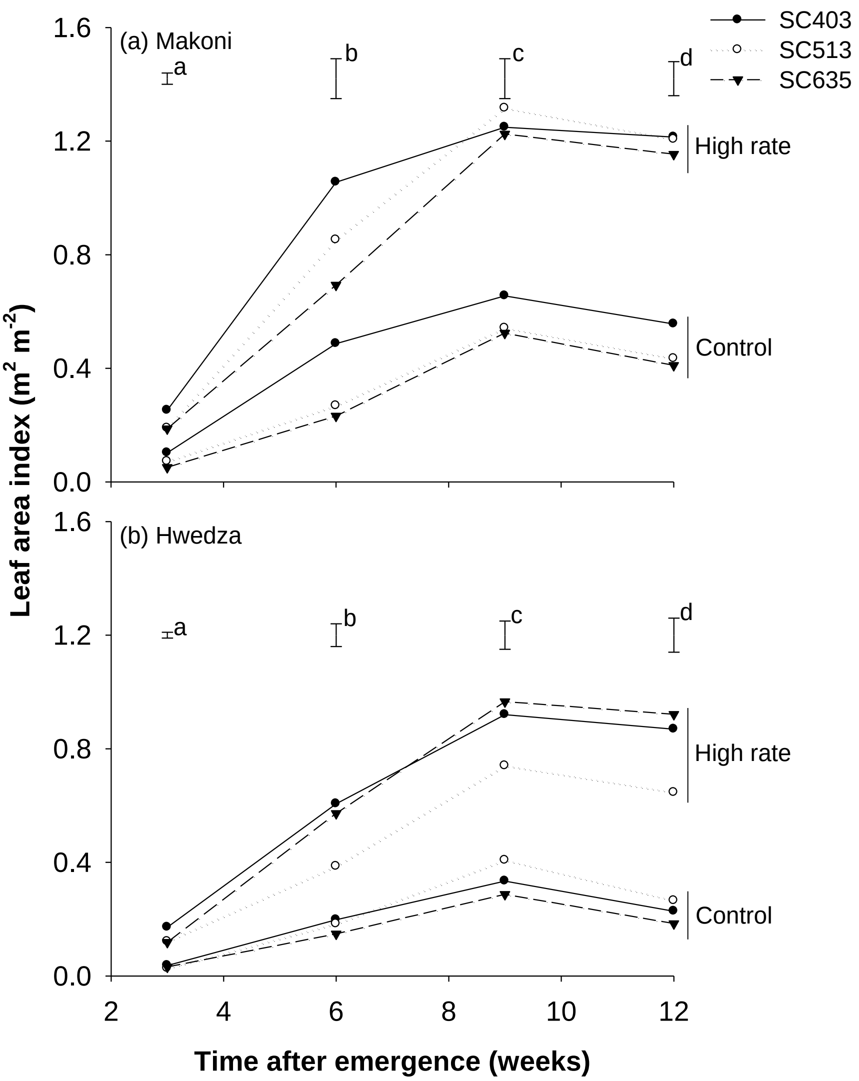

Fig. 3.5. Leaf area index (LAI) for early planted maize cultivars for high fertilization rate and for unfertilized cultivars in (a) Makoni and (b) Hwedza in the 2009/10 season. LAI under low fertilization rate is not shown because the data was similar to that of high rate. Error bars represent SED at different time intervals.

3.2.3. Influence of planting date and fertilization rate on maize grain yield

Maize grain yields for the early and normal planted cultivars were similar for each fertilization rate, (e.g. on average 5 t ha^{-1} in Makoni, and 3 t ha^{-1} in Hwedza for the high fertilization rate). Maize yields, however, decreased by > 50% when planting was delayed by about 4 weeks (late planting), regardless of the amount of nutrients applied (Fig. 3.6). There was an interaction between planting date and fertilization rate on maize grain yield (P <0.05). Similarly, there was a significant interaction between fertilization and season in both sites (P <0.05).

Across the planting dates, maize yielded more grain under high fertilization rate than for low rate (P <0.05), but the yield increased much more with fertilization of the early and normal plantings for all cultivars at both study sites (Fig. 3.6). Yields ranged between 3.5 t ha^{-1} and 5.4 t ha^{-1} for the high fertilization rate compared with 2.0 t ha^{-1} - 3.0 t ha^{-1} for the low rate, in the 2009/10 season in Makoni (Fig. 3.6a). The yields on poorer soils in Hwedza ranged between 2.0 t ha^{-1} and 3.0 t ha^{-1} for the high fertilization rate compared with 1.2 t ha^{-1} and 2.8 t ha^{-1} for the low rate (Fig. 3.6c). Grain yields for the unfertilized cultivars were < 1 t ha^{-1} on average in both seasons at both sites (Fig. 3.6). The effect of fertilization on maize grain yield decreased drastically for the late plantings in both sites. Maize grain yields for all the late-planted cultivars were < 1 t ha^{-1}, regardless of fertilization rate. Maize stover yield responded strongly to fertilization and planting date, but there was no overall significant difference between cultivars (Fig. 3.7). Maize harvest index was different for each of the three factors: cultivar, planting date and fertilisation rate in both sites and seasons (Fig. 3.8).

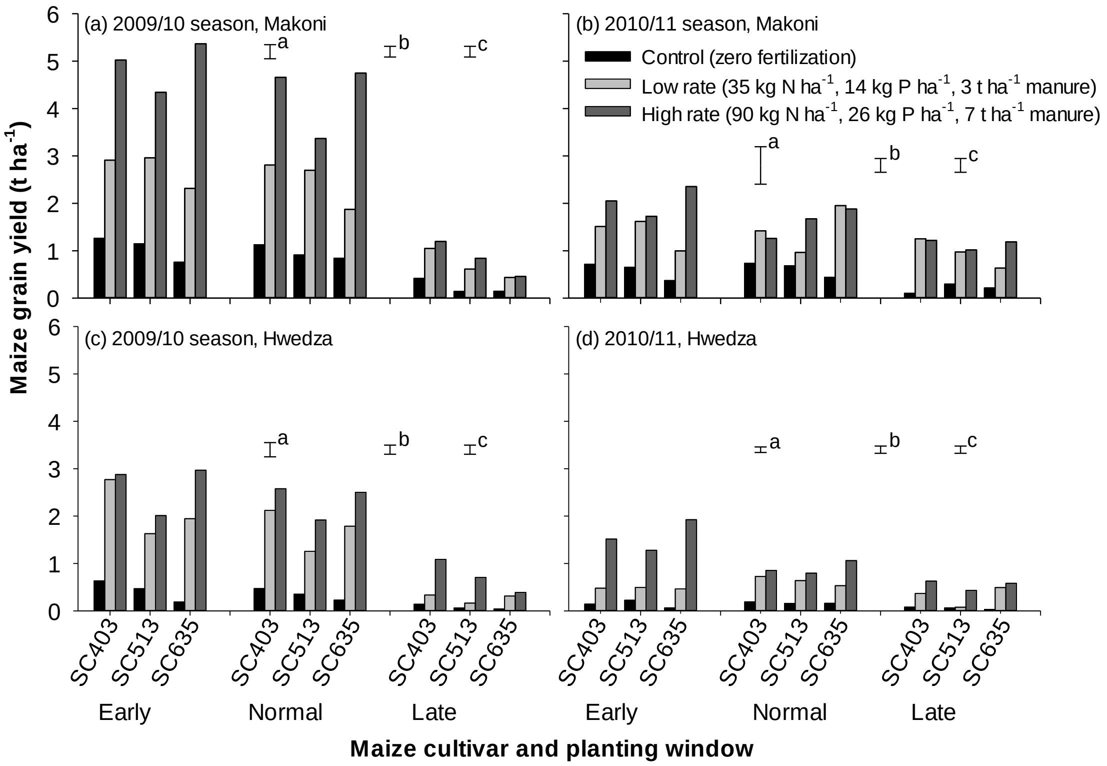

Fig. 3.6. Maize grain yield in response to cultivar, planting date, and fertilization rate for (a) 2009/10 and (b) 2010/11 seasons in Makoni; and for (c) 2009/10 and (d) 2010/11 seasons in Hwedza. Error bars represent SED for a = time of planting, b = fertilization rate, c = crop cultivar.

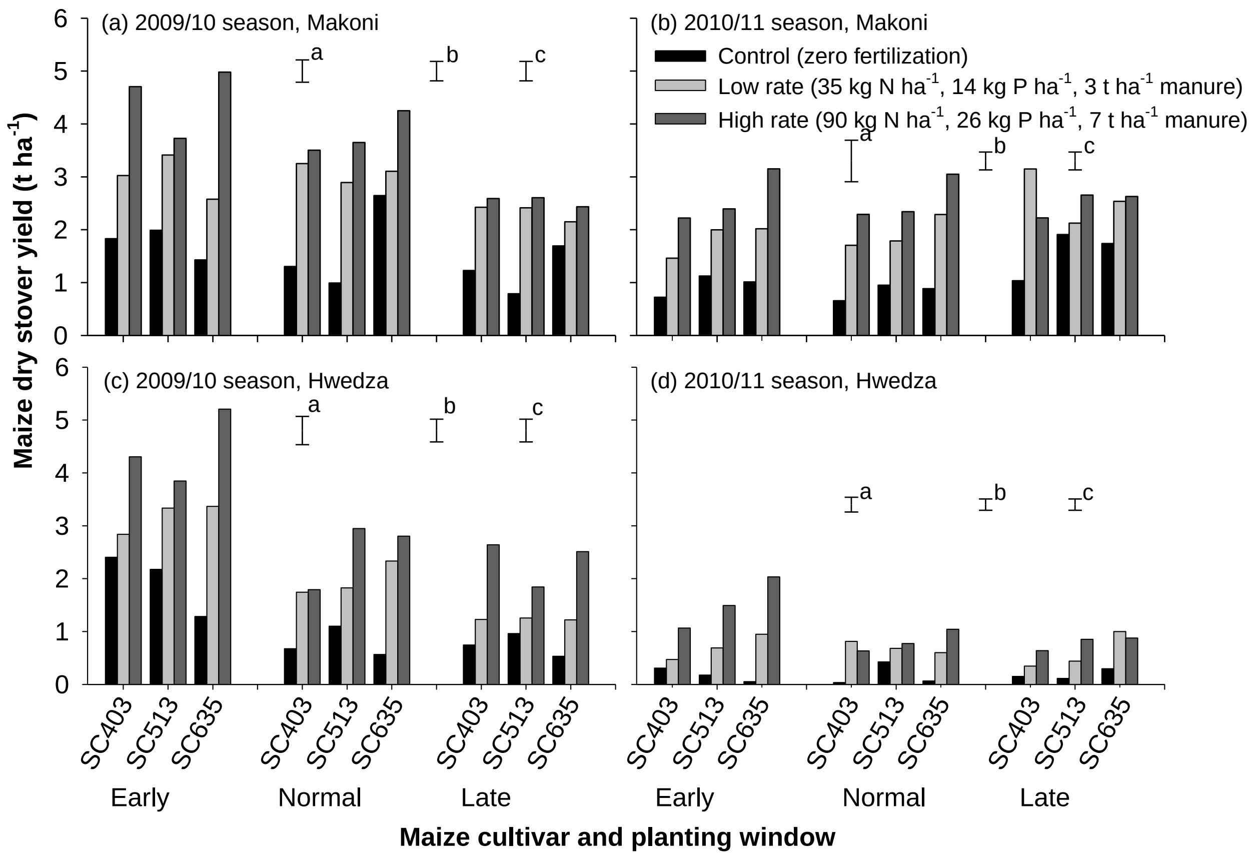

Fig. 3.7. Maize dry stover yield in response to cultivar, planting date, and fertilization rate for (a) 2009/10 and (b) 2010/11 seasons in Makoni; and (c) 2009/10 and (d) 2010/11 seasons in Hwedza. Error bars represent SED for a = time of planting, b = fertilization rate, c = crop cultivar.

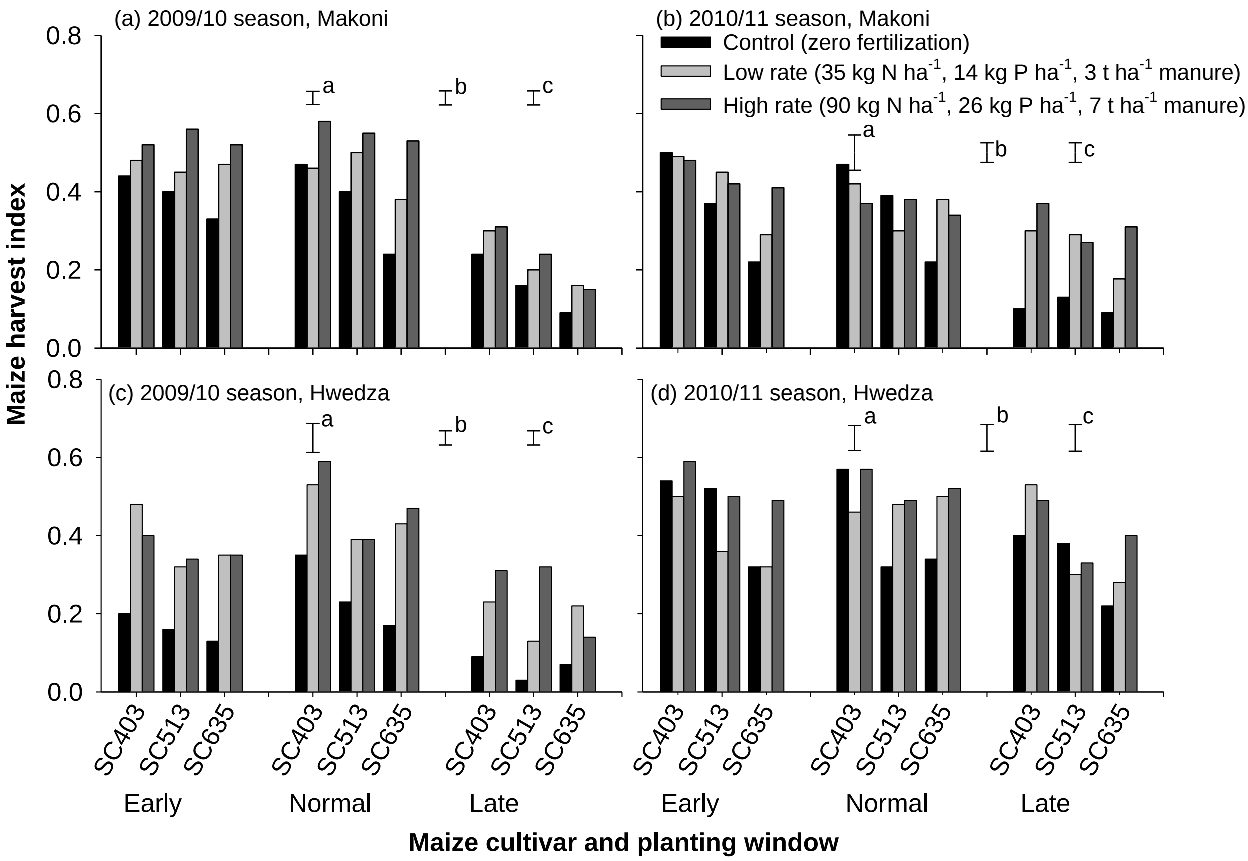

Fig. 3.8. Maize harvest index in response to cultivar, planting date, and fertilization rate for (a) 2009/10 and (b) 2010/11 seasons in Makoni; and (c) 2009/10 and (d) 2010/11 seasons in Hwedza. Error bars represent SED fora = time of planting, b = fertilization rate, c = crop cultivar.

Table 3.3. Probability of *F* responses of total dry matter, harvest index and grain yield in Makoni and Hwedza

Effect	Variable		
	Total dry matter	Harvest Index	Maize grain yield
Makoni			
Planting date (P)	0.190	0.002	0.003
Fertility (F)	<0.001	<0.001	<0.001
Cultivar (C)	0.059	<0.001	0.108
Year (Y)	<0.001	0.002	<0.001
P × F	0.016	0.548	<0.001
P × C	0.432	0.994	0.812
F × C	0.256	0.071	0.017
P × Y	<0.001	0.005	<0.001
F × Y	0.123	0.769	<0.001
C × Y	0.389	0.828	0.266
P × F × C	0.196	0.378	0.540
P × F × Y	0.836	0.022	<0.001
P × C × Y	0.691	0.079	0.821
F × C × Y	0.250	0.973	0.193
P × F × C × Y	0.542	0.172	0.076
Hwedza			
Planting date (P)	0.004	0.007	0.004
Fertility (F)	<0.001	<0.001	<0.001
Cultivar (C)	0.062	<0.001	0.058
Year (Y)	<0.001	<0.001	<0.001
P × F	0.004	0.568	<0.001
P × C	0.651	0.931	0.888
F × C	0.042	0.427	0.100
P × Y	<0.001	0.045	<0.001
F × Y	<0.001	0.006	<0.001
C × Y	0.721	0.388	0.381
P × F × C	0.242	0.907	0.118
P × F × Y	0.657	0.425	0.004
P × C × Y	0.608	0.810	0.714
F × C × Y	0.159	0.640	0.993
P × F × C × Y	0.770	0.475	0.943

3.2.4. Effects of within-season rainfall patterns on maize grain yield

Although the total rainfall was comparable between the 2009/10 and 2010/11 seasons (see Fig. 3.2), the resulting maize yields differed widely. In the 2010/11 season, all the maize cultivars yielded much less for each planting date-fertilization combination. This decrease was attributed to poor rainfall distribution. Initially the late on-set of effective rains led to a delay in planting of the early crop. Then severe waterlogging for two weeks was followed by a prolonged mid-season dry spell of 3 weeks in the second half of the cropping season (see

Fig. 3.2). In the 2009/10 season in Hwedza, the longest dry spell of 19 days occurred in January, which farmers considered common. But in the 2010/11 season the longest dry spell of 24 days in Makoni and 21 days in Hwedza occurred in February (see Fig. 3.2), coinciding with the critical flowering period of maize. Analysis of dry spells over 48 years indicated that 15 out of 48 years had similar rainfall patterns to 2010/11 season characterised mainly by a prolonged dry spell of >20 days in February. This suggests that farmers experience such rainfall patterns once in every three years.

The financial returns were positive for both seasons when high amount of fertilizer was used although greater returns were obtained in a relatively good rainfall season (Table 3.4). Analysis of the long-term yield estimates indicated that without fertilization the probability of achieving household food self-sufficiency was low, less than 0.05, even when the crop was planted early (Table 3.5). With fertilization the probability of achieving food self-sufficiency increased to about 0.6 for the low rate and 0.8 for the high rate for early and normal plantings (Table 3.5). When planting was delayed by 4 weeks the probability of food self-sufficiency decreased, independent of fertilization rate (Table 3.5). The probability of positive financial returns to fertilizer investment was about 0.6 for both the low and high fertilization rates, when the crop was planted in the early and normal windows (Table 3.5). The probability of negative financial returns was larger when the planting of the maize crop was delayed by 4 weeks (Table 3.5).

3.3. Discussion

3.3.1. Rainfall patterns and implications for the maize production

The long-term rainfall analysis closely supports farmers' perceptions that the mean annual rainfall has not changed, whereas marked changes in the pattern of rainfall within the season have occurred. The number of rain days has decreased, and the frequency of dry spells within the season has increased, which support farmers' perceptions. This suggests that heavier rain storms are occurring, which is consistent with the IPCC (2007) projections for southern Africa. Our results are consistent with those of Tadross et al. (2009) who found that the frequency of rain days has decreased, whereas the length of season dry-spells has increased in some parts of southern Africa. Chamaillé-Jammes et al. (2007) reported that droughts have worsened in north-western Zimbabwe during the 20th Century, while Mazvimavi (2010) reported that the mean annual total rainfall in Zimbabwe has not changed. However, Unganai (1996) and Hulme et al. (2001) concluded that the mean annual rainfall has decreased in Zimbabwe and other parts of southern Africa.

Farmers' perception that the onset of the rains has been delayed was not supported by long-term rainfall records. The long-term median has not changed significantly (see Fig. 3.4A (c)). Mismatches between farmers' perceptions and rainfall records have been reported elsewhere, and may be due to analytical challenges in detecting minor changes because of large inter-annual variability in the date of the onset of rainfall (Chamaillé-Jammes et al., 2007; Stern and Cooper, 2011). Stern and Cooper (2011) reported that farmers in southern Zambia overrated the risk of climate events. Mazvimavi (2010) also argued that human perceptions of climate variability and change may be influenced by their comparison of extreme climatic events such as comparing droughts to wet seasons. However, in both the 2009/10 and 2010/11 experimental seasons the onset of rains was evidently delayed, supporting farmers' recent experiences.

3.3.2. Soil fertility as an overriding factor for crop production

Fertilization led to a large increase in maize grain yield. However, the fertilization response showed a strong interaction with the year in which the experiment was conducted. In the 2009/10 season, which experienced relatively good rainfall, yields for the unfertilized maize cultivars were poor (< 1 t ha^{-1} on average) regardless of planting date. With fertilization, however, yields for early and normal planted cultivars increased three-fold (3.6 t ha^{-1}) in Makoni, and five-fold (2.1 t ha^{-1}) in Hwedza. Under the relatively poor rainfall of the 2010/11 season, the application of fertilizer increased yield by only 1.2 t ha^{-1} in Makoni and 1.0 t ha^{-1} in Hwedza. This decrease in response was due to lack of soil moisture caused by erratic rainfall and prolonged dry spells of up to 24 days in Makoni and 21 days in Hwedza. The impact of the dry spells was large because they coincided with the critical flowering stages of the maize cultivars (see Fig. 3.2). The effectiveness of fertilizer therefore varies drastically from year to year, depending on the rainfall distribution.

Overall for both years studied, soil fertility was the most limiting factor for maize production at early and normal plantings as demonstrated by the large yield gap between the unfertilized and fertilized cultivars in each season (> 1.2 t ha^{-1}). This suggests that soil fertility management is still effective for yield improvement in relatively bad rainfall years and can reduce the impact of dry spells on food security. The importance of soil fertility management to mitigate dry spells was also reported in Kenya for maize production, and Burkina Faso for sorghum (Rockström, 2004). Similarly, Klaij and Vachaud (1992) found that soil fertility was more limiting than rainfall for production of pearl millet, even under much drier conditions in west Africa. In addition to increasing the availability of nutrients for plant uptake, organic fertilizers may increase plant-available water due to increased infiltration and water retention (Nyamangara et al., 2001). A combination of increased plant nutrient uptake and water use increases crop growth and development due to increased physiological activities such as transpiration, nutrient translocation and photosynthesis (Adamtey et al., 2010). More rapid maize growth was observed in the fertilized treatments compared with the unfertilized ones as indicated by leaf area index and dry matter production (see Figs. 3.5 and 3.7). Given the widespread occurrence of arenosols across southern Africa (Hartemink and Huting, 2008), soil fertility management is of paramount importance for crop production.

Yields were reduced strongly when planting was delayed by 4 weeks (late planting) regardless of the amount of fertilizer applied. The poor yields were due to both poor biomass accumulation (Fig. 3.7) and poor grain filling as indicated by the low harvest index (Fig. 3.8). This was partly caused by lack of soil moisture, given that late plantings led to extension of the growing period into the dry season. Shortening of day length and lowering of temperatures are other factors that could affect the yields when maize is planted late (Waddington and Hlatshwayo, 1991). Greater maize grain yields were obtained with both the early and normal plantings, with no significant differences between these planting windows. This contrasts with earlier research that reported a maize grain yield reduction of about 2.3% per day of delay in planting between mid-November and mid-December in Zimbabwe (Shumba, 1989) , most likely because these studies ignored the role of soil fertility. Planting earlier increases the length of time that plants can take advantage of favourable rainfall and temperature growing conditions and early growing season flushes of nutrients (Kamara et al., 2009).

The similar performance of cultivars was mainly due to narrow differences in time to maturity between the available cultivars. A very early cultivar (SC403) and a medium cultivar (SC635) differ in maturity by only 11 days. Dry spells longer than 14 days were observed in both seasons. As the length of the dry spells is longer than the difference in time to maturity, the differences among the cultivars may be insufficient to result in different responses to the same dry spell.

3.3.3. Marginal returns and food self-sufficiency

The financial returns were positive for both seasons when high amount of fertilizer was used although greater returns were obtained in a relatively good rainfall season. Better gross margins of 59% (US$ 1652 earned per US$ 696 invested) in Makoni and 32% (US$ 1025 earned per US$ 696 invested) in Hwedza were obtained in a relatively good rainfall season (2009/10) against 29% (US$ 880 earned per US$ 629 invested) in Makoni and 6% (US$ 700 earned per US$ 660 invested) in Hwedza in a bad rainfall season (2010/11) (Table 3.4). The long-term yield analysis showed that with fertilization the probability of positive marginal returns would be more than 0.5, even when small amounts of fertilizer are applied. However, regardless of the amount of fertilizer applied, the probability of negative returns is on average 0.3 when maize is planted between early and normal windows. The benefits of adding fertilisers, however, can be enhanced by improved forecasting of rainfall patterns within the growing season to inform farmers when to apply fertilizers and in what amount (Piha, 1993).

The probability of a household achieving food self-sufficiency was greater, >0.8 for the high fertilization rate, when maize was planted early or during the normal window (Table 3.5). Even with the application of small amounts of fertilizers, the probability of food self-sufficiency was >0.5. The importance of applying small amounts of fertilizers to increase household food security has also been highlighted for arid regions (Twomlow et al., 2010). However, despite the use of fertilizers there is still a risk of household food insecurity in these rainfed smallholder farming systems. This is logical because farmers sometimes experience very poor rainfall seasons such as 1963/64, 1972/73, 1983/84 and 1991/92 (approximately 1 in every nine years) with a total rainfall of <480 mm (Fig. 3.4A), the minimum rainfall required to achieve economically acceptable yields in Zimbabwe (Unganai, 1990). To overcome these low rainfall seasons, farmers would have to maximize crop production during favourable rainfall conditions such as the 2009/10 season. Based on the results obtained with long-term yield analysis, it should be possible for farmers to compensate for drought years by storing food produced in good years, provided they use fertilizers (see Table 3.5). The strategy of storing surplus grain after favourable rainfall for future use against droughts is used in other parts of Southern Africa (Milgroom and Giller, 2013). However, without fertilization the probability of not achieving food self-sufficiency would be close to one even in a good rainfall year such as the 2009/10 season. This suggests that resource constrained farmers who apply little fertilizer rarely achieve food self-sufficiency (e.g. Eldridge, 2002).

Table 3.4. Gross margin when both low rate (LR) and high rate (HR) of fertilization was used in Makoni and Hwedza for the 2009/10 and 2010/11 seasons

		2009/10 season				2010/11 season			
		Early planting		Late planting		Early planting		Late planting	
Site / Variable	Unit	LR	HR	LR	HR	LR	HR	LR	HR
Makoni									
Maize grain yield	t ha^{-1}	2.7	5.4	1.0	1.2	1.6	2.4	1.3	1.2
Maize grain market price	US$/t	265	265	265	265	300	300	300	300
Maize stover yield	t ha^{-1}	3.0	5.0	2.3	2.5	2.0	3.2	2.5	2.6
Maize stover market price	US$/t	44	44	44	44	50	50	50	50
Gross field benefit	US$/ha	848	1652	367	428	580	880	515	490
Fertilizers cost	US$/ha	185	387	185	387	160	319	160	319
Maize seed cost	US$/ha	55	55	55	55	55	55	55	55
Labour total cost	US$/ha	219	254	219	254	219	254	219	254
Total variable cost	US$/ha	459	696	459	696	434	628	434	628
Gross margin	US$/ha	389	956	-92	-268	146	252	81	-138
Hwedza									
Maize grain yield	t ha^{-1}	2.6	3.0	0.3	1.1	0.5	2.0	0.5	0.6
Maize grain market price	US$/t	265	265	265	265	300	300	300	300
Maize stover yield	t ha^{-1}	3.1	5.2	1.2	2.2	0.7	2.0	0.6	0.8
Maize stover market price	US$/t	44	44	44	44	50	50	50	50
Gross field benefit	US$/ha	826	1025	133	389	185	700	180	220
Cost of fertilizer	US$/ha	185	387	185	387	173	351	173	351
Cost of maize seed	US$/ha	55	55	55	55	55	55	55	55
Cost of labour (manure)	US$/ha	219	254	219	254	219	254	219	254
Total variable cost	US$/ha	459	696	459	696	447	660	447	660
Gross margin	US$/ha	367	329	-327	-307	-262	40	-267	-440

Table 3.5. Probabilities of households achieving food self-sufficiency and marginal returns for different time of planting (EP – early planting, NP – normal planting, LP-late planting) and varied amounts of fertilization (control - zero fertilization; low rate - 35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure; high rate - 90 kg N ha^{-1}, 26 kg P ha^{-1}, 7 t ha^{-1} manure) for the long-term rainfall-yield response data

Variable	Category	Control			Low rate			High rate		
		EP	NP	LP	EP	NP	LP	EP	NP	LP
Household food self-sufficiency	<75	0.86	0.92	0.98	0.16	0.22	0.33	0.06	0.12	0.24
	75 - 100	0.10	0.04	0.00	0.16	0.22	0.31	0.08	0.06	0.10
	100 - 125	0.04	0.04	0.02	0.14	0.14	0.10	0.02	0.04	0.02
	>125	0.00	0.00	0.00	0.53	0.41	0.27	0.84	0.78	0.63
Marginal returns (%)	<0	-	-	-	0.27	0.39	0.57	0.27	0.41	0.57
	0-50	-	-	-	0.53	0.47	0.35	0.51	0.45	0.35
	>50	-	-	-	0.20	0.14	0.08	0.22	0.14	0.08

3.3.4. Potential entry points to adapt to climate variability and change in rain-fed cropping

The delayed on-set of rainfall with no change in the date of the end of rainy season (Fig. 3.4A) indicates that the window of planting is shortening. This delayed planting in combination with draught power shortages (Table 3.6) are likely to result in farmers planting more of their crop late in the season. For instance, for a farmer with a span (oxen team), it will take on average 10 days to plough 1.5 ha based a ploughing rate of 0.15 ha per day (Francis and Ndlovu, 1995). Farmers without oxen (about 50 % of the farmers) will therefore be automatically delayed in their planting by a minimum of 10 days, which brings them close to the normal planting window already. For farmers who do not have strong social connections with farmers who own oxen, the delay will be even longer. None of the varieties tested in this study were capable of compensating for the negative effects of late planting on productivity. Overall, the three cultivars resulted in similar grain yields, but at late planting the long duration variety SC635 yielded significantly less than the short duration varieties. Thus if farmers are forced to delay planting it is preferable to use early maturing cultivars. However, with the projected decrease in rainfall coupled with increased negative impact of temperature on crop production in Zimbabwe by 2030 (Unganai, 1996; Burke et al., 2009) such cultivars will be insufficient to stabilize yields. The only option available seems to be to diversify the range of crops grown. In the short-term diversification of crops will help to spread climatic risk across the farm. Crops such as small grains (e.g. finger millet) that had traditionally been used by farmers to stabilize household food in times of climatic shocks need to be included again. In the long-term, breeding for rapidly maturing maize cultivars may be an option, though this will curtail potential yield in good seasons. Cultivars with time to maturity of < 130 days were recommended in some parts of southern Africa (Tadross et al., 2009). Other options are related to soil management.

Table 3.6. Sources of draught power in smallholder farming areas in Makoni and Hwedza

Site	Sources of draught power (% farmers: *n* =100 in each site)					
	Own draught power	kinship	Neighbour	Barter trade	Hire	*Humwe*[a]
Makoni	60	18	2	4	6	4
Hwedza	51	25	9	6	10	8

Note: The overall percentage exceeds 100 because of multiple responses.

[a] *Humwe* refers to a local custom in which a community collectively provides labour to a fellow farming household irrespective of wealth and social status, to hasten critical and time-bound farming operations such as ploughing, weeding and harvesting. The *humwe* can be as a result of a distress call by the beneficiary member or a local leadership initiative. The host farmer provides food and beverages for energy, and as a token of appreciation to fellow farmers.

In the past farmers practiced winter ploughing (Shumba et al., 1992) with the dual objectives of reducing draught power requirements when the season starts, and conserving soil moisture that would overcome the problem of ‘false starts’ to the season and increase the success of early planting. Most farmers, however, no longer practice winter ploughing due to the perceived increased rainfall variability. Farmers recalled that they used to receive rainfall in three events before the crop growing season begins, which were used to winter plough: first one in June (namely *gukurahundi* in local Shona language), the second one in August (*bvumiramitondo*) and the third one in September (*bumharutswa*). These rainfall events are now perceived to be erratic and unreliable, making it difficult for farmers to plough when the soil is too hard. The long-term rainfall analysis for Hwedza indicated a decreasing trend in winter rainfall, but the trend was not significant (data not shown). Other studies, however, have reported a decline in winter rainfall in southern Africa including Zimbabwe (e.g. Hulme et al., 2001).

Soil fertility management, however, proved to be an entry point to buffer maize yields against emerging rainfall patterns. Maize yields > 1 t ha^{-1} were obtained in a relatively poor 2010/11 rainfall season when soil fertility was improved. Farming systems survey indicated that farmers allocate on average 2 ha of land to maize. This means the yield of 1 t ha^{-1} would be translated into 2 t $farm^{-1}$, sufficient to provide energy intake for a family of six for 12 months (FAO, 2009). The different fertilization rates used in this study can enable farmers to select a 'best fit' option depending on their specific socioeconomic and biophysical conditions. Poor farmers could use the low rate of fertilization and be able to produce sufficient food for household consumption, whereas the wealthier farmers can afford to use the high rate to maximize yield and produce for the market. The impact of soil fertility decreased when planting was delayed by 4 weeks (late planting) suggesting that farmers need to plant by mid-December to create economic yield benefits for increased investment in fertilization.

There was a large yield gap (about 70%, average for early and normal plantings) between farmers' fields (Table 3.7) and the experiment (Fig. 3.6) in a good 2009/10 rainfall season. Because farmers planted more maize between early and normal windows than the late window (Table 3.7), the poor yields from farmers' fields were mainly due to lack of nutrient inputs rather than rainfall. Farmers applied on average 32 kg N ha^{-1} and <4 kg P ha^{-1} and <4 kg K ha^{-1} from mineral fertilizers (Table 3.7) compared with the recommended rates of 120 kg N ha^{-1}, 30 kg P ha^{-1} and 25 kg K ha^{-1} in Zimbabwe (Zingore et al., 2007). The use of low fertilizer rates at early and normal planting is mainly due to difficulty in accessing fertilizer and the prohibitive costs (Nyikahadzoi et al., 2012). Farmers indicated that they use less fertilizer on late planted crops because of the anticipated poor yields. The main source of P and K in farmers' fields is manure. To apply sufficient P farmers need to use about 10 t ha^{-1} manure compared with the current rate of 5 t ha^{-1} (see Table 3.7). Accordingly, the amount of manure available to farmers is insufficient to meet the recommended rates, particularly for P. Given that more than 40% of smallholder farmers do not own cattle (see Table 3.6), the main source of manure, the prospects for improving soil fertility depend on how access to fertilizer can be improved. The scope for increasing the number of cattle in these smallholder communities is limited due to lack of pastures because of the shrinking of grazing due to increased population pressure on land (Rufino et al., 2011). Given that soil fertility management is critical for increased yields, forming or strengthening existing farmer groups may be a helpful strategy to increase their collective ability to acquire fertilizer in time and perhaps at a reduced cost.

Table 3.7. Relative size of land planted to maize (per household) by farmers (*n* = 30 in each site) during different planting windows (a: early, b: normal, c: late), and rates of soil nutrient inputs, and maize grain yields in Makoni and Hwedza in the 2009/10 season. Data in parentheses indicate ranges

Site	Area (ha)	Nutrient source							Yield (t ha^{-1})
		Fertilizer			Manure				
		[a]N (kg ha^{-1})	[b]P (kg ha^{-1})	[c]K (kg ha^{-1})	Amount (t ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	
(a) Early planting (25 October - 25 November)									
Makoni	0.8 (0.3-1.4)	32 (7-55)	1.4 (0-11)	0.8 (0-6)	5.3 (0-10)	42 (0-80)	16 (0-30)	32 (0-60)	2.9 (0.8-4.0)
Hwedza	0.3 (0-3.5)	13 (0-35)	0	0	0.3 (0-2)	2 (0-11)	0.8 (0-5)	1.5 (0-9)	1.1 (0-3.2)
(b) Normal planting (26 November - 15 December)									
Makoni	0.5 (0-1.2)	45 (35-72)	2 (0-8)	1.3 (0-4)	2.6 (0-4)	21 (0-34)	8 (0-12)	16 (0-25)	3.0 (1.0-3.5)
Hwedza	0.6 (0.3-1.2)	32 (7-43)	1 (0-5)	0.3 (0-3)	2.4 (0-10)	17 (0-70)	7 (0-30)	14 (0-60)	1.3 (0.4-2.5)
(c) Late planting (after 15 December)									
Makoni	0.1 (0-0.2)	4 (0-12)	0	0	0	0	0	0	0.2 (0.4-0.7)
Hwedza	0.4 (0.3-1.0)	46 (28-86)	0	0	2.0 (0-10)	14 (0-70)	6 (0-30)	12 (0-60)	0.8 (0.2-1.0)

[a] N was applied either as compound D basal fertilizer (7% N, 14% P, 7% K) or as ammonium nitrate top dressing (34.5% N) or both.
[b] P was applied as compound D basal fertilizer with composition: 7% N, 14% P, 7% K.
[c] K was applied as compound D basal fertilizer with composition: 7% N, 14% P, 7% K.

3.4. Conclusion

The total seasonal rainfall in eastern Zimbabwe has not changed, over the period from 1962 to 2009, but rainfall variability within the growing season has increased. Although there was an interaction between planting date and fertilization, the greater maize grain yield obtained at early and normal planting dates, suggests a relatively wide planting window providing that soil fertility is improved. This finding is in contrast with earlier research that reported a maize grain yield reduction of about 2.3% per day of delay in planting (Shumba, 1989). Maize grain yield declined profoundly when planting was delayed by 4-5 weeks after the start of the rainy season, regardless of fertilization and cultivar. This suggests that neither soil fertility management nor cultivar selection can compensate for a substantial delay in planting. Although only small differences in response were found between the cultivar maturities groups tested, the projected increase in temperatures and decrease in rainfall by 2100 in southern Africa suggests that different cultivars may be needed in future. Farmers need access to the appropriate fertilizers to increase the probability of household food security. Fertilization and timely planting can increase the probability of household food security. Thus, farmers need to maximize yields during seasons of favourable rainfall so that they can sell or store grain to buffer against drought years. Our findings provide the basis for future analysis of risks of crop production and potential adaptive management to support strategic decision-making in a changing climate.

Chapter 4

Comparative assessment of maize, finger millet and sorghum for household food security in the face of increasing climatic risk

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Abstract

Questions as to which crop to grow, where, when and with what management, will be increasingly challenging for farmers in the face of a changing climate. The objective of this study was to evaluate emergence, yield and financial benefits of maize, finger millet and sorghum, planted at different dates and managed with variable soil nutrient inputs in order to develop adaptation options for stabilizing food production and income for smallholder households in the face of climate variability and change. Field experiments with maize, finger millet and sorghum were conducted in farmers' fields in Makoni and Hwedza districts in eastern Zimbabwe for three seasons: 2009/10, 2010/11 and 2011/12. Three fertilization rates: high (90 kg N ha^{-1}, 26 kg P ha^{-1}, 7 t ha^{-1} manure), low (35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure) and a control (zero fertilization); and three planting dates: early, normal and late, were compared. Crop emergence for the unfertilized finger millet and sorghum was <15% compared with >70% for the fertilized treatments. In contrast, the emergence for maize (a medium-maturity hybrid cultivar, SC635), was >80% regardless of the amount of fertilizer applied. Maize yield was greater than that of finger millet and sorghum, also in the season (2010/11) which had poor rainfall distribution. Maize yielded 5.4 t ha^{-1} compared with 3.1 t ha^{-1} for finger millet and 3.3 t ha^{-1} for sorghum for the early plantings in the 2009/10 rainfall season in Makoni, a site with relatively fertile soils. In the poorer 2010/11 season, early planted maize yielded 2.4 t ha^{-1}, against 1.6 t ha^{-1} for finger millet and 0.4 t ha^{-1} for sorghum in Makoni. Similar yield trends were observed on the nutrient-depleted soils in Hwedza, although yields were less than those observed in Makoni. All crops yielded significantly more with increasing rates of fertilization when planting was done early or in what farmers considered the 'normal window'. Crops planted early or during the normal planting window gave comparable yields that were greater than yields of late-planted crops. Water productivity for each crop planted early or during the normal window increased with increase in the amount of fertilizer applied, but differed between crop types. Maize had the highest water productivity (8.0 kg dry matter mm^{-1} ha^{-1}) followed by sorghum (4.9 kg mm^{-1} ha^{-1}) and then finger millet (4.6 kg mm^{-1} ha^{-1}) when a high fertilizer rate was applied to the early-planted crop. Marginal rates of return for maize production were greater for the high fertilization rate (>50%) than for the low rate (<50%). However, the financial returns for finger millet were more attractive for the low fertilization rate (>100%) than for the high rate (<100%). Although maize yield was greater compared with finger millet, the latter had a higher content of calcium and can be stored for up to five years. The superiority of maize, in terms of yields, over finger millet and sorghum, suggests that the recommendation to substitute maize with small grains may not be a robust option for adaptation to increased temperatures and more frequent droughts likely to be experienced in Zimbabwe and other parts of southern Africa.

Keywords: Climate variability; Climate change adaptation; Crop diversification; Planting date; Nutrient management

4. Introduction

Since its widespread promotion in southern Africa from the 1920s, smallholder farmers have progressively shifted to maize (*Zea mays* L.) as the main cereal crop for household food and income, superseding traditional small grains such as finger millet (*Eleusine coracana* Gaertn.) and sorghum *(Sorghum bicolor* L. Moench) (Byth, 1993; Chidhuza, 1993). Thus, maize has become the most important staple food in the region, even in dry areas (Eicher, 1995). Maize is perceived to have a number of advantages by smallholder farmers. On average, the yields of maize are greater than those of small grains, particularly when the rainfall conditions are favourable (Alumira and Rusike, 2005). The produce market and the low labour demands for weeding, harvesting and processing for maize have been attractive to farmers (Easterling et al., 1992). Maize has also received more attention from breeders than small grains (Alumira and Rusike, 2005; Bänziger et al., 2006).

However, with the projected negative impacts of increasing temperatures combined with more frequent droughts, on crop production in the region (IPCC, 2013), the fundamental question is whether maize production alone will be enough to provide sufficient and stable production to meet food security of many southern African smallholder households. In Zimbabwe, mean daily maximum temperature has increased by about 0.1°C per decade in the last 40 years, and is projected to further increase by between 2^{o}C and 4^{o}C by 2100 (Unganai, 1996). Although rainfall patterns are likely to vary widely from location to location, southern Africa is generally projected to become drier (Shongwe et al., 2009). Unganai (1996) reported that the national average precipitation in Zimbabwe decreased by between 10% and 16% in the crop growing period between 1900 and 1993, and a further decrease in rainfall by similar magnitude is predicted for the year 2100. The frequency of dry spells has also increased in some parts of Zimbabwe particularly in eastern Zimbabwe (Rurinda et al., 2013).

Several modelling studies suggest that maize production is more sensitive to rainfall and temperature changes than other staple cereals such as sorghum and finger millet (Makadho, 1996; Fischer et al., 2005; Knox et al., 2012). Maize yield is projected to decline by about 30% compared with a decrease of only 2% for sorghum by 2030 in southern Africa (Lobell et al., 2008). Sorghum and millets are known to perform better in dry areas than maize (Frere, 1984). Consequently, substitution of small grains for maize has been suggested as a viable adaptation option in the face of climate variability and change (Makadho, 1996; Lobell et al., 2008). The majority of these studies focused on effects of water limitation and did not consider the impact or interaction of nutrients limitations. By contrast, Chipanshi et al. (2003) assessed the impacts of reduced rainfall and increased temperatures on crop production taking into account the effects of soil fertility. They found that yields of both maize and sorghum will decrease by about 33% in the poor soils of southern Africa. This suggests that the extent of the impacts of the changing climate on crop production will vary with location depending on other factors particularly soil fertility. Given this lack of consensus on the magnitude of climate impacts on crop production (Knox et al., 2012), and the variation in predicted rainfall amounts and distributions in most parts of the region (Sivakumar et al., 2005), the recommendation that farmers should replace maize with small grains remains controversial.

A further reason to expand the cropping areas of millet and sorghum is to diversify production. Diversifying production on farms can be a strategy not only to increase production, but also to increase resilience of agro-ecosystems (Van Staveren and Stoop, 1985; Lin, 2011). Current global debates on climate change adaptation options for smallholders need also to consider benefits for human nutrition. Fageria et al. (2008) reported that production of traditional crops such as small grains could be a strategy for reducing micronutrient deficiencies in humans. Finger millet and sorghum contain high content of minerals and vitamins (Hulse et al., 1980). Further, in smallholder communities, small grains are valued for other uses. Malted millet and sorghum have been used to brew local beverages such as opaque beer and *mahewu*, refreshments commonly used during community ceremonies and when farmers are working in the field (Zvauya et al., 1997).

The potential of different cereal crops as options for adaptation to the changing climate has been evaluated mainly through modelling studies (Chipanshi et al., 2003; Lobell et al., 2008), but there is paucity of information on field-based empirical evidence coupled with local farmers' knowledge. Field-based experiments not only increase the relevance of research findings to farmers, but also support modelling studies particularly in Africa where data is scarce (Knox et al., 2012). In this paper we assess whether small grains (finger millet and sorghum) perform as well as maize under variable rainfall and soil conditions. Our objectives were to: (i) evaluate crop emergence and yield performance of maize, finger millet and sorghum for different planting dates and fertilization rates, (ii) analyse nutrient use efficiency and water productivity for the three crop types, (iii) evaluate economic benefits and nutritional value of maize, finger millet and sorghum under smallholder management conditions.

4.1. Material and methods

4.1.1. Study sites

The study was carried out in the Nyahava smallholder resettlement area in Makoni district (18°12'S 32°24'E; 1400 m a.s.l; mean annual rainfall of 800 mm) and the Ushe communal area in the Hwedza district (18°37'S 31°34'E; 1100 m a.s.l; mean annual rainfall 750 mm), in Zimbabwe. Both areas experience a unimodal rainfall pattern extending from October to April. Granitic sandy soils prevail in both study sites with low organic carbon and low nutrients contents (Table 4.1), and poor water holding capacity (Nyamapfene, 1989). Maize (*Z. mays* L.) is the dominant crop occupying >80% of the total area under cultivation in both sites in the 2009/10 season. In addition to maize, groundnuts (*Arachis hypogaea* L.), cowpea (*Vigna unguiculata* [L.] Walp.) and tobacco (*Nicotiana tabacum* L.) are widespread in Makoni, where maize and tobacco are the main cash crops. In Hwedza, maize, groundnuts and cowpea predominate. Maize is grown for both consumption and income at both sites. A few farmers, notably the older household heads still grow small grains mainly finger millet, but they hardly apply fertilizers.

Table 4.1. Soil properties of field experimental sites in Makoni and Hwedza in 2009/10 season

Site	pH ($0.01M\ CaCl_2$)	Organic C (%)	Total N (%)	Available P ($mg\ kg^{-1}$)	Ca ($cmol_c\ kg^{-1}$)	Mg	K	Clay (%)	Sand (%)
Makoni									
Gomba field	4.8	0.76	0.08	9.4	1.6	0.8	0.4	7	88
Mandeya field	4.6	0.68	0.07	8.0	1.4	0.7	0.3	7.8	89
Hwedza									
Midzi field	4.1	0.32	0.04	3.0	0.6	0.2	0.1	6	91

4.1.2. Testing farmer identified adaptation options

Two researcher-managed experiments were conducted in farmers' fields in each site over three seasons: 2009/10, 2010/11 and 2011/12, to assess crop emergence and yield of maize, finger millet and sorghum as affected by different planting dates and fertilization. The core of the experiment was based on two seasons: 2009/10 and 2010/11. An extra experiment was conducted in the third season; 2011/12, to understand more about the emergence of sorghum and finger millet, as described subsequently. One experiment was conducted with maize, which is reported in detail in Chapter 3 while the other experiment was comprised of finger millet and sorghum.

Before the establishment of the experiments, several farmers' fields were surveyed to carefully select fields for experimentation. Criteria for selection were (i) fields had to have sandy soils, which are representative for a larger area of smallholder farming systems (Mtambanengwe and Mapfumo, 2005); (ii) fields had to have a gentle slope and similar management given that these two factors are the main causes of soil fertility gradients in the case study farming systems (Carter and Murwira, 1995); (iii) fields had to be large enough to randomize all the experiments. In Hwedza, both experiments were conducted side-by-side in one field. In Makoni, the two experiments were conducted in nearby fields (about 200 m apart) with similar soil properties and management history, as the farmers' fields were too small to randomize all treatments. Accordingly, all three fields had mostly been under maize cultivation over 40 years. The same fields were used for all three seasons of experimentation. Besides soil fertility gradients another main factor that can increase experimental error is competition effects between the plants on the different experimental plots (Gomez and Gomez, 1984). To minimize the effects of shading by the larger maize plants, small grains plots were separated from the plots with maize by 5 m in Hwedza, but the overall experimental design was maintained.

Three soil samples were randomly collected from the surface 20 cm and bulked together to form a composite sample from each experimental field before the start of the experiments. Soil samples were analysed for texture (hydrometer method), pH (0.01M $CaCl_2$), total organic carbon (Walkley-Black), total nitrogen (micro-Kjeldahl), available phosphorus (Olsen) and exchangeable Ca, Mg and K (ammonium acetate) (Anderson and Ingram, 1993) (Table 4.1).

For the maize experiment, the treatments of 3 planting dates × 3 fertilization rates × 3 hybrid maize cultivars were laid out in a split-plot block design with three replications per treatment. Planting date was assigned to the main plot, and fertilization rate × maize cultivar sub-plots were randomized within the main plot. Three planting windows, namely early (25 October – 20 November), normal (21 November – 15 December) and late (after 15 December) were defined with farmers based on observed long-term rainfall patterns in each site. The three nutrient application rates for application of mineral fertilizer and manure were; control (unfertilized), low rate (35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure) and high rate (90 kg N ha^{-1}, 26 kg P ha^{-1}, 7 t ha^{-1} manure on a dry weight basis). Manure was applied in the first season (2009/10). In the second season manure was not applied following farmers' management practice of applying manure once in two years. This pattern of applying manure has mainly been linked to limited supply of manure as they are relatively few cattle in these smallholder farming systems (Zingore et al., 2011). The three hybrid cultivars that were used in the maize experiment were, SC403, an early maturing cultivar with 131 days to maturity; SC513, a medium cultivar with 137 days to maturity; and SC635, a slightly longer duration cultivar with 142 days to maturity. These maize cultivars represent the range of maturity durations in maize available to farmers. Although the yields for the three maize cultivars tested in the maize experiment were significantly not different, SC635 that produced the best yield was selected for comparison in this study (Chapter 3; Rurinda et al., 2013).

For the small grain experiment, 3 planting dates × 3 fertilization rates × 2 crop types (finger millet landrace cultivar and sorghum) were laid out in a split-plot block design with three replications per treatment. Sorghum hybrid cultivar, macia (114 days to maturity) was used in the first season (2009/10). Because the macia cultivar was prone to bird damage, a landrace cultivar was used in the second season (2010/2011). The sorghum hybrid cultivar was bought from the market. Finger millet and sorghum landrace cultivars were bought from farmers. Similar to the maize experiment, planting date was assigned to the main plot, and fertilization rate × crop type was completely randomized within the main plot. The same planting dates and nutrient application rates of the maize experiment were used in the small grains experiment. At each site, shortly after the rains, all three crops were planted on the same day for each planting window.

Fields were prepared by ploughing and ridging using draught animals as per farmers' practice. Each subplot had an area measuring 3 m × 7 m. Plant spacing was 0.75 m × 0.30 m for maize, and 0.45 m × 0.10 m for both finger millet and sorghum, resulting in population densities of about 44 000 plants ha^{-1} for maize and about 220 000 plants ha^{-1} for small grains. A basal mineral fertilizer, compound D (7% N, 14% P_2O_5 and 7% K_2O), was applied at planting with the amounts: 230 kg ha^{-1} and 425 kg ha^{-1} for the low and high fertilization rates, respectively. Ammonium nitrate (34.5%) as top dressing was applied in two splits, 34 kg ha^{-1} for low rate and 92 kg ha^{-1} for high rate, at 4 weeks after emergence; and 51 kg ha^{-1} for low rate and 139 kg ha^{-1} for high rate, at 6 weeks after emergence. The nitrogen applied at planting was taken into account in calculating the required amount of top dressing ammonium nitrate. The total nitrogen in manure used in the experiment was 0.8% in Makoni, and 0.7% in Hwedza. The total P in manure was 0.3% in Makoni, and 0.26% in Hwedza. Total N and P in manure were measured using micro-Kjeldahl digestion method (Anderson and Ingram, 1993). Weeding was done twice manually using a hand hoe. Daily rainfall was recorded by farmers from rain gauges placed at each site. No major pests or diseases were observed during the course of the study.

Grain yield for each crop type was determined at physiological maturity from net plots of 12.42 m^2 (3 rows × 4.6 m) for maize and 6.75 m^2 (3 rows × 5 m) for small grains. Grain yields were calculated at 12.5% moisture content. Sorghum was protected from quelea birds (*Quelea quelea)* by randomly selecting 10 plants in each plot and covering their panicles using nets at flowering stage. The rest of the sorghum crop that was not protected was completely destroyed by birds. Harvest index of the protected sorghum heads was used to estimate sorghum grain yield. Stover samples were oven dried at 70 ^{o}C to a constant weight before dry matter yield was determined.

4.1.3. Effect of fertilization on emergence of finger millet and sorghum

Because of poor crop emergence without nutrient amendment that was observed in the experiments conducted during the 2009/2010 and 2010/2011seasons, an extra experiment was conducted in a third season (2011/2012) to assess the effects of fertilization on emergence of finger millet and sorghum. The number of fertilization treatments was increased in this experiment. Five fertilization rates × two crop types (finger millet and sorghum) were laid out in a randomized complete block design replicated three times. The five fertilization rates applied at planting were: (i) manure only at 7 t ha^{-1} manure, (ii) mineral fertilizer only at 30 kg N ha^{-1}, 26 kg P ha^{-1}, 25 kg K ha^{-1}, (iii) manure-fertilizer combination high rate at 30 kg N ha^{-1}, 26 kg P ha^{-1}, 25 kg K ha^{-1}, 7 t ha^{-1} manure, (iv) manure-fertilizer combination low rate at 16 kg N ha^{-1}, 14 kg P ha^{-1}, 13 kg K ha^{-1}, 3 t ha^{-1} manure, and (v) an absolute control without fertilization.

The manure alone and fertilizer only treatments were included to differentiate effects of manure from that of mineral fertilizer on crop emergence since results of the previous two seasons were from the combination of the two nutrient resources. These fertilization treatments also mimicked management practices of farmers who use either manure or fertilizer or both. Crop emergence for each crop type was determined within the three to four weeks after planting (when the plants had 3 to 4 leaves), by counting the total number of emerged plants in each plot and calculated as a percentage of the total number of seeds planted.

4.1.4. Estimating nitrogen use efficiency and water productivity

Agronomic efficiency (AE) of nitrogen use was calculated as kg grain yield produced per kg N applied:

$$\mathrm{AE} = \frac{\mathrm{Yield_{treatment}} - \mathrm{Yield_{control}}}{\mathrm{N_{applied}}} \, \mathrm{kg\ grain\ (kg\ N)^{-1}} \qquad (1)$$

$\mathrm{Yield_{treatment}}$ and $\mathrm{Yield_{control}}$ refer to grain yields (kg ha^{-1}) for the treatment and the control where N_{applied} was the amount of fertilizer N applied (kg N ha^{-1}).

A combination of both mineral and organic fertilizers was applied. Thus, the N contribution from manure was taken into account by assuming a mean N equivalency of 25% (Murwira et al., 2002).

Water productivity is generally defined as the ratio of agricultural outputs (mass of produce or in economic terms as net value) to the amount of water consumed. It provides a robust measure of the ability of agricultural systems to convert water into food (Kijne et al., 2003). The water productivity index was calculated as:

Crop water productivity = Grain yield (kg ha^{-1}) / total season rainfall (mm)

4.1.5. Statistical analysis

The main effects of year and crop type (maize and small grains: finger millet and sorghum), were analysed using analysis of variance (ANOVA) procedures for a split-split plot design (GenStat Edition 14). Year and crop type were selected as the main factors, planting date as plot factor and fertilization rate as subplot factor, for each study site. All four factors were considered fixed. The main effects and the two-way, three-way and four-way interactions on emergence, nutrient use efficiency, water productivity and grain yield, were considered as significant at a probability level of ≤ 0.05.

4.1.6. Financial returns and nutritional value of maize, finger millet and sorghum

Marginal rates of return were calculated to evaluate the benefit of introducing a new practice i.e. changing from one fertilization rate for each planting date and for each crop type. The gross benefit of each practice was obtained by multiplying the yield by the farm gate price for each crop type. The variable cost for each practice was the sum of only those costs that vary by shifting to another treatment. Costs of production included fertilizers and seeds, and labour for manure handling, weeding and harvesting. Labour was determined based on existing labour rates in each community using farm diaries and informal interviews for each crop type where labour for: maize was 44 labour days ha^{-1} (weeding = 32 labour days ha^{-1}, fertilization = 2 labour days ha^{-1}, harvesting = 10 labour days ha^{-1}); finger millet was 64 labour days ha^{-1}(weeding = 38 labour days ha^{-1}, fertilization = 2 labour days ha^{-1}, harvesting = 24 labour days ha^{-1}; sorghum was 53 labour days ha^{-1}(weeding = 35 labour days ha^{-1}, fertilization = 2 labour days ha^{-1}, harvesting = 16 labour days ha^{-1}). The cost of labour per day was US$ 4.00 for each season in each site. Farm gate prices were US$ 0.25 kg^{-1} grain for maize and US$ 0.5 kg^{-1} grain for small grains. Although the price for each crop has generally not changed across the two seasons of experimentation, the price normally varies from season to season depending mainly on timing of selling and that is a context specific decision by the farmer which is difficult to capture (Waddington et al., 2007). It was not possible to estimate the range of prices for each crop based on literature due to hyperinflation experienced in Zimbabwe between 2001 and 2008. The marginal rate of return was determined by calculating the difference between the net benefit of each practice as a percentage of the difference of the total cost. A rate of return of 50% was used as the minimum acceptable rate (CIMMYT, 1988).

4.2. Results

4.2.1. Rainfall patterns within the two seasons of experimentation

The rainfall pattern during the two experimental seasons was markedly different although the total seasonal rainfall for the two seasons were similar at each site (Fig. 4.1). The rains started earlier during the 2010/11 season than in the 2009/10 season (Fig. 4.1), but the rainy season for 2010/11 was characterized by an early season dry spell (false start to the season) that led to a two weeks delay in planting of the early crop. Mid-season dry spells occurred during both seasons but at different periods of the crop development which had contrasting effects on crop yield. In the first season (2009/10), a prolonged mid-season dry spell occurred in January when the crops were at vegetative stage of development, whereas, there was a very late on-set of effective rainfall in the 2010/11 season. Severe waterlogging was experienced for two weeks early in the season. This was followed by a prolonged mid-season dry spell in February lasting almost three weeks (Fig. 4.1) when the crops were at the critical flowering stage of development.

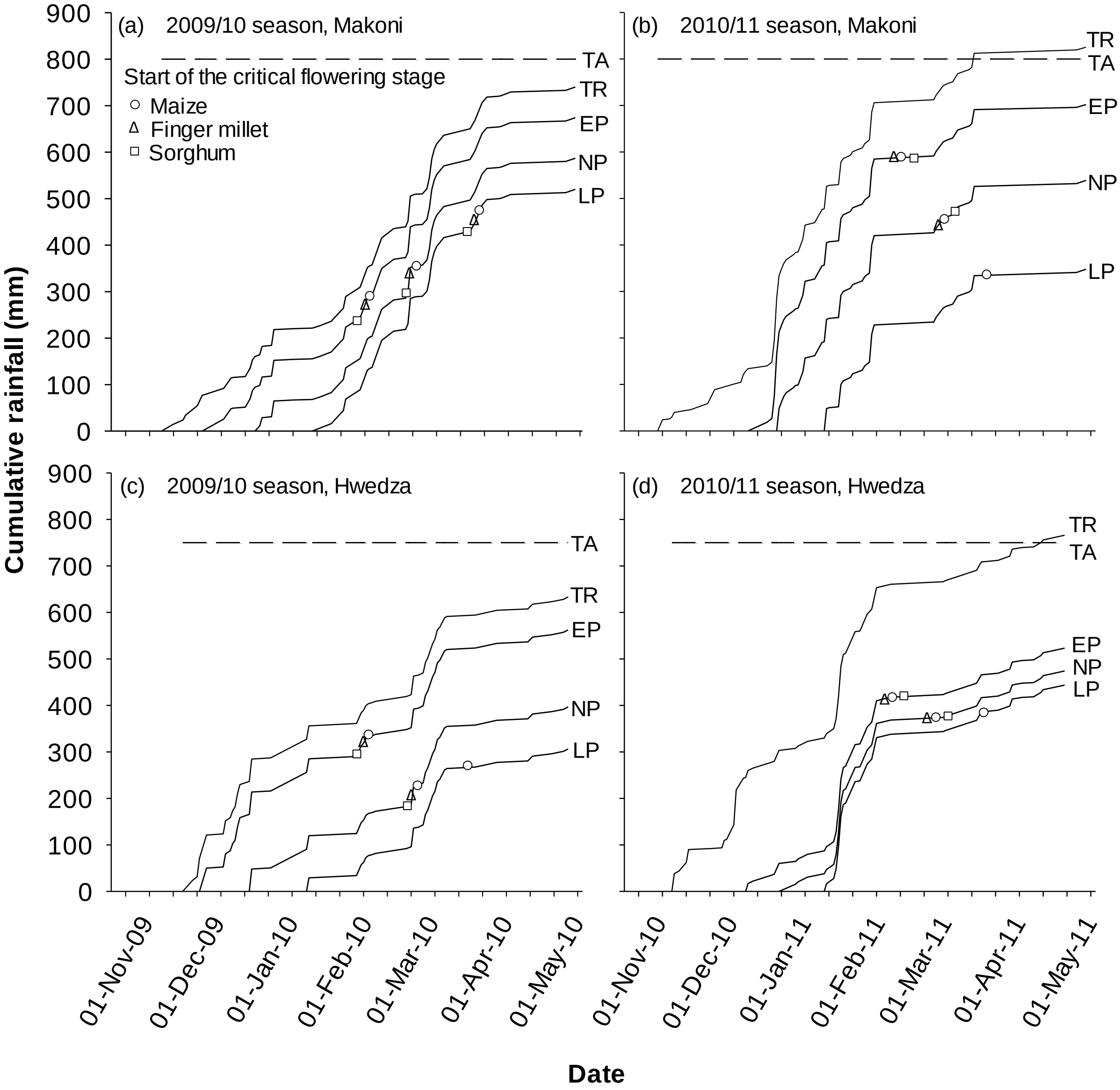

Fig. 4.1. Daily cumulative rainfall for total seasonal rainfall (TR), early planting (EP), normal planting (NP) and late planting (LP), and long-term mean rainfall (TA) for Makoni (a and b), and for Hwedza (c and d), for the 2009/10 and 2010/11 seasons.

4.2.2. Fertilization effect on crop emergence

Emergence for the unfertilized finger millet and sorghum was < 15% on average at each site across all three seasons (Figs. 4.2 and 4.3). Similarly, emergence for finger millet and sorghum was <15% when the soil was amended with manure alone (Figs. 4.2 and 4.3).When sorghum and finger millet were fertilized with either mineral fertilizer alone or manure-mineral fertilizer combinations emergence was > 70% (Figs. 4.2 and 4.3).The emergence of maize was > 80% regardless of fertilization and planting date at each site in both seasons (Fig. 4.2). The similarities in emergence among all three crops when the soil was fertilized with either mineral fertilizers or a combination of mineral fertilizers and manure, suggest that the physiological quality of seed for all three crops was good.

4.2.3. Performance of maize, finger millet and sorghum under different planting dates and fertilization

Maize yielded more than both finger millet and sorghum when the crops were planted early or during the normal planting window under the high fertilization rate (Fig. 4.4A and B). Early planted maize yielded 5.4 t ha^{-1}, finger millet 3.1 t ha^{-1} and sorghum 3.3 t ha^{-1} in the 2009/10 rainfall season in Makoni, the site with relatively fertile soils (Fig. 4.4A). In Hwedza, where soils were less fertile, early planted maize yielded 3.0 t ha^{-1}, finger millet 1.6 t $ha^{-1}$and sorghum 2.8 t ha^{-1} in the 2009/10 season (Fig. 4.4B). There was an interaction between yield of each crop and the season (P <0.05). In the poorer 2010/11 rainfall season, yields of all crops were significantly depressed. Early planted maize yielded 2.4 t ha^{-1}, finger millet 1.6 t ha^{-1} and sorghum 0.4 t ha^{-1} in the 2010/11 season in Makoni (Fig. 4.4A). In Hwedza, early planted maize yielded 1.9 t ha^{-1} finger millet 0.6 t ha^{-1}, and sorghum 0.2 t ha^{-1} in the 2010/11 season (Fig. 4.4A). All three crops yielded less when low amounts of fertilizer were applied, particularly in the better 2009/10 rainfall season (Fig. 4.4).

Although grain yield for each crop increased with increase rates of nutrients applied, maize responded more strongly to the high rate of fertilization than finger millet or sorghum in the better rainfall season of 2009/10 in Makoni, the site with more fertile soils (Fig. 4.4A). The difference in grain yield between the low and high fertilization rates was 135% for maize and about 45% for both finger millet and sorghum. In Hwedza, the site with poorer soils, maize responded less strongly to fertilization and the response was comparable to that of finger millet and sorghum (Fig. 4.4B). Without fertilization grain yield for each crop was <0.5 t ha^{-1}, on average, across seasons at each site (Fig. 4.4A and B).

Grain yields for early and normal plantings were generally similar for each crop type particularly in the 2009/10 season in Makoni (Fig. 4.4A). However, when planting was delayed by 4 weeks, yields of maize and sorghum decreased drastically to < 0.5 t ha^{-1} regardless of fertilization rate in the 2009/10 season. Whereas, finger millet yielded > 1 t ha^{-1} in Makoni, in the better rainfall season of 2009/10 (Fig. 4.4A). In Hwedza, the yield of each crop decreased drastically to < 0.5 t ha^{-1} in the 2009/10 season. In the poorer 2010/11 rainfall season, finger millet and sorghum failed completely, and yet maize yielded only 1 t ha^{-1} when planting was delayed by 4 weeks in Makoni (Fig. 4.4A and B). There was an interaction (P <0.05) between fertilization and planting date on grain yield of each crop type, demonstrating that effects of fertilization on yield were dependent on planting date.

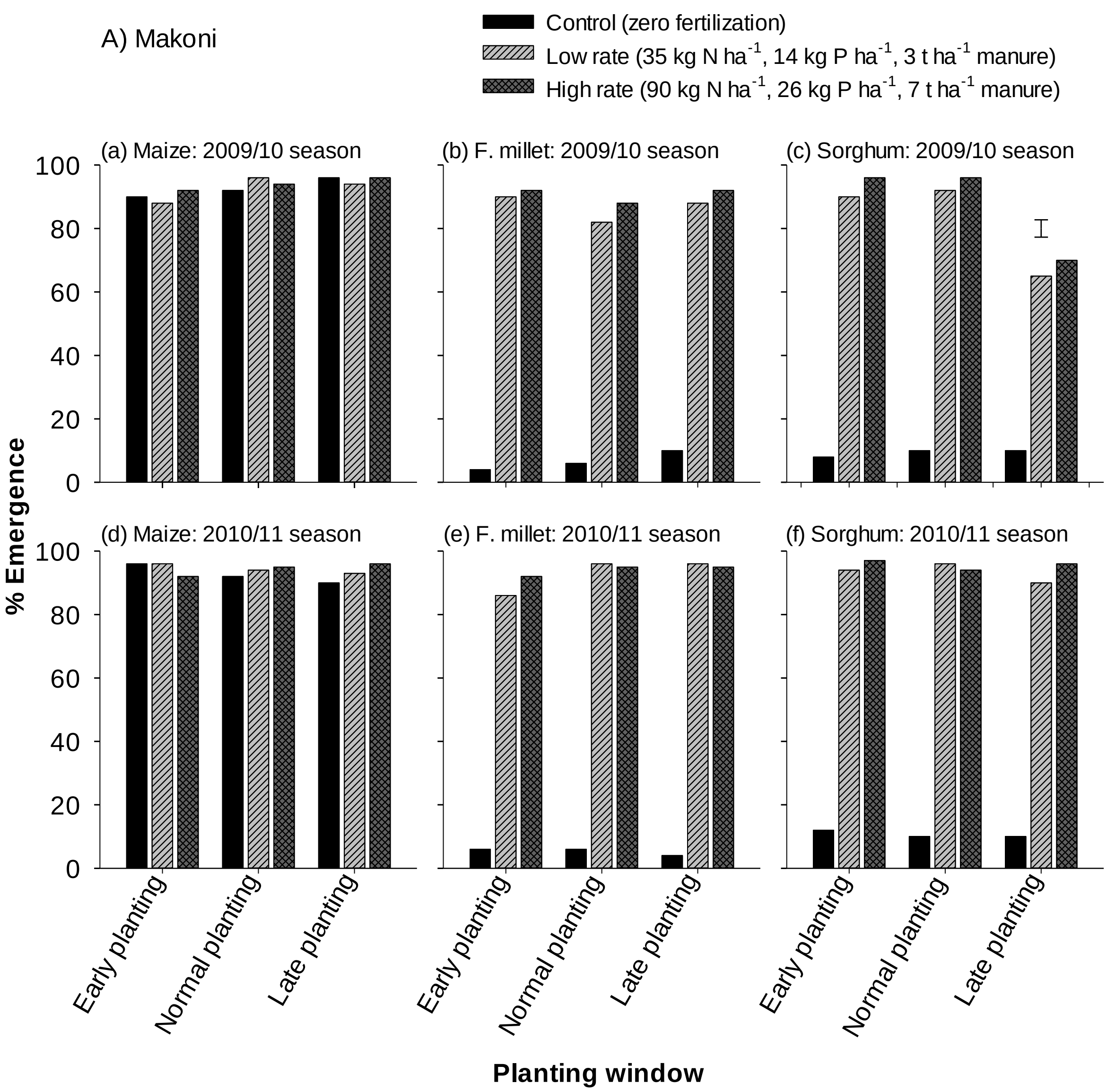

Fig. 4.2. Percentage emergence for maize, finger millet and sorghum in response to different planting dates and fertilization levels, for the 2009/10 and 2010/11 seasons in (A) Makoni and (B) Hwedza. The bar represents Standard Errors of the Differences between means (SED) for the interactions of year, crop type, planting date and fertilization rate.

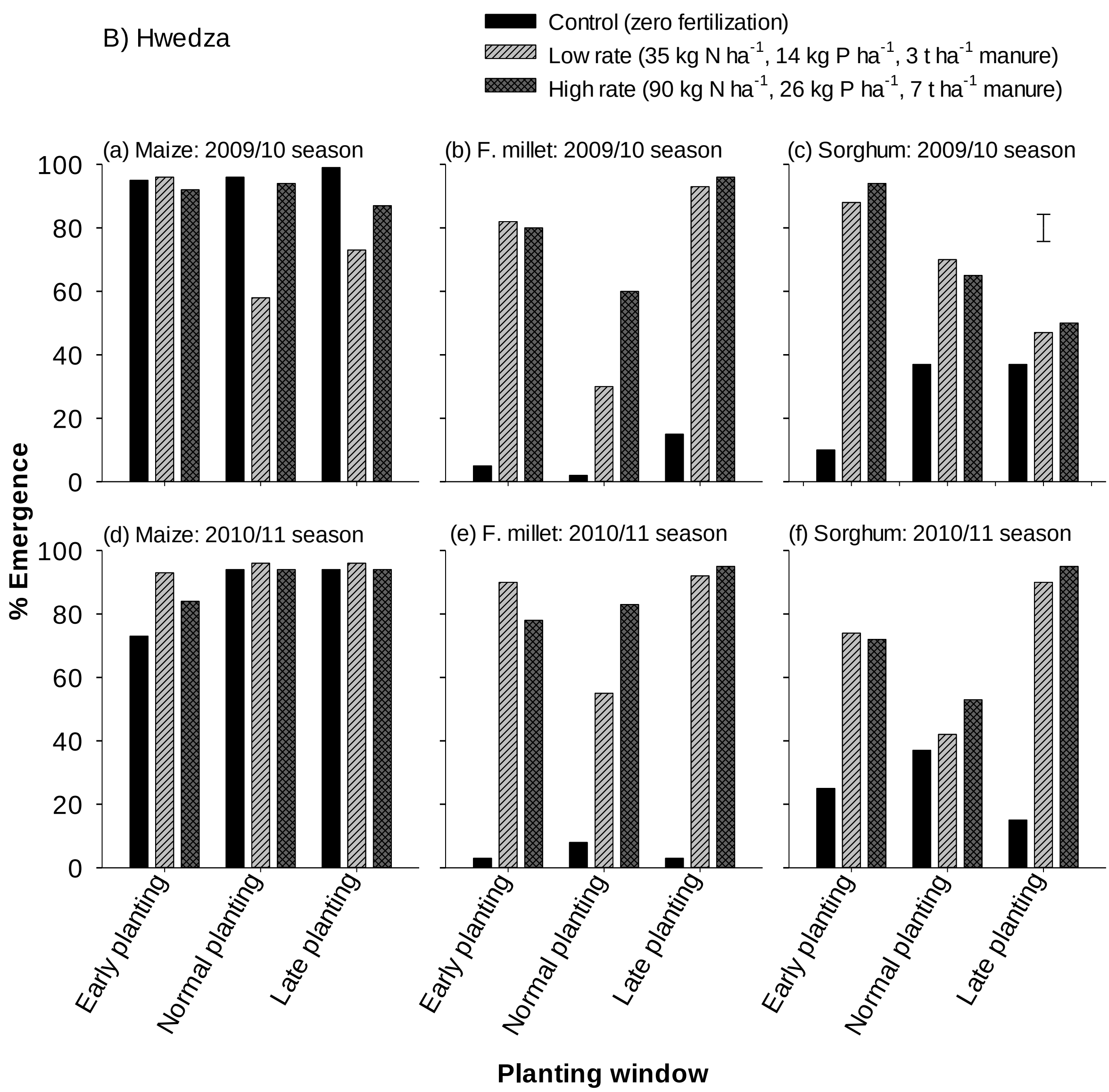

Fig. 4.2. continued.

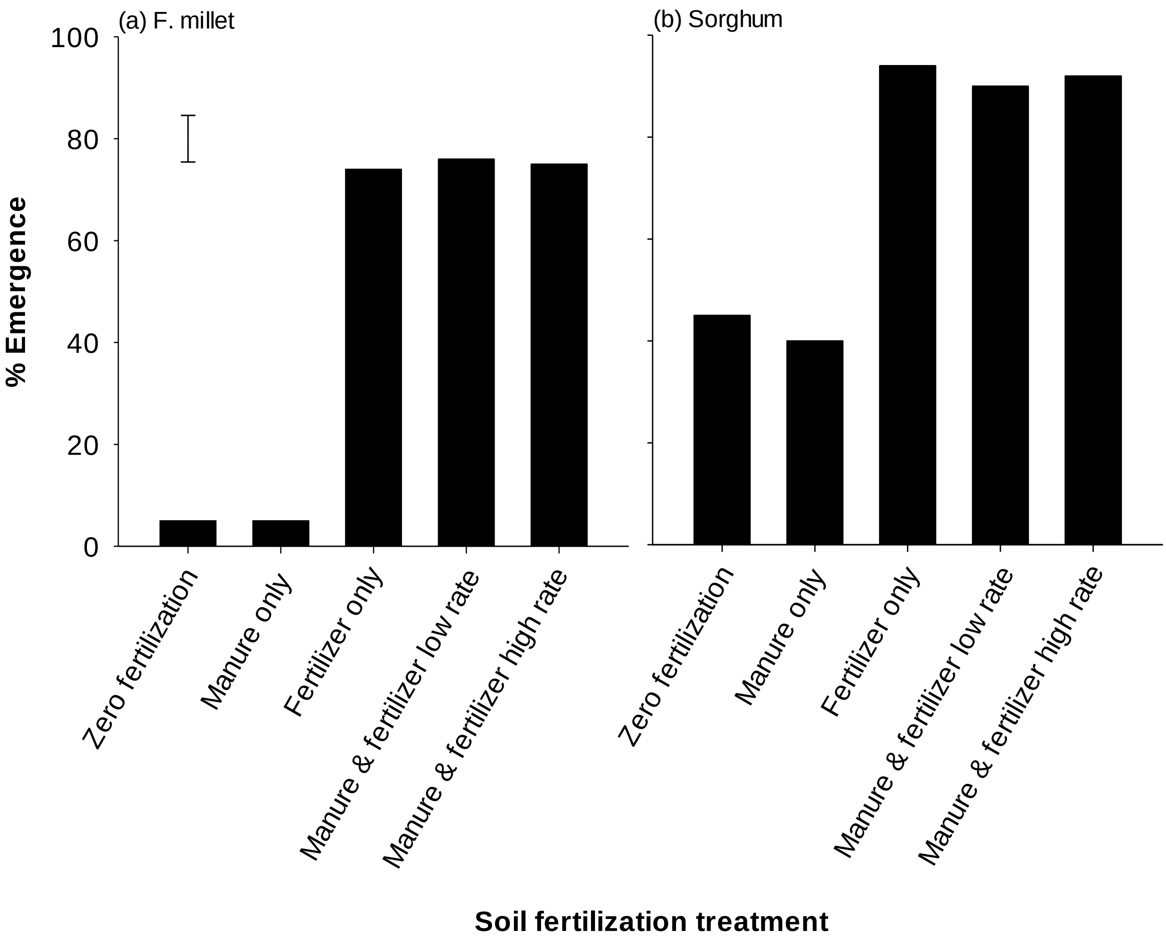

Fig. 4.3. Percentage emergence for finger millet and sorghum in response to different nutrient amendments in Hwedza for the 2011/12 season. The bar represents Standard Errors of the Differences between means (SED) for the interaction of crop and soil nutrient amendment.

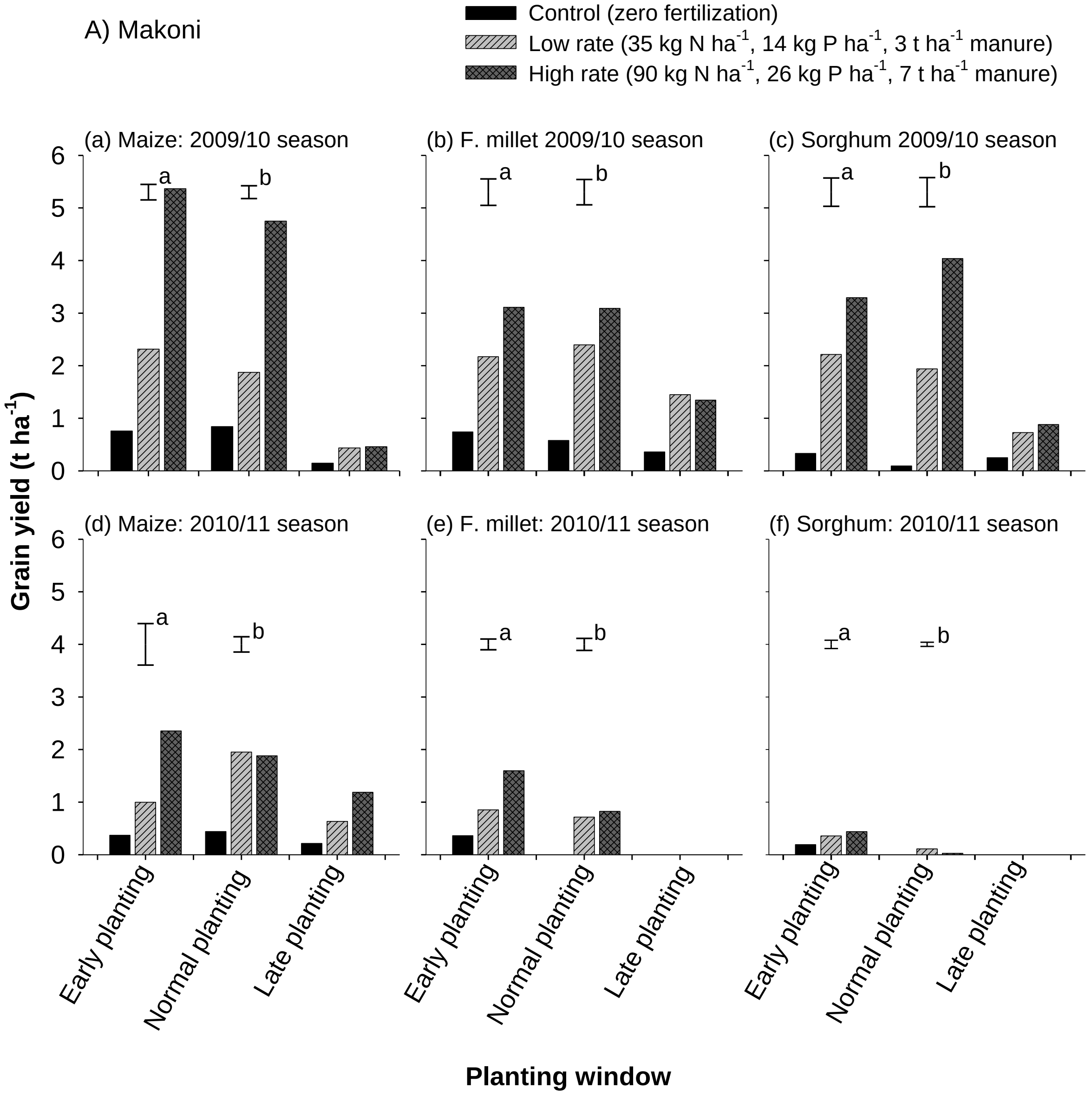

Fig. 4.4. Maize, finger millet and sorghum grain yields responses to planting date and fertilization rate for the 2009/10 and 2010/11 seasons in (A) Makoni and (B) Hwedza. Bars represent Standard Errors of the Differences between means (SED) for a = planting date and b = fertilization rate. In the 2010/11 season late planted sorghum failed completely to yield in Makoni due to waterlogging.

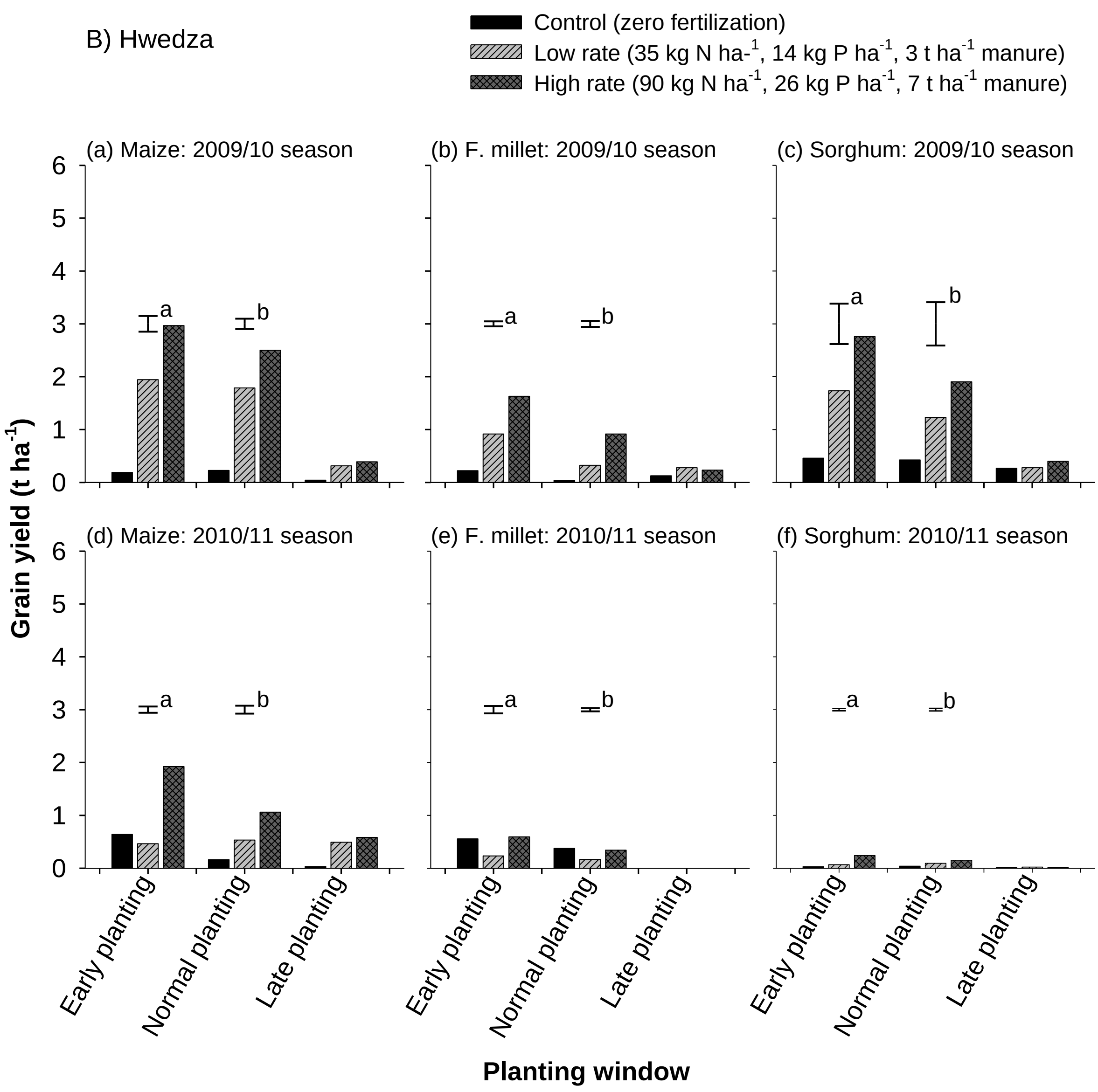

Fig. 4.4. continued.

4.2.4. Agronomic nitrogen use efficiency and water productivity

Agronomic efficiencies of N use were generally higher for maize (>24 kg (kg N)$^{-1}$) than for finger millet and sorghum at each site when the crops were planted either early or during the normal window (Table 4.2). In Hwedza, the site with poorer soils, N use efficiency for each crop was poor (Table 4.2). When planting of each crop was delayed by 4 weeks, the efficiency of N use for each crop decreased to <20 kg (kg N)$^{-1}$ (Table 4.2). The N use efficiencies of each crop for the normal plantings were similar to those of early plantings (data not shown).

Table 4.2. Agronomic efficiency of nitrogen use [kg (kg N)$^{-1}$] for maize, finger millet and sorghum for different planting dates, and for low and high fertilization rates, in Makoni and Hwedza for the seasons 2009/10 and 2010/11. Fertilization rates: Low rate - 35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure; High rate - 90 kg N ha^{-1}, 26 kg P ha^{-1}, 7 t ha^{-1} manure

Site/crop type	2009/10 season				2010/11 season			
	Early planting		Late planting		Early planting		Late planting	
	Low rate	High rate	Low rate	High rate	Low rate	High rate	Low rate	High rate
Makoni								
Maize	38	44	7	3	35	44	14	12.5
Finger millet	37	24	19	13	27	27	0	0
Sorghum	30	42	15	7	6	9	0	0
Hwedza								
Maize	40	25	9	5	40	25	9	5
Finger millet	18	14	4	1	10	12	0	0
Sorghum	22	23	0.3	3	2	5	0.4	0

Standard error of differences (SED): Makoni: crop type = 4.4; planting date = 2.3; fertilization = 3.6; year = 3.6; standard error of differences (SED): Hwedza: crop type=2.0; planting date = 2.2; fertilization = 1.7; year = 1.7

Water productivity for each crop planted between early and normal windows increased with increase in the amount of fertilizer applied, but differed among the crops (Table 4.3). Maize had the highest water productivity (8.0 kg grain mm^{-1}) followed by sorghum (4.9 kg grain mm^{-1}) and then finger millet (4.6 kg grain mm^{-1}) when a high fertilizer rate was applied for the early plantings (Table 4.3). The water productivity for each crop also varied with season. In Makoni, water productivity for maize planted early with high amount of fertilizer, fell from 8.0 kg grain mm^{-1} for the good 2009/10 rainfall season to 3.4 kg grain mm^{-1} for the poor 2010/11 rainfall season. For the finger millet, the observed variation on water productivity was narrower decreasing from 4.6 kg mm^{-1} in the 2009/10 season to 2.3 kg grain mm^{-1} in the 2010/11 rainfall season. Water productivity for sorghum decreased from 4.9 kg grain mm^{-1} in the 2009/10 season to 0.6 kg grain mm^{-1} in the 2010/11 season (Table 4.3).

Table 4.3. Water productivity (kg grain mm^{-1} rainfall ha^{-1}) for maize, finger millet and sorghum for different planting dates and fertilization rates, in Makoni and Hwedza for the seasons 2009/10 and 2010/11. Fertilization rates: control (CR) - zero fertilization; low rate (LR) - 35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure); high rate (HR) - 90 kg N ha^{-1}, 26 kg P ha^{-1}, 7 t ha^{-1} manure

	2009/10 season									2010/11 season								
	Early planting			Normal planting			Late planting			Early planting			Normal planting			Late planting		
Site / crop type	CR	LR	HR	CR	LR	HR	CR	LR	HR	CR	LR	HR	CR	LR	HR	CR	LR	HR
Makoni																		
Maize	1.1	3.4	8.0	1.4	3.2	8.1	0.3	0.8	0.9	0.5	1.4	3.4	0.8	3.6	3.5	0.6	1.8	3.4
Finger millet	1.0	3.2	4.6	1.0	4.1	5.3	0.7	2.8	2.6	0.5	1.2	2.3	0.0	1.3	1.5	0.0	0.0	0.0
Sorghum	0.5	3.3	4.9	0.2	3.3	6.9	0.3	1.4	1.7	0.3	0.5	0.6	0.0	0.2	0.1	0.0	0.0	0.0
Hwedza																		
Maize	0.4	3.5	5.3	0.6	4.5	6.3	0.1	1.0	1.3	0.1	0.9	3.6	0.2	1.1	2.2	0.1	1.1	1.3
Finger millet	0.4	1.6	2.9	0.1	0.8	2.3	0.4	0.9	0.8	0.1	0.4	1.1	0.1	0.4	0.7	0.0	0.0	0.0
Sorghum	0.8	2.2	4.9	1.1	4.3	4.8	0.9	0.9	1.3	0.1	0.1	0.5	0.1	0.2	0.3	0.0	0.0	0.0

Standard error of differences (SED): Makoni: crop type = 0.20; planting date = 0.13; fertilization = 0.20; year = 0.16; standard error of differences (SED): Hwedza: crop type= 0.15; planting date = 0.09; fertilization = 0.15; year = 0.12

4.2.5. Financial returns and nutritional value for maize, finger millet and sorghum

Marginal rates of return for early and normal planted maize were more attractive for the high fertilization rate (157%) than for the low rate (42%) in the 2009/10 season in Makoni (Table 4.4). In contrast, the financial returns for small grains were generally more lucrative for the low fertilization rate than for the high rate. Marginal rate of return for finger millet was 160% and for sorghum 235%, for the low fertilization rate compared with 59% and 79%, respectively, for the high rate (Table 4.4). In Hwedza, the marginal rate of return for finger millet was below 50% for both low and high fertilization rates. In a relatively poor 2010/11 rainfall season, only maize had marginal rates of return of above 50%, a minimum acceptable rate of return, at each site (Table 4.4). The financial returns for normal plantings were similar to that of early plantings for each crop (data not shown). When planting was delayed by 4 weeks (late planting), the marginal rates of return were zero for each crop regardless of the amount of fertilizer applied (data not shown). Although the yield of maize was greater than finger millet, the latter had a higher content of minerals, particularly calcium (Table 4.5).

Table 4.4. Marginal rates of return for maize, finger millet and sorghum for early planting date and different fertilization rates (control (CR), low rate (LR) and high rate (HR), in Makoni and Hwedza in the seasons 2009/10 and 2010/11

Crop type/variable	Unit	Makoni						Hwedza					
		2009/10 season			2010/11 season			2009/10 season			2010/11 season		
		CR	LR	HR	CR	LR	HR	CR	LR	HR	CR	LR	HR
Maize													
Grain yield	t/ha	0.8	2.3	5.4	0.4	1.0	2.4	0.2	1.9	3.0	0.1	0.5	1.9
Gross field benefit	US$/t	152	463	1073	93	249	588	47	486	742	17	123	510.00
Cost of fertilizer	US$/ha	0	185	387	0	160	319	0	185	387	0	185	387
Cost of labour	US$/ha	176	211	246	176	211	246	176	211	246	176	211	246
Total variable cost	US$/ha	176	396	633	176	371	565	176	396	633	176	396	633
Net benefit	US$/ha	-24	67	440	-84	-122	23	-129	90	109	-159	-273	-123
Marginal rate of return	%	-	42	157	-	-	75	-	99	8	-	-	63
Finger millet													
Grain yield	t/ha	0.7	2.2	3.1	0.4	0.9	1.6	0.2	0.9	1.6	0.6	0.2	0.6
Gross field benefits	US$/t	296	868	1244	145	341	639	89	367	652	222	93	237
Cost of fertilizer	US$/ha	0	185	387	0	190	396	0	185	387	0	190	396
Cost of labour	US$/ha	240	291	326	240	291	326	240	291	326	240	291	326
Total variable cost	US$/ha	240	476	713	240	481	722	240	476	713	240	481	722
Net benefit	US$/ha	56	392	531	-95	-140	-84	-151	-109	-61	-17	-388	-485
Marginal rate of return	%	-	142	59	-	-	-	-	18	20	-	-	-
Sorghum													
Grain yield	t/ha	0.3	2.2	3.3	0	0	0	0.5	1.7	2.8	0	0	0
Gross field benefits	US$/t	132	885	1317	0	0	0	183	680	1104	0	0	0
Cost of fertilizer	US$/ha	0	190	396	0	190	396	0	185	387	0	190	396
Cost of labour	US$/ha	196	247	282	196	247	282	196	247	282	196	247	282
Total variable cost	US$/ha	196	437	678	196	437	678	196	432	669	196	437	678
Net benefit	US$/ha	-64	448	638	-196	-437	-678	-12	248	435	-196	-437	-678
Marginal rate of return	%	-	212	79	-	-	-	-	111	79	-	-	-

Table 4.5. A comparative analysis of main attributes for the characteristics of maize, finger millet and sorghum for improved livelihood systems in Southern Africa

Main attribute	Maize	Finger millet	Sorghum	Reference
Attainable yield (t ha^{-1})[a]	3.0–7.0	1.2 – 6.0	1.5 -6.0	(Mnyenyembe, 1994; Mangombe and Mushonga, 1996)
Farmer's average yield (t ha^{-1})	1.5 (0.4-4.0)	0.5 (0.35-0.75)	0.6 (0.4-1.5)	(Mnyenyembe, 1994; Chuma et al., 2001)
Drought resistance	Less drought resistant	Does not readily tolerate intermittent droughts	More drought resistant	(Hulse et al., 1980; Frere, 1984)
Tolerance to waterlogging	Does not readily tolerate waterlogging	Does not readily tolerate waterlogging	Endure temporary waterlogging	(Hulse et al., 1980)
Post-harvest losses	Quickly damaged (store up to nine months)	Store for more than six years	Store for more than two years	(Kamanula et al., 2011; Chuma et al., 2001)
Bird damage	Not prone to bird damage	Less prone to bird damage	Very prone to bird damage	(Dogget, 1988; Macgarry, 1990)
Main uses	Staple food (*sadza*) Cash crop Stover for cattle feed	Brewing beer (clear and opaque) Household food reserve	Brewing opaque beer Household food reserve	(Zvauya et al., 1997; Chuma et al., 2001)
Output Markets	Easily marketable	Poor marketing structure	Not easily marketable	(Alumira and Rusike, 2005)
Taste[b]	Good taste	Less taste	Less taste	(Chuma et al., 2001)
Labour demand	Low	Very high	High	(Alumira and Rusike, 2005)
Nutrition[cd]				(Hulse et al., 1980)
Carbohydrates (g)	76.0 (72.5-89.0)	75.0 (70.8-83.0)	81.1 (69.8-87.0)	
Protein (N×6.25) (g)	10.4 (7.5-25.0)	9.0 (6.8-13.0)	10.4 (7.5-16.6)	
Fat (g)	4.5 (3.5-7.2)	1.5 (0.8-5.7)	3.4 (2.5-5.1)	
Calcium (mg)	26.0 (10.4-48.0)	350.0 (257.0-528.0)	25.0 (13.5-48.0)	
Iron (mg)	2.5 (0.4-9.5)	5.0 (4.5-9.2)	4.5 (0.6-11.1)	

Note: The nutritional composition provided in the table give a general overview because not all varieties were covered for each crop.
[a] Under smallholder conditions; [b] Taste was according to farmers' perceptions.
[c] Nutrition composition per 100 g edible portion at 12% moisture content.
[d] Nutrition composition for each crop was derived from several varieties studied in Africa.

4.3. Discussion

4.3.1. Yield performance of maize, finger millet and sorghum

Overall, maize yielded more than finger millet and sorghum, regardless of time of planting and seasonal rainfall pattern. Maize yielded > 1 t ha^{-1} for early and normal planting dates when high amounts of fertilizer were applied, while finger millet and sorghum failed completely in some cases. These results are similar to Traore et al. (2013), who reported that maize out-yielded sorghum and pearl millet under different rainfall conditions in southern Mali. The emergence for maize was also greater regardless of the amount of fertilizer applied. In contrast, the emergence for finger millet and sorghum was poor when the soil was amended with manure only or with no fertilization (absolute control). Furthermore, the sorghum harvest was completely damaged by quelea birds, a problem that has also been reported in other parts of Zimbabwe (Macgarry, 1990; Murungweni, 2011) and other regions (Dogget, 1988). The better performance of maize over finger millet and sorghum in this experiment suggests that the recommendation to substitute small grains for maize as a viable adaptation option to a changing climate (Makadho, 1996; Lobell et al., 2008), will neither be the best option for robust adaptation nor attract farmers in sub-Saharan Africa, although we discuss below that dietary considerations can nuance these outcomes.

Sorghum yielded almost double the amount of finger millet in a relatively good rainfall season, when the crops were planted early or during the normal window. The better performance of sorghum was probably due to the high yield potential of the sorghum hybrid cultivar compared with the landrace finger millet. Hybrid cultivars of sorghum generally perform better than landraces when the growing conditions are favourable (Frere, 1984). However, in a season characterized by intervals of very wet and prolonged dry spells, the yield of finger millet was greater than that of sorghum. This suggests that the poor yield of finger millet is offset by a relatively high stability of yield under highly variable rainfall, similar to the yield patterns reported for pearl millet across regions (Pearson, 1985; Muchow, 1989; Chidhuza, 1993).

4.3.2. Crop production and rainfall

Total seasonal rainfall was similar for the two experimental seasons, but the distribution within seasons differed (Fig. 4.1). Consequently, the yield for each crop type declined markedly in the relatively poor 2010/11 rainfall season regardless of planting date and amount of fertilizer applied. The rainfall pattern in the 2010/11 season resulted in both waterlogging and a prolonged dry spell of about three weeks in each site (Fig. 4.1). The prolonged dry spell coincided with the critical flowering period of each crop type and had a profound impact on yields. Since sorghum is more resistant to dry spells than maize partly due to a better developed root system (Frere, 1984), the complete failure of sorghum and finger millet was very likely caused by waterlogging experienced during the initial stages of crop development. This is in marked contrast to another study in Zimbabwe where it was argued that sorghum was found to be more tolerant to waterlogging than maize (Chidhuza, 1993).

Analysis of long-term rainfall over 48 years for Hwedza, indicated that 15 out of 48 years had similar rainfall patterns to that of 2010/11 season characterized by prolonged dry spells of >20 days around end of January to early February (Rurinda et al., 2013). Maize has been reported to perform better than sorghum when total seasonal rainfall is more than 600 mm (Chidhuza, 1993). However, our recent study on analyses of long-term rainfall in the same study sites indicated that this threshold is highly uncertain, and is strongly affected by rainfall distribution (Rurinda et al., 2013). Given that the analysis of historical long-term rainfall data for Hwedza showed that 36 of 48 growing seasons had a total rainfall of above 600 mm (Rurinda et al., 2013), maize production would out-perform small grains three out of four years while small grains would out-compete maize only once in every four years. Thus, based on total rainfall only, sorghum and finger millet could play a role in complementing maize in order to stabilize household food self-sufficiency, given that the region is projected to become increasingly drier due to the changing climate (IPCC, 2013).

Although sorghum has been reported to produce better yields than maize in low rainfall years, the crop is prone to damage by quelea birds. This is one of the reasons why farmers have been shifting to maize even in drier areas, because bird-scaring requires a huge amount of labour (Chuma et al., 2001). Yet, farm-level labour availability is a major constraint in many smallholder farming areas of Zimbabwe and other parts of sub-Saharan Africa (Dorward, 2013). Maize is currently the staple crop in the region and farmers have become accustomed to it. Furthermore, in Zimbabwe the crop has been supported by the government and relief organizations though provision of inputs such as seed (Alumira and Rusike, 2005). Thus, the prospects for increasing area under sorghum may not be viable, unless large areas are planted to sorghum, so that the damage by the birds dilutes over the area. According to the farmers, when sorghum was grown in many fields the damage from birds was shared among farmers, leading to less impact at individual household level. Breeding sorghum cultivars that are not prone to bird damage and increasing the marketing structure of the crop might attract farmers to integrate sorghum into their maize-based farming system.

4.3.3. Crop productivity influenced by fertilization and planting date

Fertilization gave significant improvements in yield of each crop although there was an interaction with planting date and season. The larger the amount of fertilizer applied, the greater the yield obtained particularly in a relatively good 2009/10 rainfall season. The strong response to high amount of fertilizer by small grains, often regarded as less nutrient-demanding crops (Carter and Murwira, 1995), demonstrated that the soils are so poor in fertility that more investment in soil fertility management is a pre-requisite for increased yields. In the poorer 2010/11 rainfall season the impact of fertilization on yield was much smaller. The weak responses of crops to fertilization when the rainfall patterns were erratic were probably caused by the following factors. First, the nutrients could have been leached because of the waterlogging early in the season (Murwira and Kirchmann, 1993). Second, the prolonged dry spell that was experienced during the flowering stage coupled with the poor water holding capacity of these sandy soils could have meant that the soils had insufficient moisture for active nutrient uptake by the growing plants (Hussein, 1987). Another explanation could be that the drought limited further shoot growth, thereby limiting N needs and subsequent N uptake (Tardien, 2006). Accordingly, the financial returns to fertilizer investment were much more attractive in the good 2009/10 rainfall season compared with the poor 2010/11 season (see Table 4.4).

The high fertilization rate had much larger effect on yield of each crop than the low rate for the early and normal planting dates particularly in a season of good rainfall (2009/10). Use of the high rate of fertilizer was financially attractive for maize production with good rainfall, while the low rate was financially attractive for small grains in the good rainfall season. Thus, in favourable seasons, resource-poor farmers can maximize financial returns through production of finger millet, while resource-endowed farmers can maximize financial returns through maize.

Without fertilization, however, the yields of all three crops were poor even in the 2009/10 season when the rainfall amount and distribution were favourable. Farmers generally grow small grains with no or little external nutrient input. Consequently, they obtain yields as low as 0.2 t ha^{-1} as demonstrated by the control treatments (see Fig. 4.4A and B). Carter and Murwira (1995) reported that although farmers responded to the 1991/92 drought by allocating more land to small grains than maize, about 83% of mineral fertilizers was used on maize and only 2% on small grains. This suggests that although farmers recognize the importance of small grains during drought years, their limited access to affordable fertilizers forces them to allocate more fertilizers to maize regardless of seasonal rainfall pattern. Farmers prioritize maize not only because the production process of maize is easy (Alumira and Rusike, 2005), but also because maize is easier to sell on the market than finger millet and sorghum (Easterling et al., 1992).

Planting date also strongly impacted the final yield of each crop, as reported in other studies conducted in southern Africa (Shumba et al., 1992; Crespo et al., 2011; Waha et al., 2013). Yields for the early and normal planted crops were greater because of the increase in the length of time that plants can take advantage of favourable growing conditions, especially soil moisture. However, there was a decrease of > 50% in yield of each crop when planting was delayed by four weeks (late planting). This could have been due to lack of soil moisture caused by shortening of the rainy season and other factors such as decreasing temperatures (Waddington and Hlatshwayo, 1991). Although the yield of each crop decreased for the late plantings, yield of finger millet was less sensitive in a relatively fertile soil in Makoni in a relatively good rainfall season of 2009/10. This goes against a frequent farmers' suggestion that small grains need to be planted very early in the season to obtain yields as high as 1 t ha^{-1}. However, to reduce competition for labour demands between maize and small grains, farmers can dry plant finger millet just before the start of the rainy season, but they need to apply mineral fertilizer to ensure crop establishment as the emergence of small grains was very poor without fertilizer. It has been reported that no weed management was applied to the small grains when planted late because farmers focus their labour allocation on maize, whereas weeding was done for finger millet fields that were planted early (Carter and Murwira, 1995).

Improved management of soil nutrients and agronomic timing of planting increased the effective use of the scarce rain water, thereby resulting in more crop yield per drop of rain water. This is demonstrated by the increase in water productivity for all three crops with increase in the amount of fertilizers applied when crops were planted early or during the normal window (Fig. 4.5). Makurira et al. (2011) also reported that average water productivity increased with the applied innovations such as water conservation techniques.

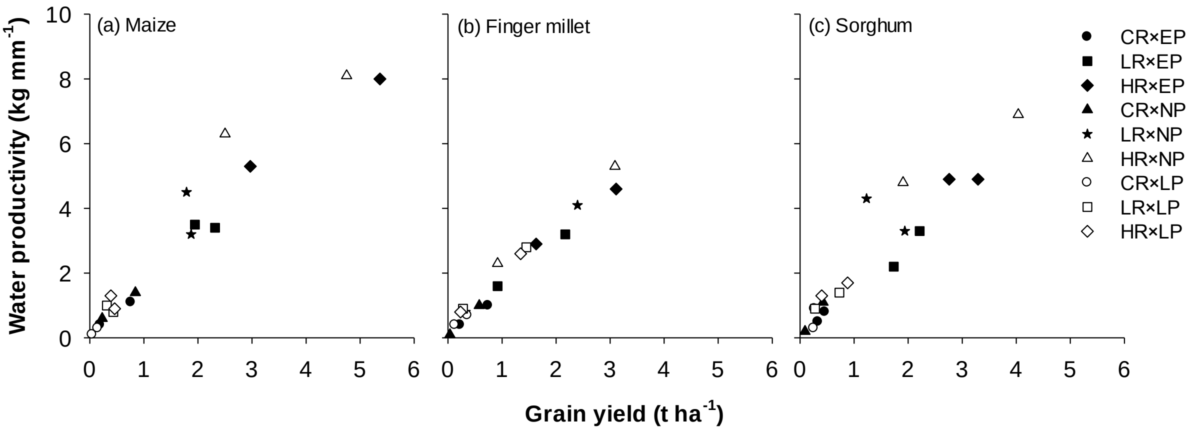

Fig. 4.5. Variation in water productivity with grain yield for maize, finger millet and sorghum under different management of soil fertilization (CR: zero fertilization, LR: low rate- 35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure, HR: high rate- 90 kg N ha^{-1}, 26 kg P ha^{-1}, 7 t ha^{-1} manure), and planting date (EP: early planting, NP: normal planting, LP: late planting), combined for both Makoni and Hwedza.

4.3.4. Impact of fertilization on crop establishment

Emergence for finger millet and sorghum was strongly determined by type and amount of soil nutrient amendment. Sole application of manure gave similar emergence to those under no fertilization, averaging <15%, and yet application of mineral fertilizer solely or in combinations with manure increased the emergence of small grains five-fold. The poor emergence suggests soils that are so depleted that they can no longer support cropping of small grains without external nutrient inputs. For >100 years in many smallholder settlements across southern Africa including Hwedza, land has been cultivated each season with little or no external nutrient inputs (Smaling et al., 1997; Mapfumo and Giller, 2001). This has been worsened by limited recycling of nutrients *in situ* since the crop residues are used as livestock feed, with limited return of the nutrients to the field through manure. Amendment with manure causes initial immobilization of nitrogen in the first eight weeks (Murwira and Kirchmann, 1993).

In contrast, the emergence for maize was >80% regardless of fertilization type and amount. The better emergence of maize is presumably due to the greater nutrient reserves in its larger seed. Because the seed for finger millet and sorghum was obtained from farmers, the quality of recycled seed could have deteriorated. Yet under favourable growing conditions, i.e. when fertilizer was applied, all three crops emerged well. Overall, these findings suggest that without application of mineral fertilizer any future attempt to boost production of small grains as an adaptation measure to impacts of a variable and changing climate is likely to fail.

4.3.5. Opportunities for integrating small grains in maize based farming systems to reduce climatic risk

Although the yields of maize were greater than those of small grains, finger millet and sorghum are important in the human diets in the region (Table 4.5). Finger millet has a higher content of minerals, especially calcium, and dietary fibre than maize (Table 4.5). Lack of nutritionally balanced diet is a major problem in smallholder livelihood systems (UN, 2010). Thus, the production of finger millet is an option to improve human nutrition, particularly for the poorest farmers. To promote production of finger millet there is need for a policy that can bring about a production-marketing model for finger millet and other crops that improve human nutrition such as legumes (Nyagumbo and Rurinda, 2012). The bottom-up approach could be used to understand farmers' needs to increase adoption of such nutritious crops. Policy measures are required to address a number of issues associated with the production of small grains. The marketing structure for finger millet should be improved. The lack of post-harvest processing technologies has affected the development of alternative formal markets for finger millet (Alumira and Rusike, 2005). Some of the issues associated with expanding the area under small grains cause the syndrome known as the "maize poverty trap", where by farmers focus primarily on maize production, even in very dry regions were the crop fails almost every season due to dry spells (Mapfumo, 2009). This has been demonstrated by the continued production of maize each season in the semi-arid to arid regions of the country despite failure of the crop almost each season, and the available information on the robustness of small grains to droughts (Chuma et al., 2001).

Another challenge with the production of maize is how to protect maize grain from post-harvest insect pests in granaries. Traditionally, farmers in Southern Africa have stored surplus grain in granaries as a fall back mechanism against drought years. Maize grain stored in granaries can be heavily damaged by insect pests such as the large grain borer (Kamanula et al., 2011; Milgroom and Giller, 2013). Finger millet can be an alternative to complement household food because its storage losses in general are less than with maize (Chuma et al., 2001). Farmers stated that finger millet could be stored for more than five years with minimum damage from insect pests. This suggests that a good production year for finger millet such as 2009/10 season means multiple years of household food self-sufficiency.

Given that farmers experience poor rainfall patterns once in three or four years and meteorological droughts once in nine or ten years in southern Africa (Chapter 3; Rockström, 2004), farmers could avoid household food self-insufficiency in such bad years by strategically integrating finger millet in their cropping system. During interviews many farmers suggested a strategy to grow finger millet once in two or three years depending on the previous season's harvest. This cropping pattern was decided solely based on the objective of meeting household food self-sufficiency since finger millet grain can last for multiple years with minimum damage from post-harvest pests. To add another objective of improving human nutrition and also, given the uncertainty in predicting a season's rainfall pattern, farmers should allocate a portion of land to finger millet production in each season. Farmers indicated that when they use finger millet to prepare *sadza*, a family of six would consume about 0.6 tonnes of the grain per year, which is half that of maize. As such, finger millet can be a viable option for increasing household food security of poor farmers. Assuming a relatively good rainfall season such as the 2009/10 and when the crop is planted by mid-December with high amount of fertilizer, farmers can allocate about 0.2 ha of land to finger millet. Out of the total normally planted land of about 2.0 ha (Carter and Murwira, 1995), the allocation of 0.2 ha to finger millet would not significantly reduce the production of their preferred maize crop.

4.3. Conclusion

The yield performance of maize was greater than that of finger millet and sorghum regardless of fertilization, planting date and season rainfall quality. The emergence of finger millet and sorghum were greater when the soil was amended with mineral fertilizers, but when the soil was amended with manure alone or when the soil was not fertilized the emergence of small grains was poor. Thus, without farmers having access to mineral fertilizers at affordable prices, the integration of small grains into the currently maize-based cropping systems in southern Africa, as an adaptation option to the changing climate will not likely succeed. This despite some obvious advantages of small grains, for example finger millet can play an important role in improving human nutrition particularly provision of calcium, given that malnutrition is a major problem. Finger millet can also complement maize for household food security particularly during drought years because finger millet experiences less post-harvest and storage losses than maize. Because sorghum was prone to bird damage, increasing the area under sorghum is likely be unattractive to farmers. Breeding of sorghum cultivars that are resistant to bird damage may be necessary. Overall, maize production remains highly competitive and the recommendation to substitute maize with small grains will neither attract farmers nor build a robust adaptation option to climate variability and change. This field-based comparative assessment of yield performance of maize, finger millet and sorghum provides data that can form a basis for simulation modelling studies to understand yield response of each crop to long-term weather data.

Chapter 5

Simulating maize yield responses to climate change and adaptive farm management options for supporting smallholder farmers decisions in Zimbabwe

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Abstract

Concern about food security has increased in southern Africa because of a changing climate. We quantified the response of maize yield to projected climate change and to planting date, fertilization and maize cultivar choice as three key management options using APSIM. We focus especially on the interactions between these factors, to assess how the efficiency of interventions might change in the future in southern African. Three climate periods were selected to cover both near and long term climates: 2010-2039; 2040-2069; 2070-2099, against a baseline, 1976-2005. Future climate data for two Representative Concentration Pathways (RCPs): rcp4.5 with radiative forcing of 4.5 W m^{-2} and rcp8.5 with radiative forcing of 8.5 W m^{-1}, were generated from an ensemble of five global circulation models. The surface air temperature is projected to increase significantly in Makoni and Hwedza by 2100. Yet there is no clear evidence that the annual rainfall in the two study sites will change by 2100 under both the low and high emission scenarios. Yield responses for all three maize cultivars to future changes in climate were similar regardless of the adaptive management of planting date and soil nutrient input. Compared with the baseline climate, the simulated average grain yield for all three maize cultivars declined by an average of 11% for the time slices, 2010-2039 and 2040-2069, and 17% for 2070-2099, under the low radiative forcing when planting before mid-December with high fertilization rate, for Hwedza. Under the high radiative forcing, the simulated grain yield further declined by an average of 17% for the time slices, 2010-2039 and 2040-2069, and 25% for 2070-2099 when planting before mid-December with high fertilization rate, for Hwedza. Similar trend in yield changes were observed for Makoni. The simulated average maize yield increased gradually with planting date from early November to mid-December for each study site. Then after mid-December the simulated maize yield decreased drastically. Fertilization increased yield significantly under both the baseline and future climates particularly when planting before mid-December. The response of maize to increase in the amount of nitrogen decreased for all three climate periods for each radiative forcing, as compared with the baseline climate. For example, at 80 kg N ha^{-1}, maize yield of about 4.5 t ha^{-1} was simulated for the baseline climate, against maize yields of about 3.5 t ha^{-1} for the climate periods, 2010-2069 and 3 t ha^{-1} for 2070-2099 under the rcp4.5. In conclusion there is a reasonably wide planting window if the rains start on time, but if the start of the rains is delayed until after the beginning of December this advantage is lost and planting should be done as soon as possible. Soil fertility management will remain a key strategy for stabilizing maize yield, even under a changing climate although wealthier farmers who apply high rates of fertilizers may need to reduce their rates to increase returns to investment.

Key words: Climate change; Adaptation; Maize; Fertilization; Planting date; Simulation modeling

5. Introduction

Concern about food security has increased in southern Africa because of a changing climate, which poses a great threat to food crop productivity. Rising temperatures and changing rainfall patterns, which are already evident in southern Africa, are the major climatic variables threatening crop production in the region (Lobell et al., 2008; Neukom et al., 2013). In Zimbabwe, mean daily maximum temperature has increased by 0.1°C per decade between 1962 and 2009 (Rurinda et al., accepted), and is projected to further increase by between 2^{o}C and 4^{o}C by 2100 (Unganai, 1996) similar to global projections (IPCC, 2013). A large area of southern Africa is projected to experience a decrease in rainfall by 2100 (Shongwe et al., 2009). Neukom et al. (2013) indicated that rainfall already declined in southern Africa between 1796 and 1996. Other studies have indicated that the total rainfall has so far not changed, but that there is increased rainfall variability characterized by a delayed onset of the rainy season and more frequent droughts (Tadross et al., 2009; Rurinda et al., 2013). Overall, although rainfall projections contain a large uncertainty and spatial variation, southern Africa is expected to become drier (IPCC, 2013).

The increasing temperatures, in combination with more severe and frequent droughts, will profoundly reduce soil water available for plant uptake. Fraser et al. (2013) projected that soil moisture will decline by 25% in southern Africa because of more frequent droughts. Rising temperatures will shorten the crop growth period and will increase plant water demand through higher transpiration rates, both potentially reducing plant production (Ludwig and Asseng, 2006; Springate and Kover, 2014). Furthermore, increasing temperatures will directly affect plants through heat waves and this impact will be larger when coupled with soil moisture deficits. Lobell et al. (2011) found that each degree day spent above 30°C reduced maize yield by 1.7% under drought conditions, compared with a decrease of 1% under favourable rain-fed conditions in Africa. Given that the impacts of higher temperatures are most pronounced on sandy soils (Ludwig and Asseng, 2006), the predominant soil type in smallholder cropping areas of southern Africa (Hartemink and Huting, 2008), smallholder farmers in this region face a high risk of declining crop yields.

Climate change is also anticipated to positively influence crop production. For example, crop productivity is anticipated to improve due to increased concentration of carbon dioxide (CO_2) in the atmosphere (IPCC, 2007). However, maize, the main staple cereal crop in Southern African is a C_4 plant which will benefit relatively little from increased CO_2 concentrations (Easterling et al., 1992). The low soil nutrient availability on the highly weathered sand soils which cover a large area of smallholder farming areas in the region, can reduce the yield benefit of elevated CO_2 (Tubiello and Ewert, 2002). It is therefore likely that the impacts of increased temperatures coupled with soil moisture deficits will override the compensating effects of increased CO_2 on maize yields in southern Africa (Rosenzweig and Parry, 1994).

Efforts have been made to understand and quantify the impacts of increased temperatures and changing rainfall patterns on crop production in southern Africa (Fischer et al., 2005; Zinyengere et al., 2013). Using a statistical model, Lobell et al. (2008) predicted that maize production will decline by between 20% and 40% in southern Africa due to warming temperatures and change in rainfall patterns. These studies quantified the possible effects of climate change on crop production, but did not analyse how these effects interact with the possible opportunities of adaptive farm management such as cultivar choice, timing of farming operations and adjusting soil nutrient inputs (White et al., 2011). Yet the net impact of climate change on crop yield depends strongly on the interactions between climate and management (Reidsma et al., 2009).

To provide a comprehensive assessment of climate change effects on crop yields, it is critical to understand the interactions between climate and possible adaptive farm management options. Howden et al. (2007) argued that a relatively small change in farm management and selection of different crop varieties can significantly reduce any negative impact of moderate climate change. Through field experimentation, Rurinda et al. (2013) demonstrated that improved timing of planting and adjusting soil nutrient inputs can stabilise maize yields under variable rainfall conditions in Zimbabwe. By modelling the current cropping systems in sub-Saharan Africa, Folberth et al. (2013) showed that under irrigation, increasing soil nutrient supply in combination with improved cultivars would allow for a doubling of maize yields. However, the outcome for the same strategies is likely to be different under rain-fed conditions because of the interaction between fertilization and rainfall.

In the few impact studies that have taken into account farmer adaptive management options (Crespo et al., 2011; Waha et al., 2013), the broad scale of assessment makes their findings difficult to translate into knowledge that can drive local solutions. Although there is much debate about the appropriate scale to operate (Challinor et al., 2009), local studies with crop models allow for better calibration and validation (e.g. soil nutrients and water conditions), compared with regional approaches (Fischer et al., 2005), and can also help farmers to make appropriate decisions.

Further, the impacts of the changing climate on crop yields vary with location due to spatial variability in climate, particularly rainfall (White et al., 2011). For example, responses of maize in southern Africa to the changing climate can be as wide as –40% to +10% (Zinyengere et al., 2013). Thus, more work is needed to assess risks and to reduce the uncertainty concerning the possible impacts of the changing climate on crop yields. In particular, risk assessment is critical in African countries where research on climate impact and adaptation is still scarce (White et al., 2011). In addition, many adaptive farm management options have been identified through a top-down approach (e.g. Phillips et al., 1998). Because of the uncertainties associated with the changing climate (Dessai and van der Sluijs, 2007), and the differences in endowments among farmers (Mtambanengwe and Mapfumo, 2005), a bottom up approach can be useful for integrating local farmers' and expert empirical knowledge as well as linking knowledge with action.

In this study, we quantified the response of maize yield to projected climate change and to planting date, fertilization and maize cultivar choice as three key management options. We especially focus on the interactions between these factors, to assess how the efficiency of interventions might change in the future in southern African. We hypothesize that: i) the average yields for maize will decrease with increasing temperatures and changes in rainfall patterns for the future periods, 2010-2039, 2040-2069 and 2070-2099, compared with average yields for baseline climates in Zimbabwe; 2) the response of maize yield to fertilization and planting date will change with climate change, 3) this response will be affected by the choice of maize cultivar and therefore that improved management of planting date, fertilization and choice of crop cultivar can compensate for the predicted decrease in crop yields due to climate change.

5.1. Materials and Methods

5.1.1. Study sites

The focus study sites were Makoni and Hwedza districts in eastern Zimbabwe. These two districts have dry sub-humid and semi-arid tropical contrasting climates, respectively. Rainfall in Zimbabwe as in many parts of southern Africa is seasonal and falls between October and April with the highest rainfall amounts received between December and February. Within-season rainfall variability is currently the main climatic driver for crop production in Makoni and Hwedza, with average annual rainfall of 850 mm and 700 mm, respectively (Rurinda et al., 2013). In both sites, average monthly temperatures are normally above 20°C between October and April, and temperatures are highest in October, before the start of the rains. Crop production in Zimbabwe is considered to be mainly determined by the availability of soil water with temperature not a major limiting factor (Hussein, 1987). Given that the two study sites are hotspots for increased climatic risk, particularly increased temperatures coupled with more frequent droughts (Rurinda et al., 2013; Thow and de Blois, 2008), temperature will also play a key role in determining crop yields. The soils in both sites are granite derived sandy soils, mainly Lixisols and Arenosols (World Soil Resource Base, 1998), with a low water available for plant uptake. The farming system in the two sites is maize-based with cattle providing draught power and manure for crop production.

5.1.2. Application of the APSIM crop simulation model

Maize yield responses to planting date and amount of nitrogen applied were simulated using the Agricultural Production Systems Simulator (APSIM), version 7.5. APSIM is a process-based model developed to simulate biophysical processes in farming systems in response to management decisions and in the face of climatic risk (Keating et al., 2003). The model estimates plant growth and crop yield using a daily time step. APSIM has been tested widely against field experimental data in a wide range of growing conditions across the globe (Keating et al., 2003), including semi-arid and sub-humid regions of southern Africa (Whitbread et al., 2010; Chikowo, 2011). The model is described in detail by Keating et al. (2003).

In this study the APSIM model was used to quantify the sensitivity of maize yield to different adaptive farm management options under future predicted daily weather, including possible changes in rainfall, temperature and solar radiation. Daily weather data for baseline and future climates were generated using ensembles of climate circulation models (GCMs), described below. The main APSIM modules used in this study included the plant (maize); environment (meteorological input module, soil water, soil nitrogen and organic matter dynamics, soil phosphorus); and management. The soil phosphorus module was included because phosphorus is a limiting nutrient in soils of Zimbabwe (Nyamapfene, 1989) and the region (Hartemink and Huting, 2008).

Each APSIM module demands a number of parameters. For the SOILWAT model, which simulates the dynamics of soil water, the inputs included soil bulk density, soil water lower limit (*LL15*) and upper limit (*DUL*), and two parameters, *U* and *CONA*, which determine first and second stage soil evaporation. *LL15* and *DUL* were derived based on soil classification using regression equations calculated by Hussein (1983). Soil saturation was estimated from bulk density. The parameters, *U* and *CONA* were set at 6.0 mm day^{-1} and 3 mm day^{-1}, respectively, values acceptable for tropical conditions (Chikowo, 2011). A value of 0.7 was used for *SWCON*, a coefficient that specifies the proportion of the water in excess of field capacity that drains to the next layer in one day (Chikowo, 2011). The bare soil runoff curve number (*CN*) was set at 50 to take into account the low runoff associated with sandy soils because of high infiltration rates (Hussein, 1987). For the soil N model the organic matter content for each soil layer was measured in farmers' fields during the experiments that were conducted in Makoni and Hwedza districts of Zimbabwe, between 2009 and 2012 (Rurinda et al., 2013). The initial soil N was set at 35 kg ha^{-1} (23 kg ha^{-1} NO^{3-}-N and 12 kg ha^{-1} NH^{4+}-N) based on field measurements (Mtambanengwe and Mapfumo, 2006). The major soil parameters used in APSIM are provided in Table 5.1.

Default cultivars in APSIM that are commonly used in Zimbabwe were selected for simulation because their phenology and physiology are similar to those used during field experiments. Accordingly, APSIM crop parameters for SC401, a very early maturing cultivar; SC501, an early maturing cultivar; and SC625, a medium maturing cultivar (Table 5.2), were selected to represent cultivars used in the field experiments namely SC403, a very early maturing cultivar; SC513, an early maturing cultivar; and SC635, a medium maturing cultivar, respectively (Rurinda et al., 2013). During simulations, soil organic matter, nitrogen, phosphorus and water, were re-initialized at the start of each planting window for each growing season.

Table 5.1. Soil physical and chemical properties used for the simulations in APSIM

Soil depth (m)	BD (Mg m^{-3})	OC (%)	LL15 (m^3 m^{-3})	DUL (m^3 m^{-3})	SAT (m^3 m^{-3})	NO_3-N mg kg^{-1})	NH_4-N (mg kg^{-1})	Labile P (mg kg^{-1})	P sorption (mg kg^{-1})	pH_{H2O}
0.00-0.10	1.44	0.57	0.06	0.17	0.30	5	0.8	5.0	80	5.4
0.10-0.20	1.50	0.37	0.06	0.18	0.30	3	0.2	2.0	80	5.5
0.20-0.41	1.48	0.21	0.07	0.19	0.32	2	0.6	1.0	100	5.5
0.41-0.68	1.50	0.11	0.07	0.19	0.33	1.8	1.2	1.0	150	5.6
0.68-0.94	1.53	0.07	0.08	0.20	0.34	1.6	1	1.0	200	5.5
0.94-1.20	1.57	0.05	0.08	0.21	0.35	1.5	1.4	1.0	250	5.7

BD = bulky density; OC = organic carbon; LL= Lower limit (volumetric water content at -15 bar pressure potential); DUL = drained upper limit; SAT = Saturation volumetric water content.

Table **5.2.** Crop parameters for three maize cultivars used for the simulations in APSIM

Parameter or variable		SC403	SC513	SC635	Units
Thermal time accumulation	Emergence-end juvenile	230	250	280	°C day
	End juvenile- floral initiation	0	0	0	°C day
	Flag leaf-flowering	10	10	10	°C day
	Flowering-start grain filling	170	170	170	°C day
	Flowering - maturity	730	730	750	°C day
	Maturity harvest (ripe)	1	1	1	
Photoperiod	Day length photoperiod to inhibit flowering	12.5	12.5	12.5	H
	Day length photoperiod for insensitivity	24	24	24	H
	Photoperiod for insensitivity	23	23	23	°C/H
	Base temperature	10	10	10	°C
Grain	Grain maximum number per head	500	520	560	
	Grain growth rate	9	9	9	mg/grain/day

5.1.3. Description of climate models

A critical way of dealing with uncertainties in the future climate is to use a range of possible future climate change scenarios rather than a single projection, to be able to address a range of future climate possibilities (Challinor et al., 2009). Future climate data for two Representative Concentration Pathways (RCPs): rcp4.5 with radiative forcing of 4.5 W m^{-2} and rcp8.5 with radiative forcing of 8.5 W m^{-1}, were generated from an ensemble of five global circulation models (GCMs) (CNRM-CM5, ECEARTH, HADGEM2-ES, IPSL-CM5A-LR and MPI-ESM-LR). These climate models were also used in the current IPCC report (2013). RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which Integrated Assessment Models produced corresponding emission scenarios (IPCC, 2013). While radiative forcing is the change in the balance between incoming and outgoing radiation to the atmosphere caused by changes in atmospheric constituents, such as carbon dioxide (Moss et al., 2010). The rcp8.5 is a high emissions scenario, corresponding to projections of high human population (12 billion by 2100), high rates of urbanization and limited rates of technological change, all resulting in emissions approaching 30 Gt of carbon by 2100 compared with 8 Gt in 2000 (Riahi et al., 2007). The rcp4.5 scenario is an intermediate mitigation scenario characterized by continuously increasing human population but at a rate lower than in the rcp8.5 scenario, intermediate levels of economic development and less rapid and more diverse technological change (Moss et al., 2010). The concept of running multiple models, i.e. ensembles, and aggregating the outputs, is known to improve the accuracy and precision of the projections compared with individual models (Van der Linden and Mitchell, 2009; IPCC, 2013). The climate data was obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (http://pcmdi3.llnl.gov/esgcet/home.htm, last accessed 4 January 2014).

The GCMs' projections were re-gridded to a spatial resolution of 0.5 x 0.5 degree and bias corrected according to the method by Piani et al. (2010) using the Watch data set as a reference (http://www.eu-watch.org). Although this approach introduces uncertainty, many studies have shown that bias-corrected climate data improves impact assessment results (e.g. Supit et al., 2012).

Because all five models were driven by the same emission scenarios, all runs represented an equally possible projection of the future change of the climate. Accordingly, daily mean values for temperature, rainfall and solar radiation generated by the five GCMs were used in APSIM to simulate maize growth. The sensitivity of maize yield was assessed for three future climate periods: 2010-2039; 2040-2069; 2070-2099, against a simulated historical climate for the period, 1976-2005. These three climate periods were selected to cover both near-term climates relevant for assessing relatively immediate benefits to agricultural investments (Lobell et al., 2008), and long-term climate for sustainable crop production and illustrating the situation in which climate change is more clearly separated from natural climate variability (Ruane et al., 2013).

5.1.4. Adaptive management options identified by farmers and field experimentation for testing APSIM

Maize yield-planting date and maize yield-nitrogen response curves simulated in this study were based on the adaptive management options that were identified by farmers through participatory approaches. These were: adjusting planting dates; adjusting soil nutrient inputs and use of different maize cultivars (Mapfumo et al., 2013).

Data used to test APSIM performance were derived from experiments conducted between 2009 and 2011 in farmers' fields in the study sites (Rurinda et al., 2013). Three maize cultivars, three planting dates, and three fertilization rates were laid out in a split-plot block design with three replications per treatment. Planting date was assigned to the main plot, and fertilization rate × maize cultivar sub-plots were randomized within the main plot. The three maize cultivars were SC 403 (131 days to maturity), SC 513 (137 days to maturity) and SC 635 (142 days to maturity). These represent the range of maize cultivars currently available on the market, and important to note is the relatively small difference in days to maturity between the cultivars. The three planting windows were 25 October - 20 November, 21 November - 15 December, 16 December - 1 January. In the two experimental seasons the planting windows were revisited together with farmers to match each season' rainfall pattern (Rurinda et al., 2013). The three fertilization rates were a control treatment (unfertilized), low rate (35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure, on a dry weight basis) and high rate (90 kg N ha^{-1}, 26 kg P ha^{-1}, 7 t ha^{-1} manure, on a dry weight basis). The basal application was applied as compound D (7% N, 14% P_2O_5 and 7% K_2O) and the top dressing as ammonium nitrate (34.5%). Rainfall was recorded at both sites for the two experimental seasons: 2009/10 and 2010/11. Yield and biomass data from these experiments were used to test the model performance. Model error was expressed as the mean squared error (RMSE), which is the most commonly used estimate to measure the predictive accuracy of a model (Tedeschi, 2006). In addition to RMSE, the coefficient of determination of regressions of predicted against observed yields was used to evaluate the precision of the model.

In assessing maize yield responses to planting date, three scenarios were simulated based on the three fertilization rates mentioned above. The maize cultivars were planted at an interval of one week from one November to ten January. In assessing maize yield responses to N input, increasing rates of ammonium nitrate at an interval of 5 kg N ha^{-1} from 0 up to 120 kg N ha^{-1} (the recommended rate, (Zingore et al., 2007)). The nitrogen was applied at 35 days after sowing. Phosphorus was applied at planting at a rate of 26 kg P ha^{-1}. The maize yield-nitrogen response curves were simulated for the three planting windows defined by farmers as mentioned above. In all scenarios the maize cultivars were planted at 37 000 plants ha^{-1} in each season, following 20 mm of rainfall in 3 consecutive days. If the rainfall condition was not met in a particular defined planting window, the crop was planted at the end of the window.

5.2. Results

5.2.1. Performance of APSIM model

APSIM performed well in predicting yields for maize planted early or during the normal window, for all fertilization rates and cultivars in the relatively good 2009/10 rainfall season in both sites (RMSE <0.5, R^2 >0.8;) (Fig. 5.1). Similarly, the model predicted the biomass reasonably well for the 2009/10 season (Fig. 5.1). However, the model over-predicted yields and biomass for the late planted cultivars in the 2009/10 season (RMSE >1, R^2 = 0.5) (Fig. 5.1). In the 2010/11 season characterized by waterlogging conditions and prolonged dry spells, APSIM over predicted both yield and biomass, especially for the nutrient depleted soils in Hwedza (Fig. 5.1).

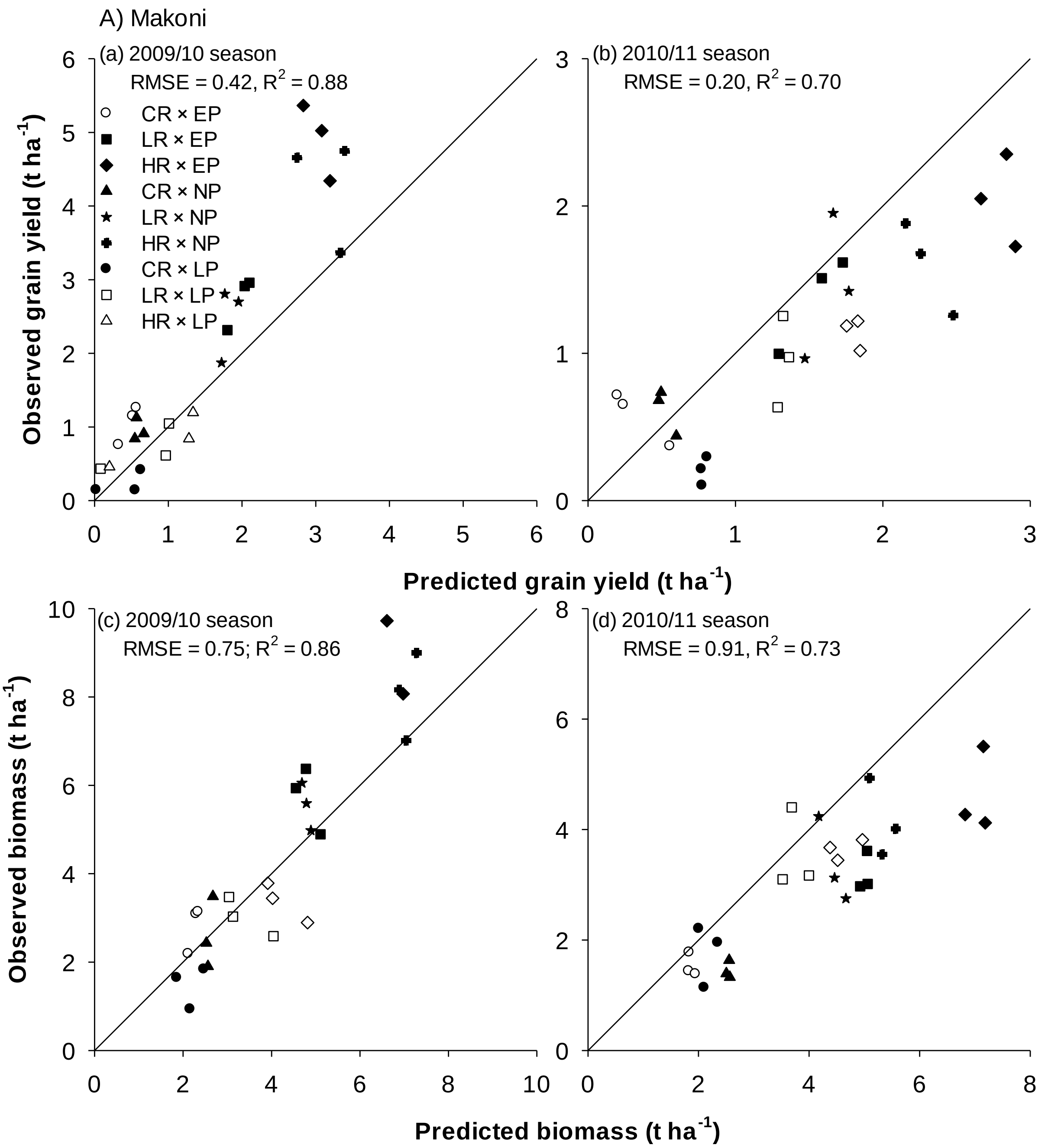


Fig. 5.1. APSIM performance in predicting yields for (a) 2009/10 season and (b) 2010/11 season; and biomass for (c) 2009/10 season and (d) 2010/11 season, for all three adaptive management options: three planting dates (early (EP), normal (NP) and late (LP)), three fertilization rates (zero fertilization (CR), low rate (LR): 14 kg P ha^{-1}; 35 kg N ha^{-1}, 3 t ha^{-1} manure, and high rate (HR): 26 kg P ha^{-1}; 90 kg N ha^{-1}, 7 t ha^{-1} manure) and three maize cultivars (SC403; SC513 and SC635), for A) Makoni and B) Hwedza.

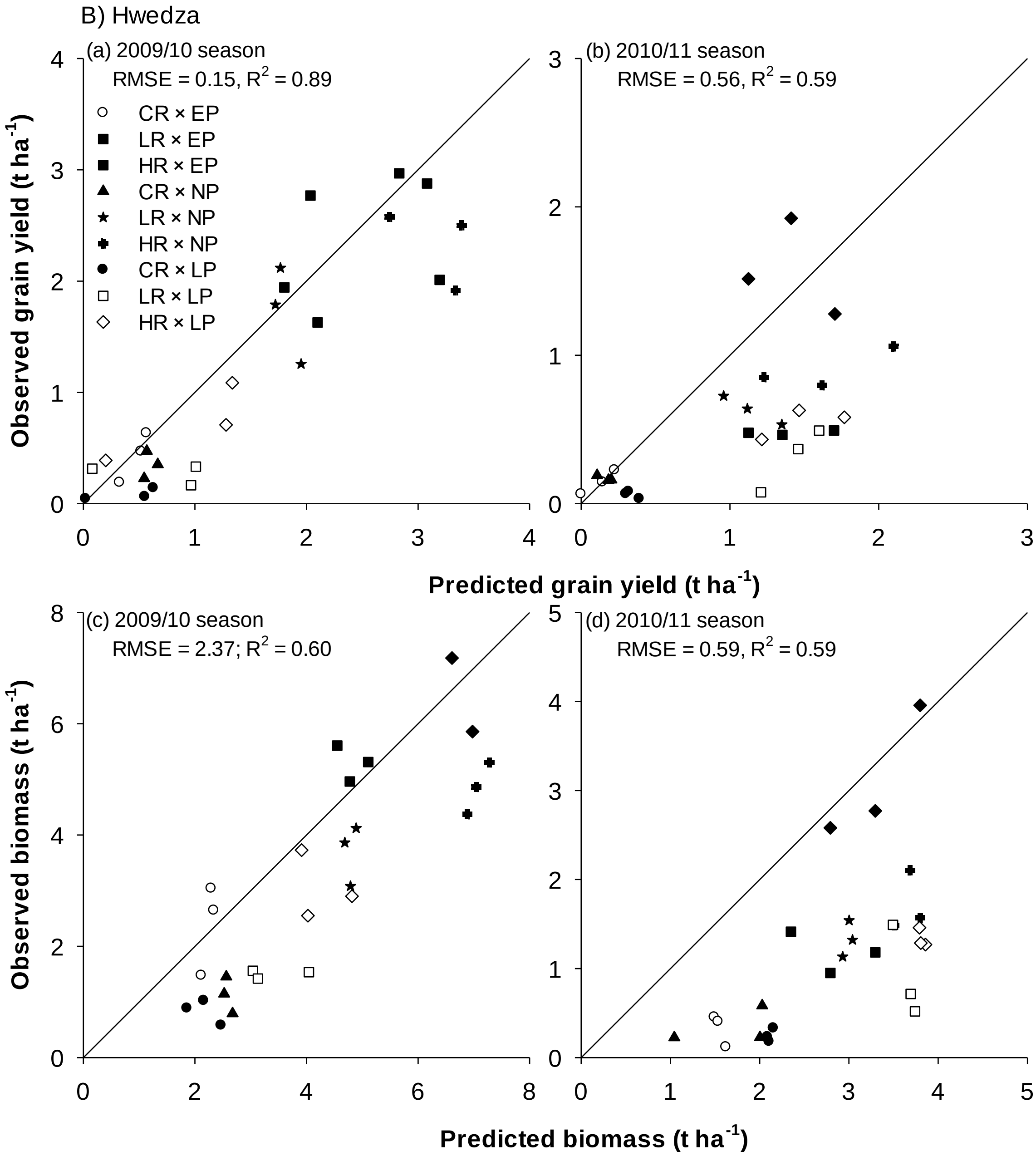


Fig. 5.1. continued.

5.2.2. Projected temperature and rainfall conditions by 2100

The temperature is projected to increase significantly with time and with increase in the radiative forcing for both Makoni and Hwedza (Fig. 5.2). As such, the greatest increase in temperature is projected for the time slice 2070-2099, under the high radiative forcing of 8.5 W m^{-2} (Fig. 5.2). The direction of possible change in total rainfall is less clear in the future for all three future time slices and for each radiative forcing (Fig. 5.3). Thus, the total amount of rainfall is unlikely to change by 2100 in Makoni and Hwedza (Fig. 5.4).

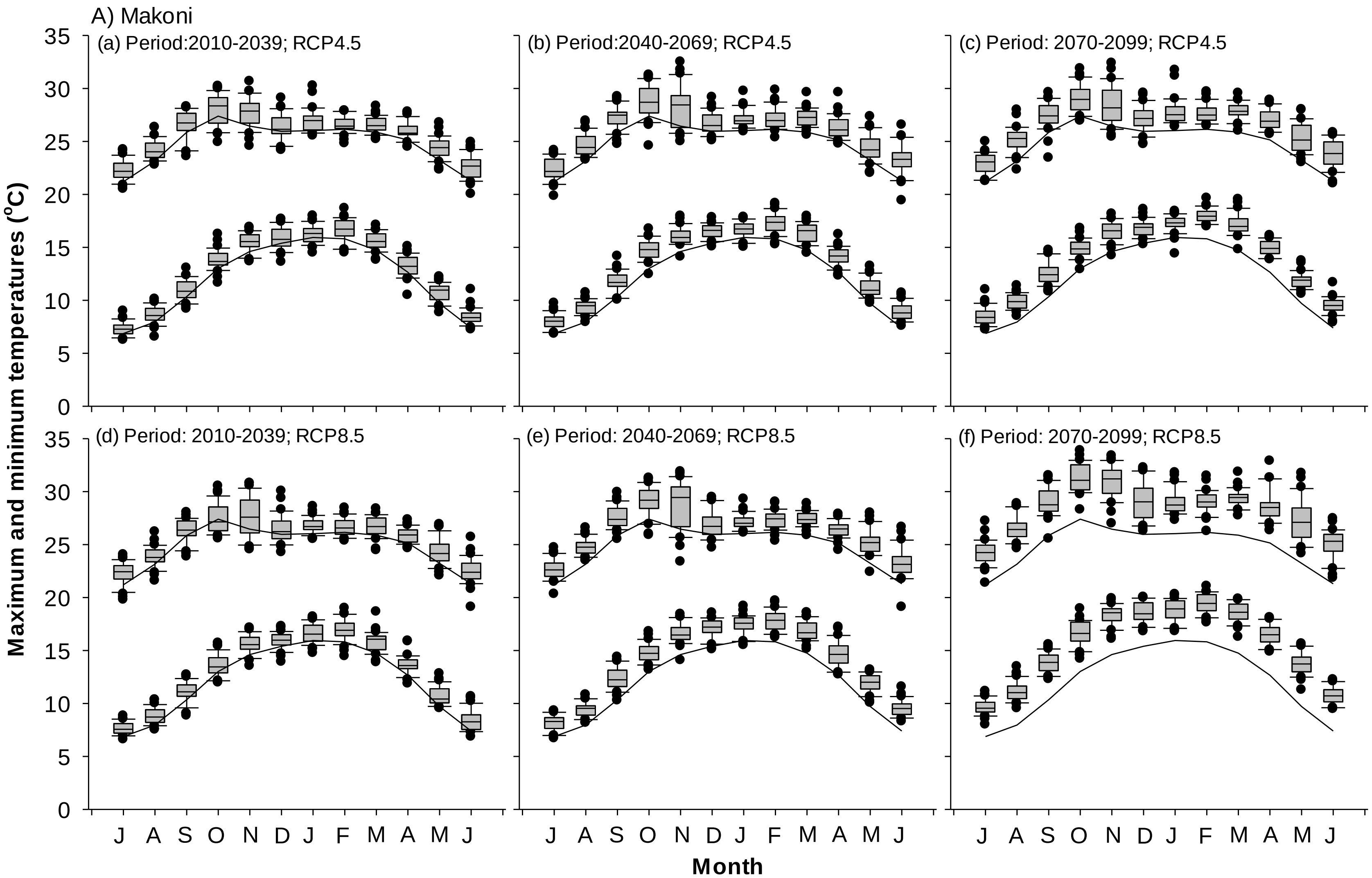


Fig. 5.2. Projected maximum and minimum temperatures for three climate change periods: near-term (2010-2039), mid-term (2040-2069) and long-term (2070-2099), against simulated baseline temperatures (solid lines), for two radiative forcings: RCP 4.5 and RCP 8.5, for A) Makoni and B) Hwedza. The Box and Whisker plots show the temperature variation based on the ensembles of five GCMs.

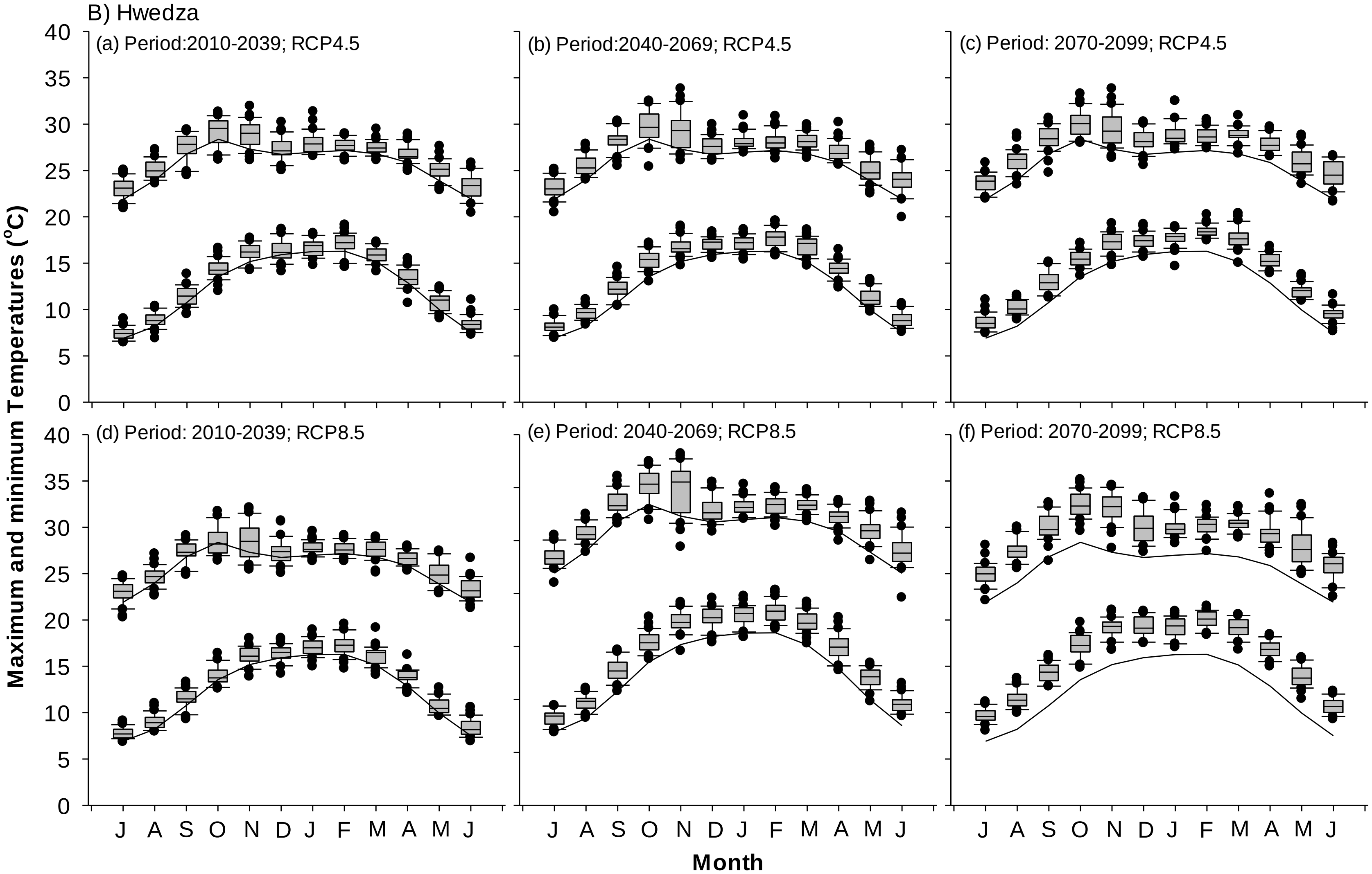


Fig. 5.2. continued.

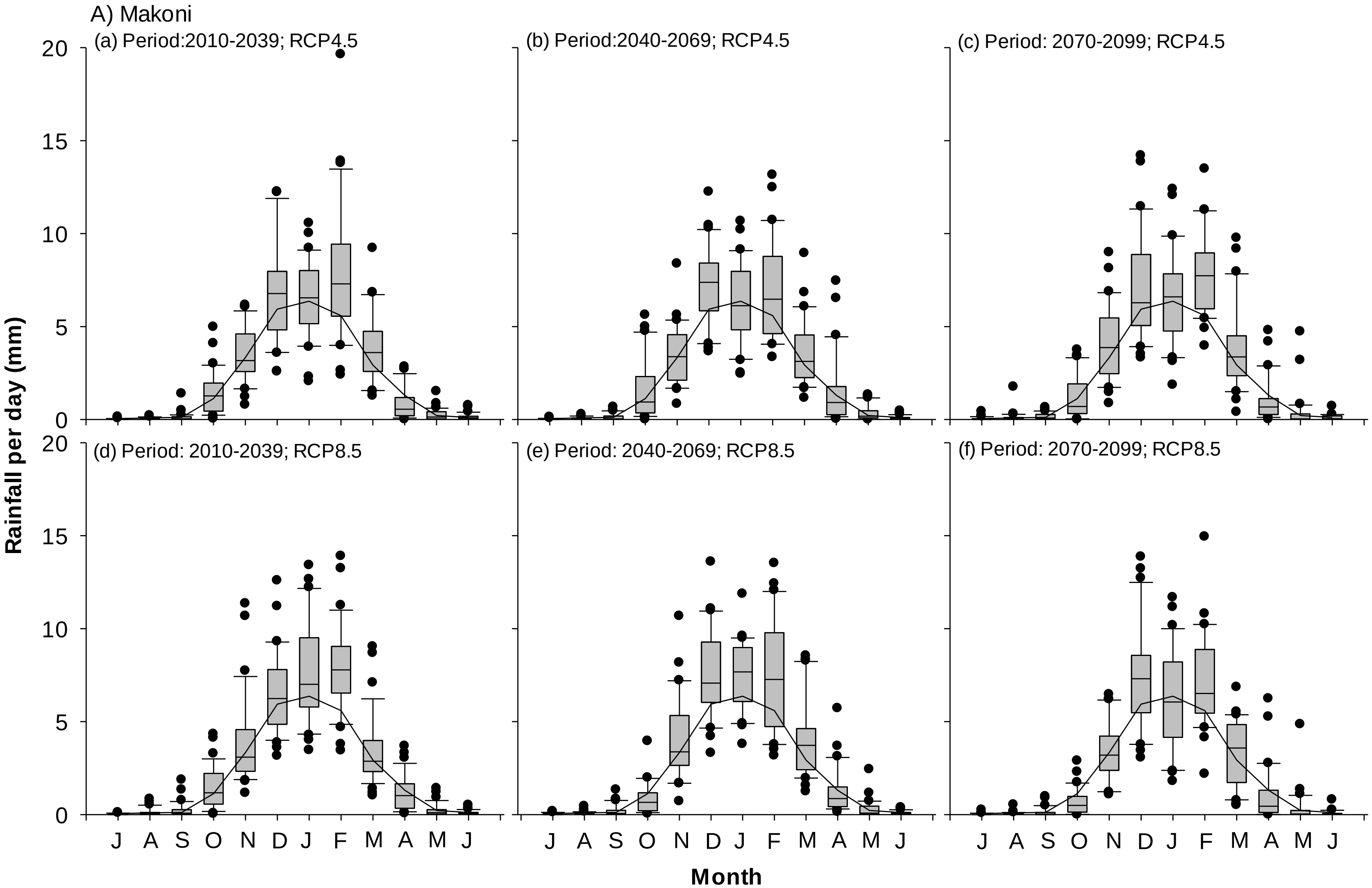
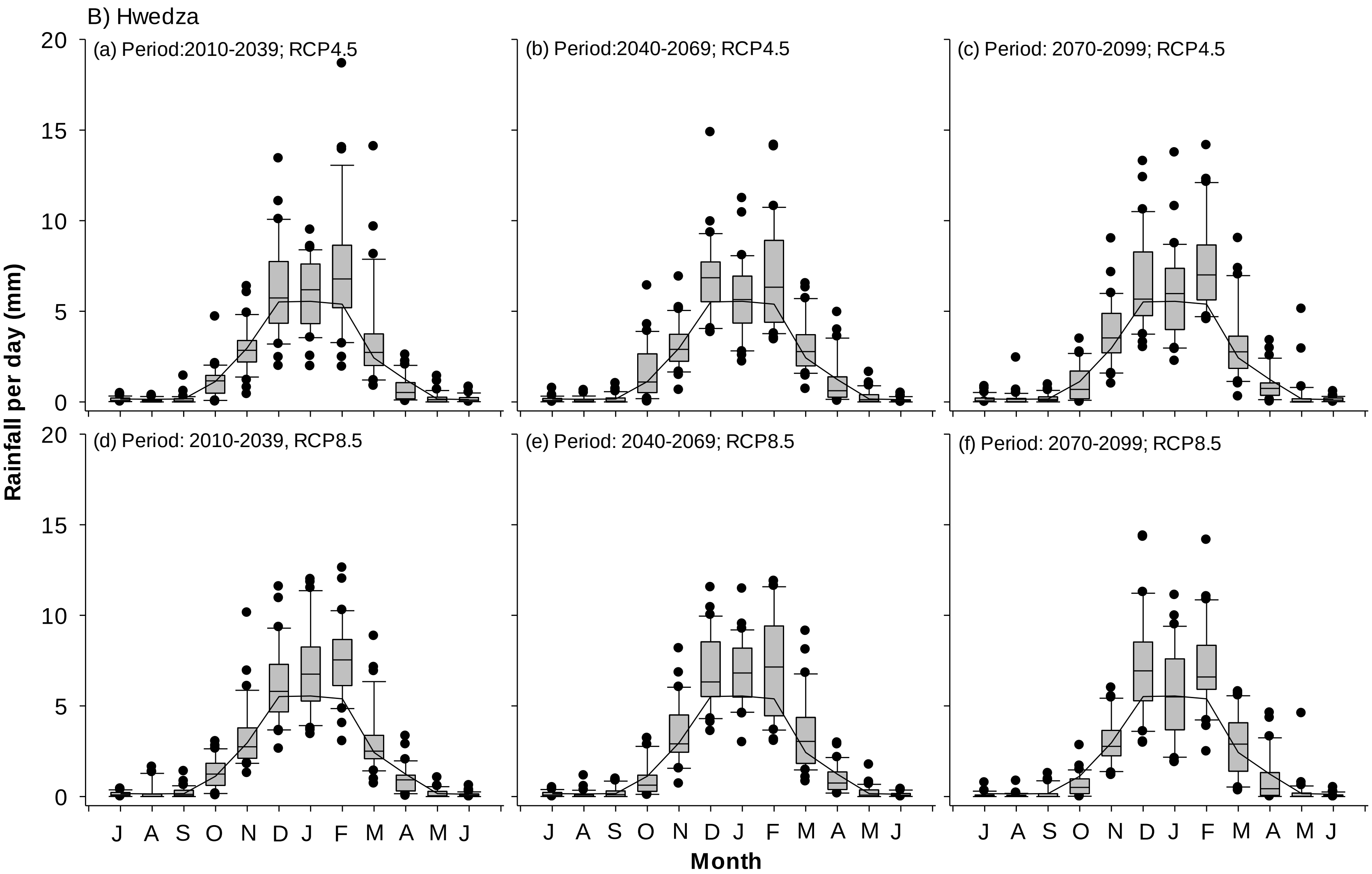


Fig. 5.3. Projected daily rainfall in each month for three resampled climate change periods: near-term (2010-2039), mid-team (2040-2069) and long-term (2070-2099), against simulated baseline rainfall (solid lines), for two radiative forcings: RCP 4.5 and RCP 8.5, for A) Makoni and B) Hwedza. The Box and Whisker plots show the rainfall variation based on the ensembles of five GCMs.



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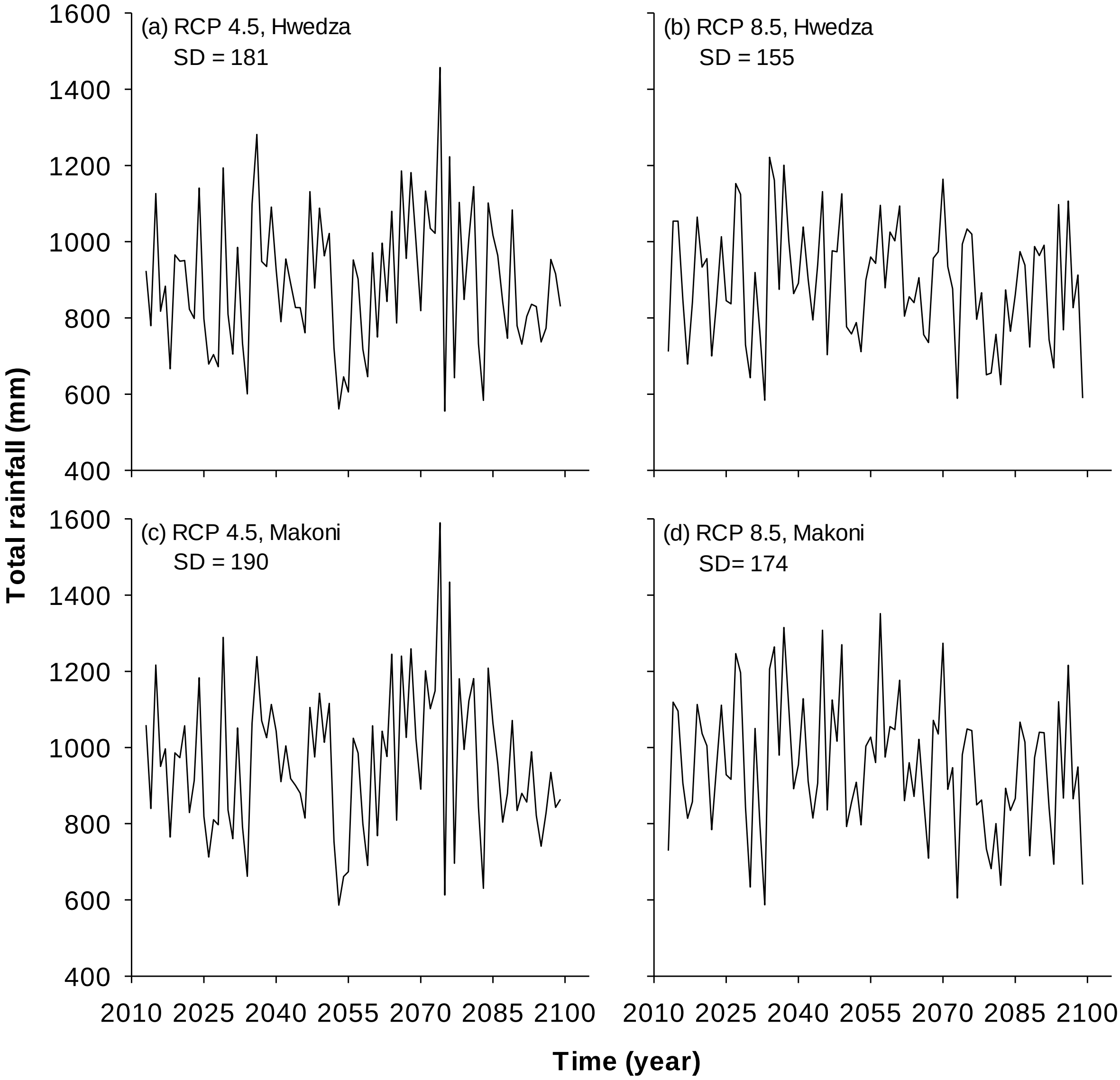

Fig. 5.4. Projected long-term annual rainfall for two radiative forcings: rcp4.5 and rcp8.5 for Makoni and Hwedza in the 21st Century.

5.2.3. Consequences of the changing climate and its interaction with adaptive management options on maize yield

5.2.3.1. Impact of maize cultivar choice on yield under varied scenarios of future temperatures and rainfall patterns

Maize yield simulated with the modelled historical climate data was larger by about 0.6 t ha^{-1} than that simulated with the observed historical climate data (Fig. 5.5). Yield responses for all three maize cultivars to future changes in climate were similar regardless of the adaptive management of planting date and soil nutrient input (Fig. 5.6). Compared with the baseline climate, the simulated average grain yield for all three maize cultivars declined by an average of 11% for the time slices, 2010-2039 and 2040-2069, and 17% for 2070-2099, under the low radiative forcing of 4.5 W m^{-2} when planting before mid-December with high fertilization rate, for Hwedza (Fig. 5.6A). Under the high radiative forcing of 8.5 W m^{-2}, the simulated grain yield further declined by an average of 17% for the time slices, 2010-2039 and 2040-2069, and 25% for 2070-2099 when planting before mid-December with high fertilization rate, for Hwedza (Fig. 5.6A). Climate change effects on maize were very small when low rates of fertilizer were used (Fig. 5.6). Thus, the greatest maize yield loss is projected towards the end of the 21st Century mostly under the high radiative forcing of 8.5 W m^{-2} when high rates of fertilizer is applied. Although a greater yield loss was simulated for Hwedza, the change in yield was generally similar with that for Makoni (Fig. 5.6B).

5.2.3.2. Delayed planting effects on maize yield under increased temperatures and varying rainfall patterns

The simulated average maize yield increased gradually with planting date from early November to mid-December for each study site (Fig. 5.6). In other words the yield increased slightly with a small delay in planting. Then after mid-December the simulated maize yield decreased drastically. Overall, the maize yield response to planting date was similar from November to mid-December for all three future climate periods for each radiative forcing (Fig. 5.6). When planting was substantially delayed i.e. after mid-December, the maize yield responses to planting date decreased drastically (Fig. 5.6).

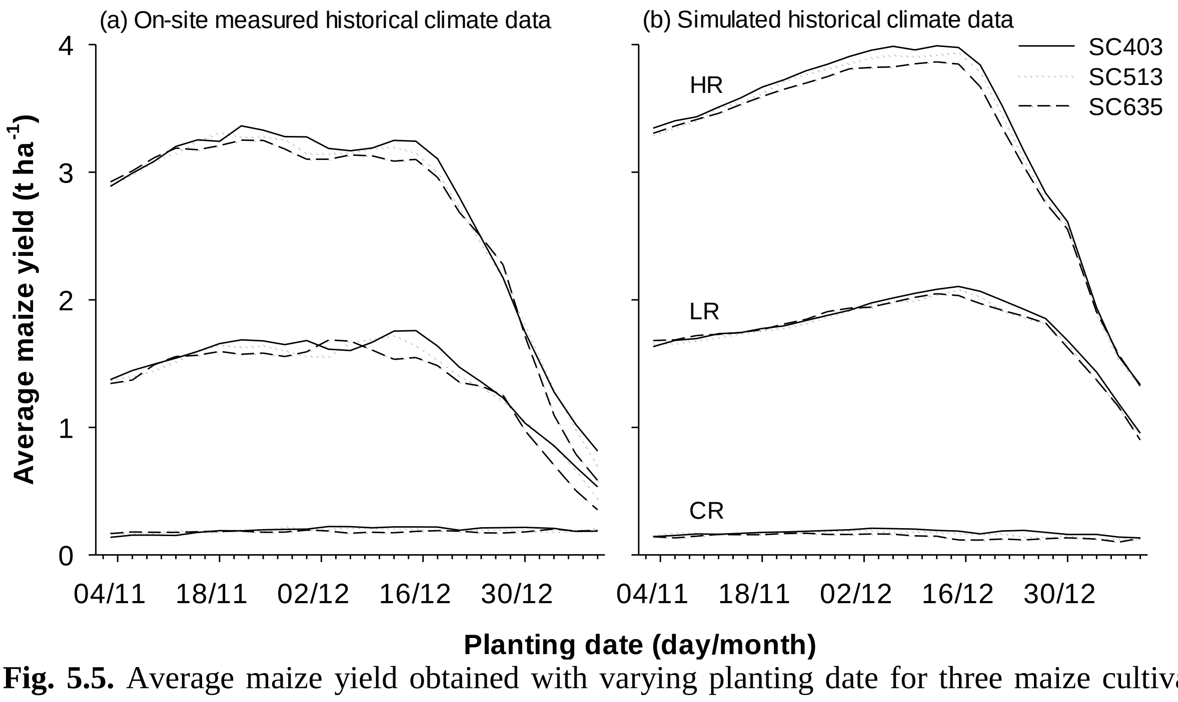

Fig. 5.5. Average maize yield obtained with varying planting date for three maize cultivars (SC403, SC513 and SC635) under three fertilization rates (CR-zero fertilization, LR-low rate: 35 kg N ha^{-1}; 14 kg P ha^{-1}; 3 t ha^{-1} manure and HR-high rate: 90 kg N ha^{-1}; 26 kg P ha^{-1}; 7 t ha^{-1} manure), for (a) on-site measured historical climate data and (b) simulated historical climate data, for Hwedza for the time slice 1976-2005.

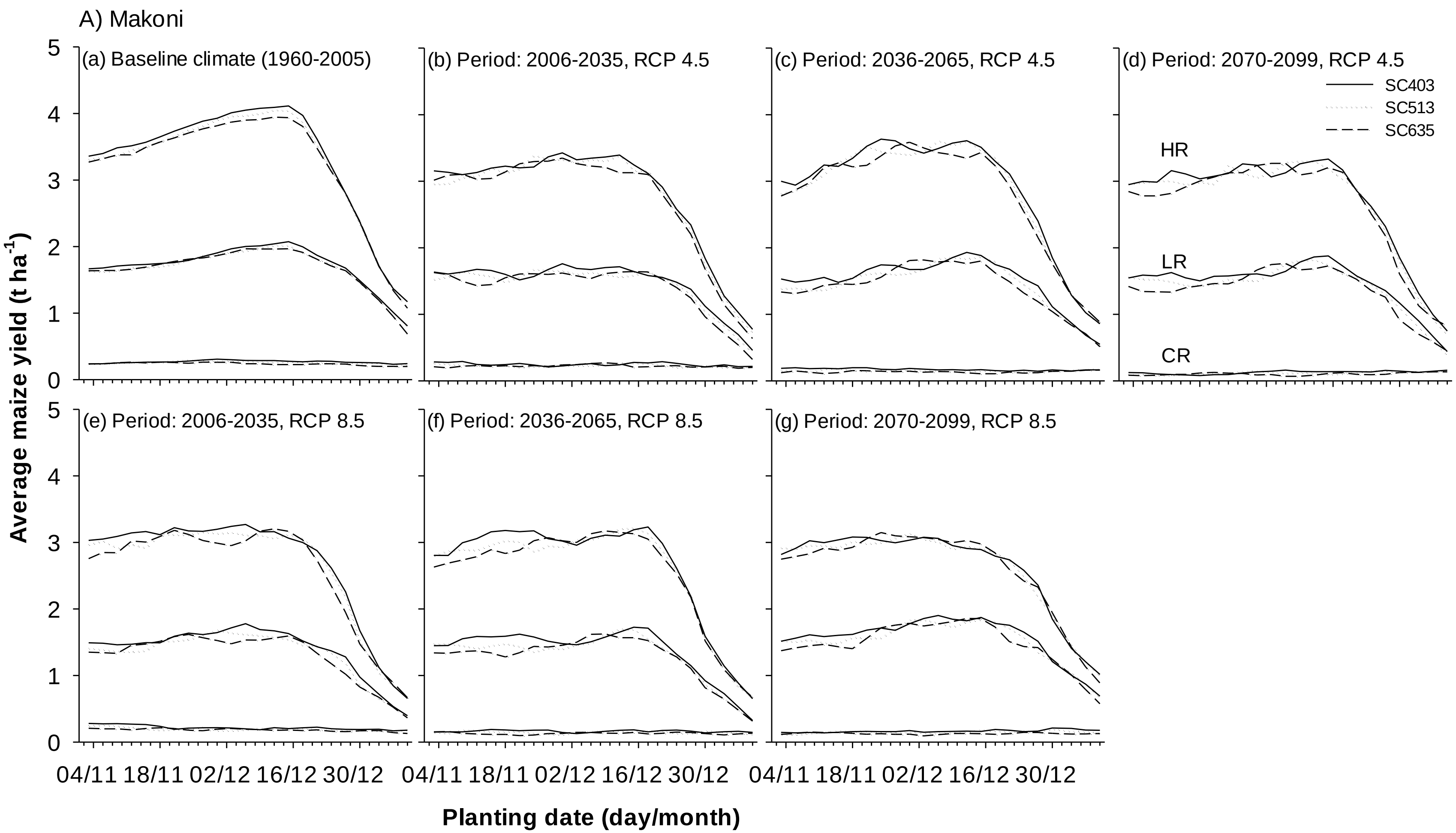

Fig. 5.6. Average seasonal yield distribution with planting date for three maize cultivars (SC401, SC513, SC635) under three fertilization rates (CR-zero fertilization, LR-low rate: 35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure, HR-high rate: 90 kg N ha^{-1}, 26 kg P ha^{-1}, 7 t ha^{-1} manure), in response to climate change for three resample periods: near-term (2006-2035), medium term (2036-2065) and long-term (2070-2099) and for two radiative forcings: RCP 4.5 and RCP 8.5, for A) Makoni and B) Hwedza.

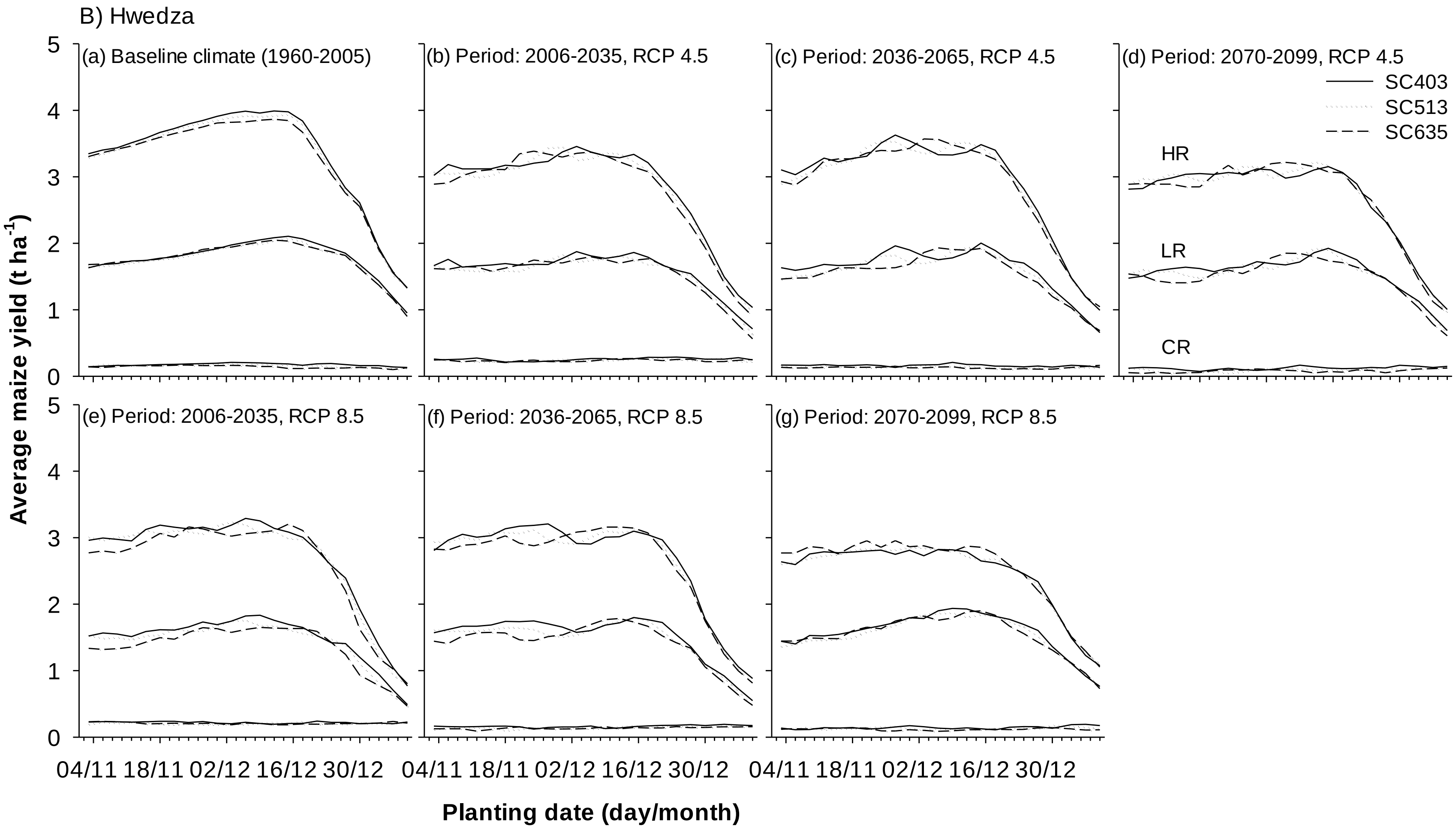

Fig. 5.6. continued

5.2.3.3. Responses of maize yield to adjustments in the amount of nitrogen under changing climate

Fertilization increased yield significantly under both the baseline and future climates particularly when planting before mid-December (Fig. 5.6). However, when planting was substantially delayed, i.e. planting after mid-December, the impact of fertilization on yield decreased drastically (Fig. 5.6). Similar to average maize yields, the response of maize to application of nitrogen differed between observed and simulated historical climate data (Fig. 5.7). The response of maize to increase in the amount of nitrogen decreased for all three climate periods for each radiative forcing, as compared with the baseline climate. For example, at 80 kg N ha^{-1}, maize yield of about 4.5 t ha^{-1} was simulated for the baseline climate, against maize yields of about 3.5 t ha^{-1} for the climate periods, 2010-2069 and 3 t ha^{-1} for 2070-2099 under the rcp4.5 (Fig. 5.8). Maize yield responses to nitrogen were comparable between climate periods, 2010-2039 and 2040-2069 for each radiative forcing (Fig. 5.8). Maize yield responses to nitrogen further decreased with progressing climate change. The lowest yield response to nitrogen was simulated for the climate period, 2070-2099 and for the high radiative forcing of 8.5 W m^{-2}. For example, a maximum yield benefit of only about 2.5 t ha^{-1} was simulated at about 60 kg N ha^{-1} for the period 2070-2099 for rcp8.5. Therefore, beyond 60 kg N ha^{-1}, very little or no extra grain was simulated per extra kg of N (Fig. 5.8).

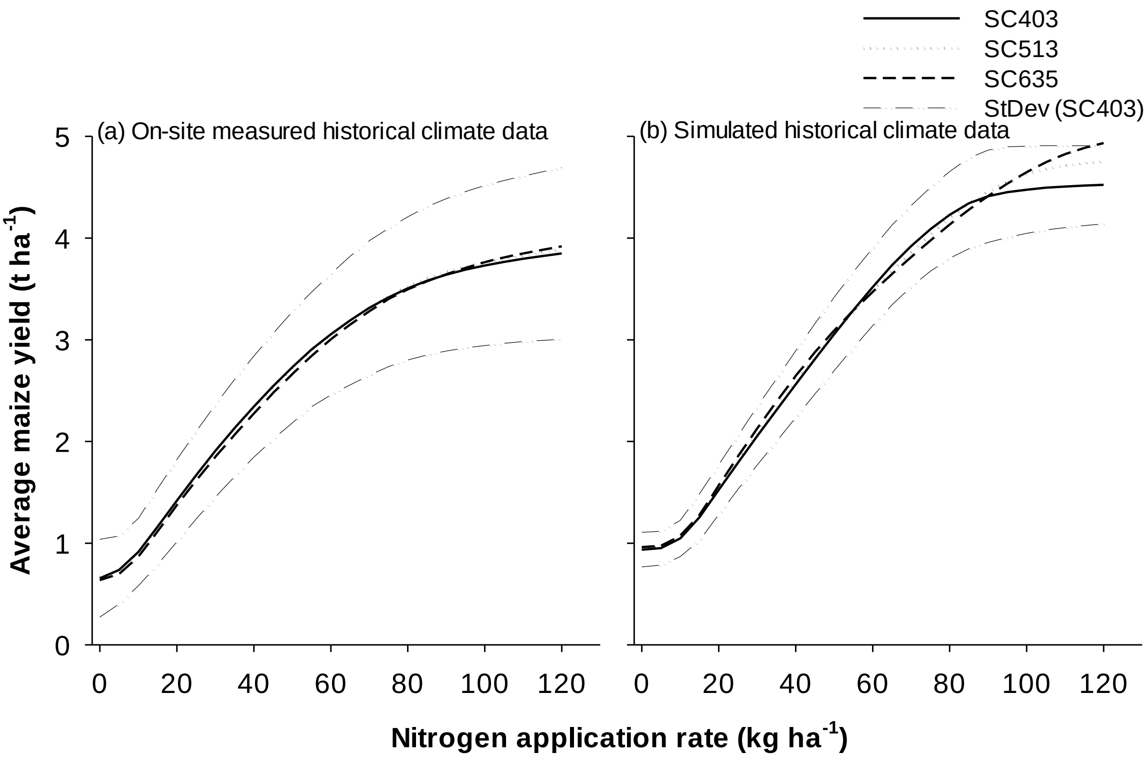

Fig. 5.7. Simulated grain yield for three maize cultivars planted early: SC403, SC513 and SC635, in response to nitrogen fertilization, for measured historical (a) and simulated historical climate data (b), for Hwedza. The standard deviation (StDev) presented is for one cultivar (SC403) because the yield performance for all three cultivars were similar.

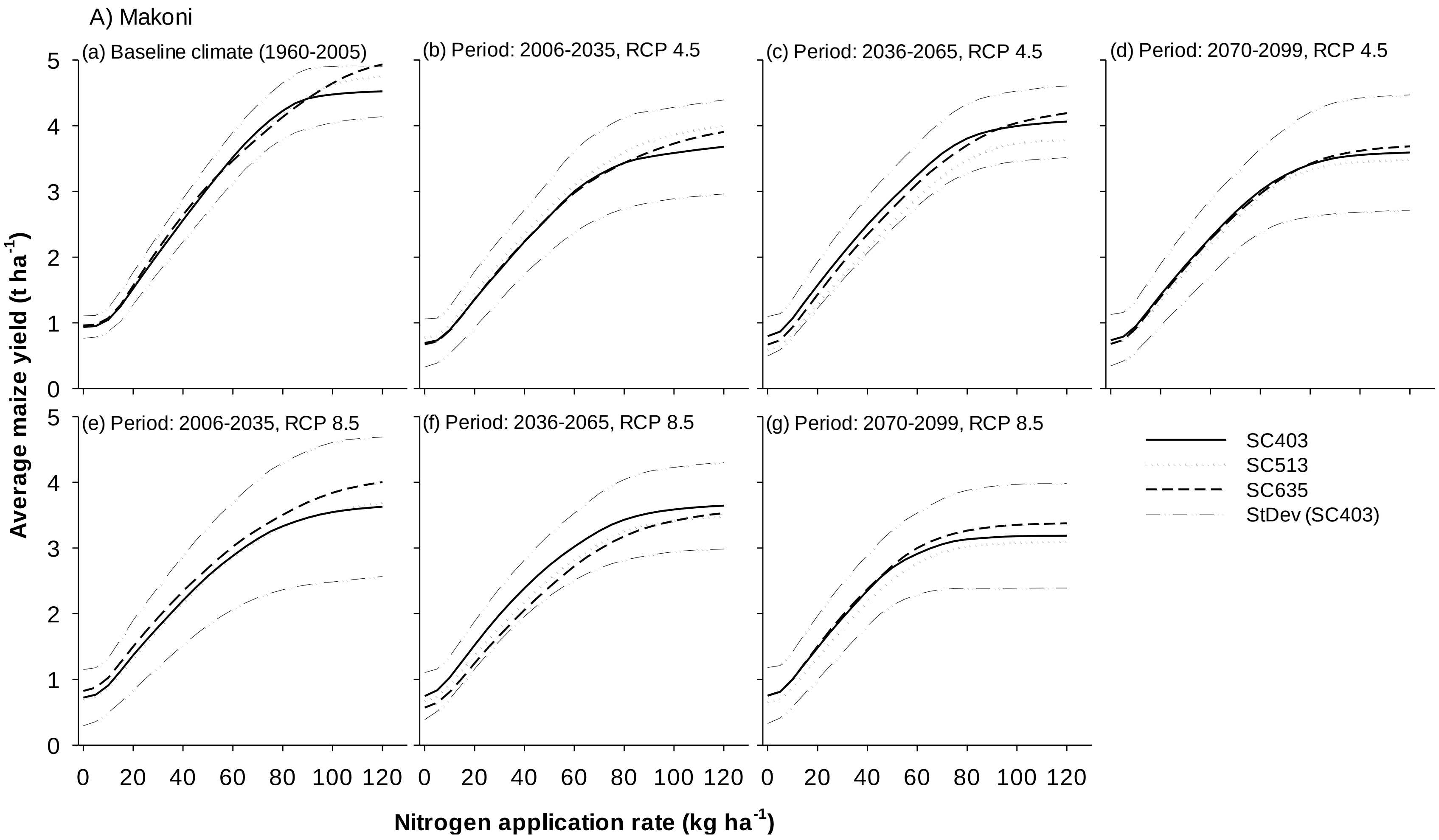

Fig. 5.8. Simulated average maize yield for three maize cultivars planted early: SC403, SC513 and SC635, in response to nitrogen fertilization for three climate change periods: 2006-2035, 2036-2065 and 2070-2099, against a baseline climate, 1960-2005, for two radiative forcings: RCP 4.5 and RCP 8.5, for (A) Makoni and (B) Hwedza. The standard deviation (StDev) presented is for one cultivar (SC403) because the yield performance for all three cultivars were similar.

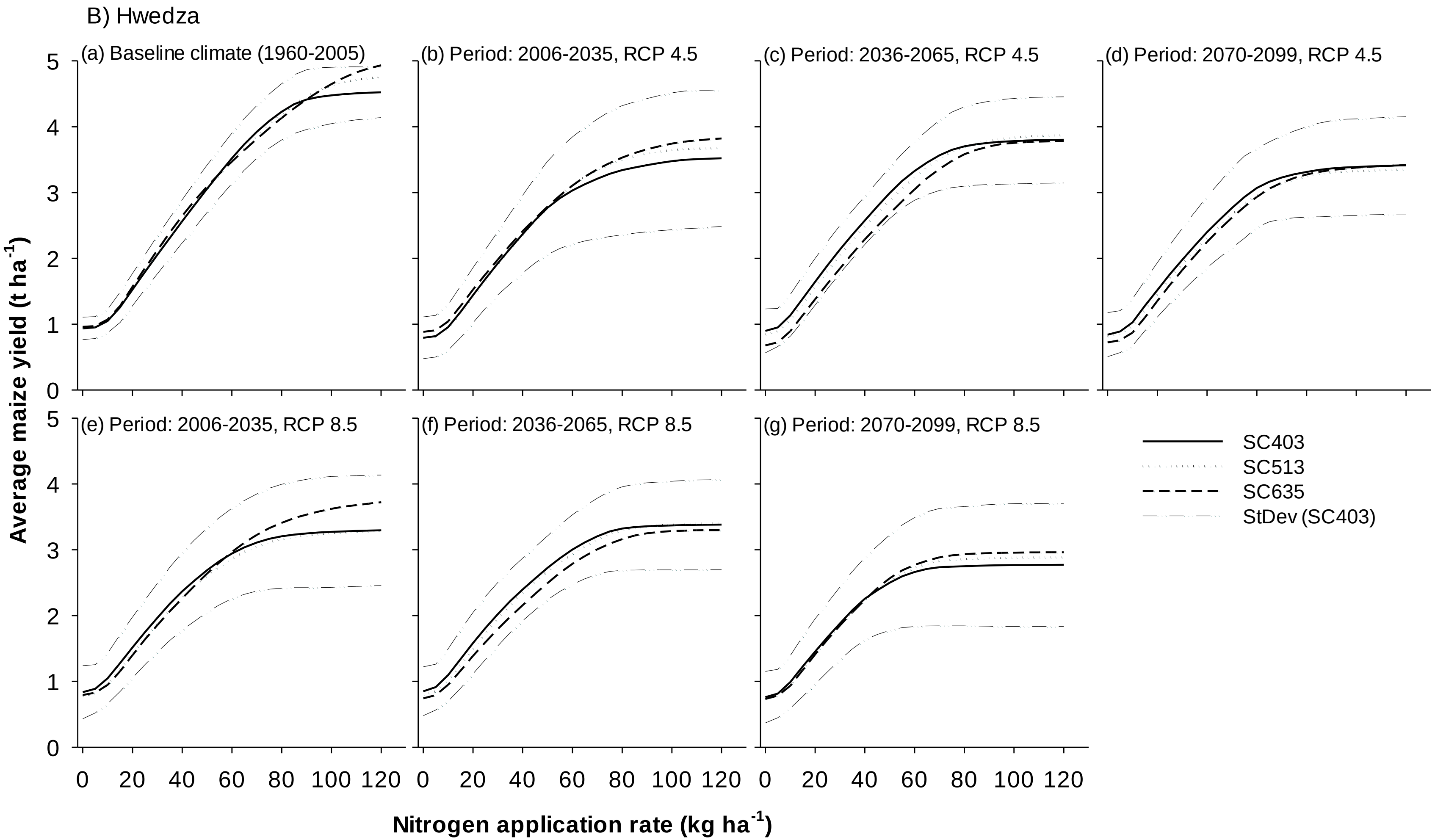

Fig. 5.8. continued.

5.3. Discussion

5.3.1. Future climate change in eastern Zimbabwe

The surface air temperature is projected to increase significantly in Zimbabwe by 2100, consistent with projections for global surface air temperature (IPCC, 2013). Yet there is no clear evidence that the annual rainfall in Zimbabwe will change by 2100 under both the low and high emission scenarios (see Fig. 5.4). In contrast other studies have projected a decrease in rainfall by between 15% and 20% in southern Africa by 2100 (Unganai, 1996; Christensen et al., 2007). Fraser et al., (2013) has also reported that the largest decline in precipitation with climate change is for southern Africa by 2100. Many of these results however were based on a single global circulation model (GCM) and Ruane et al. (2013) demonstrated that results generated by a single GCM are problematic as there are considerable outliers. However, the duration of droughts during the growing season are projected to increase in Zimbabwe and other parts of southern Africa by 2100 (Appendices 1(A, B and C)), as also reported by other studies conducted in the region (Shongwe et al., 2009; Tadross et al., 2009).

5.3.2. Field level analyses of consequences of the changing climate for average maize yield for different cultivars

The simulations suggest that the impact of climate change on maize yield will increase as time progresses and as temperature continues to increase as a consequence of future greenhouse gas emissions. Although maize production will decline in the near future when compared with the baseline climate, the yield decline will be relatively small (- 11%) until the middle of the 21st Century particularly for the low greenhouse gas emission scenario. Lobell et al. (2008) used a statistical model and they projected much larger maize yield losses (< -30%) in southern Africa in the near future, i.e. by 2030, because of increased temperatures and decreased rainfall. However, in our more detailed, site-specific study, larger yield losses (≤ -25%) are only projected for the more distant future i.e. towards the end of the 21st Century, and under the high radiative forcing scenario of 8.5 W m^{-2}. The projected impacts of climate change on maize yield are substantially smaller for the low radiative forcing scenario (rcp4.5), as expected.

The predicted decline in future yields was driven mainly by increasing temperatures that increased the crop maturation rate and hence shortened the crop growing period (Springate and Kover, 2014). The impact of rainfall was small compared to the impact of temperature because the total rainfall is unlikely to change by 2100. Lobell and Burke (2008) have projected that increasing temperature is likely to be the major driving factor for the negative impact on maize production in Africa particularly those rely on rain-fed crop production.

The yield performance for all three cultivars, which are representative of the cultivars on the market in Zimbabwe and other parts of southern Africa, is likely to be similar in the predicted future climates. The time to maturity of these cultivars are quite similar, with a difference between the relatively short (SC403) and long (SC635) duration cultivars of only 14 days. Consequently, such small differences did not compensate for the yield loss. Under current climate conditions, field experimental studies have shown that cultivar effects on yield are small in Zimbabwe (Rurinda et al., 2013), as well as in southern Mali (Traore et al., 2014), and for both these locations this is unlikely to change in the future. Thus breeding for cultivars with significant difference in time to maturity could help to stabilize crop production in future. By simulating the yield potential of possible new future crop cultivars in central

Africa, Tingem et al. (2009) found that the use of later maturing new cultivars will be effective in stabilizing crop production in the face of a changing climate. However, given that smallholder farmers cannot benefit much from the yield gains offered by current hybrid maize cultivars due to resource and bio-physical constraints, new cultivars will only help farmers if these other constraints are alleviated (Tittonell and Giller, 2013).

5.3.3. Delayed planting effects on maize yield under a changing climate

In smallholder farmers' fields in southern Africa a wide window of planting dates is encountered (Rurinda et al., 2013). Delays in planting are mainly caused by operational constraints particularly lack of draught power, farm labour and timely-availability of fertilizer (Shumba et al., 1992; Rurinda et al., 2013), or farmers' perceptions (Mtambanengwe et al., 2012). The delays in planting date are often directly associated with lower yields (e.g. Shumba, 1989; Waddington and Hlatshwayo, 1991). Yet contrary to these earlier studies, we found that the response of maize yield to delay in planting was not linear. Average maize yield did not decline for the planting dates from November to mid-December, but even increased slightly with small delays. Only when maize was planted later than mid-December, did the yields decline drastically.

The similarity in yield among the planting dates until mid-December further reinforced the finding from our earlier experimental studies that there is no yield difference between crops planted early (25 October-20 November) or during what farmers considered the normal planting window (21 November-15 December) (Rurinda et al., 2013). Overall, this suggests that a reasonably wide window exists for planting before a yield penalty is caused by a delay, even under a changing climate. This finding is contrary to the intuition that delayed planting reduces crop production in Zimbabwe and other parts of southern Africa (Spear, 1968), and widely applied 'rules-of-thumb' which define a 2.3% of grain yield decline per day delay in planting (Shumba, 1989) over the period October to mid-December.

Although planting before mid-December will give slightly higher yields, pushing for very early planting will not bring much yield benefit under a changing climate, while the risk of losing the crop might increase if rainfall variability during the start of the growing season increases (Raes et al., 2004). Similarly, in other regions of Africa, changing sowing dates during the crop growing period is projected to be ineffective in counteracting adverse climatic effects because of the narrow window of early showers that affects timing of planting as the soil would be too hard to get the plough through the soil (Tingem et al., 2009).

5.3.4. Crop fertilization under a changing climate

The maize response to mineral nitrogen is projected to decline as climate changes, although effects only become substantial towards the end of the 21st Century. Fertilization will therefore remain a key strategy to stabilize crop production against decreases caused by climate change (Rurinda et al., 2013). The simulation results indicate that maize yields in future might plateau at smaller mineral nitrogen additions than under current climate (Fig. 5.8). This would mean that recommended application rates for southern Africa should be reduced in future, unless breeding can compensate for the reduced yields. Our simulation results indicate that wealthier farmers who can afford to buy more fertilizers could reduce their application rate to about 80 kg N ha^{-1} by mid-century and 60 kg N ha^{-1} towards the end of the century (see Fig. 5.8), compared with the current recommendation rate of 120 kg N ha^{-1}

in Zimbabwe (Zingore et al., 2007). This would increase nutrient use-efficiency and returns to fertilizer in the face of a changing climate.

5.3.5 Uncertainty associated with projecting climate change impacts on crop production

Although in general the use of GCMs ensembles improves the modelling of climate data (Van der Linden and Mitchell, 2009; IPCC, 2013), aggregating outputs from several models can mask the effects of growing season dry spells. This was demonstrated by the difference in yields between the simulations performed with the observed historical climate data and those performed with the aggregated simulated climate data (see Fig. 5.5 and 5.7). We therefore decided to focus in this study only on the average predicted yields, rather than to focus on the risk of low yields. Furthermore, the modelled historical grid data has been interpolated from a number of weather stations using an automatic procedure and in Africa these stations are sparsely positioned due to limited resources. Over time many of these stations stopped to supply data to the Global Telecommunications system (GTS) and have been replaced by other stations (Supit et al., 2012), further increasing the uncertainty of especially the rainfall data. Given the fact that rainfall variability is currently the main driver of crop production in Zimbabwe (Rurinda et al., 2013) and other parts of sub-Saharan Africa (Traore et al., 2013) there is an urgent need to improve the reliability of the rainfall predictions.

Chapter 6

General discussion

6.1. Sources of vulnerability to a changing climate in African smallholder farming livelihood systems

Smallholder farmers in southern Africa are faced with multiple stresses and often balance their livelihoods on a 'tipping point', consistent with the idea of 'hanging in' as articulated by Dorward et al. (2009). Of the five livelihoods capitals of sustainability, smallholder farmers depend strongly on the interactions among the natural, social and human capitals. The physical and financial capitals are often too weak or absent, to leverage their livelihoods (Fig. 6.1). Some farming households have important "rural-urban connections" that buffer the household from shocks due to having family members working in town - and that this can support the family in town at times as well. This study has shown that livelihoods of smallholder farmers are supported mainly by four sub-systems: cropping, livestock production, natural resources and social safety nets (Chapter 2), which are generally subsets of the three livelihood capitals earlier identified as key. The strong dependence of smallholder farmers on few livelihood assets suggests that their livelihoods are inherently vulnerable.

Any environmental or social change that can upset the delicate balance among the aforementioned three livelihoods capitals would threaten the livelihoods of smallholder farmers. Climate change and increased climate variability have been identified as the major global environmental changes that can alter the interactions and roles played within the three livelihood capitals (Fig. 6.1). In this study, it has been apparent that smallholder farmers in both Makoni and Hwedza, as in many areas of Southern Africa, have increasingly been exposed to rising temperatures and increased rainfall variability due to a changing climate. Surface air temperatures have increased by about 0.5°C per decade in Hwedza between 1962 and 2000 (Chapter 2) and a further increase is projected by 2100 (Chapter 5), consistent with earlier projections for the region (e.g. Unganai, 1996). Yet the total rainfall has so far not changed and is unlikely to change by 2100, but there was evidence of increased season dry spells and decreased number of rainy days (Chapters 3 and 5). Tadross et al. (2009) have also reported that the number of rainy days has decreased and the frequency of droughts increased in southern Africa.

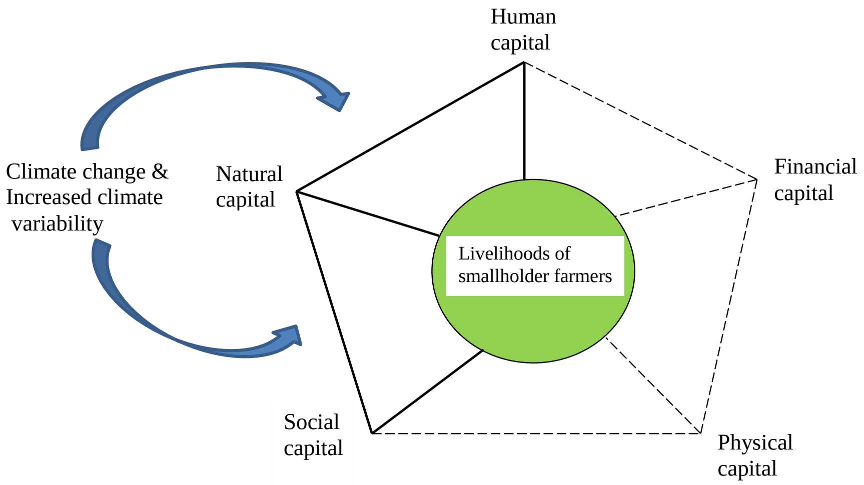

Fig. 6.1. A modified sustainable rural livelihoods framework. The solid and dotted lines indicate strong and weak interactions between the livelihoods assets as identified in this study. (Adapted from Scoones (2009)).

Although in general smallholder farmers in southern Africa are increasingly exposed to rising temperatures and more frequent and severe droughts, the impacts differ from farmer to farmer.

First, smallholder households of different endowments depend on varied sub-systems of the broader farming livelihood system and these sub-systems are exposed to different aspects of climatic risk (Chapter 2). For example, livestock production, the prioritized livelihood option for wealthier farmers, is mostly threatened by more frequent droughts, which affect the quantity and quality of grazing land and the amounts of crop residues available for livestock in addition to drinking water. Crop production, the key option for households with intermediate resources, is at high risk of a combination of rising temperatures and prolonged dry spells both of which affect productivity. The resource-constrained households, who depend on social safety nets and common natural resource pools, were vulnerable to both extreme temperatures and increased rainfall variability (Chapter 2).

Second, farmers have access to different resources such as fertilizer and farm labour inputs (Mtambanengwe and Mapfumo, 2005). Consequently, they respond uniquely to the changing climate. For example, in Makoni and Hwedza districts, farmers revealed that timely access to fertilizer and draught power can buffer crop production against increased rainfall variability (Chapter 2). The importance of fertilizer in increasing crop yields has empirically been confirmed in this study through on-farm experiments and simulation modelling (Chapters 3, 4 and 5). Timely access to fertilizers and draught power can help farmers to synchronize their farming operations with seasonal rainfall pattern. Similarly, farmers who have access to cash for buying supplementary livestock feed or have strong social networks for transhumant movement, can reduce the impacts of droughts on livestock (Chapter 2; (Scoones, 2009)).

Thus, alongside climate variability and change, smallholder farmers are also faced with biophysical and socioeconomic challenges, and these often have interactions with prevailing adaptation options. As such, the resilience of smallholder farmers will eventually depend on management of the interacting pathways of the changing climate, and biophysical and socioeconomic conditions (Vermeulen et al., 2012).

6.2. Promising adaptation options for smallholder farmers in a changing climate

Due to differences in natural and social production resources among smallholder households (Giller et al., 2011), there is no one 'size-fit all' solution to address the challenge of household food insecurity within smallholder farming systems in the face of climate variability and change. Chapter 3 has demonstrated that even with a combination of field-level adaptation options there is still a risk of complete crop failure, particularly in drought years. Thus, farmers need to spread the risk and combine a number of adaptation options to increase household food and nutrition security and meet other household needs. Fig. 6.2 provides an overview of a number of adaptation options that can be used singly or in combination depending on local conditions by smallholder farmers against climatic shocks. The benefits of these adaptation options are obviously a function of the nature of climate change and the scale of impact (Howden et al., 2007).

6.2.1. Managing soil fertility as an entry point for building a resilient smallholder cropping system in a changing climate

Table 6.1. Projected household food self-sufficiency (indicated by the food self-sufficiency ratio-FSSR) for maize production under different management of adjusting fertilization and planting date for three climate periods derived by two emission scenarios: Representative Concentration Pathways (RCPs): rcp4.5 with radiative forcing of 4.5 W m^{-2} and rcp8.5 with radiative forcing of 8.5 W m^{-1}, for households of three resource categories, for Hwedza

		Climate periods													
		1976-2005		2010-2039				2040-2069				2070-2099			
Farmer category	Current practice & adaptation	Baseline (t farm^{-1})	FSSR (%)	RCP4.5 (t farm^{-1})	FSSR (%)	RCP8.5 (t farm^{-1})	FSSR (%)	RCP4.5 (t farm^{-1})	FSSR (%)	RCP8.5 (t farm^{-1})	FSSR (%)	RCP4.5 (t farm^{-1})	FSSR (%)	RCP8.5 (t farm^{-1})	FSSR (%)
Resource-endowed	Current practice	3.7	308	3.2	267	3.1	258	3.3	275	3	250	3	250	2.7	225
Resource-intermediate	Current practice	1.8	150	1.7	142	1.7	142	1.8	150	1.7	142	1.7	142	1.7	142
	Fertilizer	2.7	225	2.5	208	2.5	208	2.8	233	2.5	208	2.6	217	2.5	208
	Timely planting	0.8	70	0.7	60	0.8	70	1.0	80	0.7	60	0.8	70	0.7	60
	Fertilizer + timely planting	3.2	266	3	249	2.9	241	3.1	258	3	250	2.8	233	2.6	217
Resource-constrained	Current practice	0.2	17	0.2	17	0.2	17	0.2	17	0.2	17	0.2	17	0.2	17
	Fertilizer	1.8	150	1.7	142	1.7	142	1.8	150	1.7	142	1.7	142	1.7	142
	Timely planting	0.4	35	0.4	35	0.4	35	0.5	40	0.4	35	0.4	35	0.4	35
	Fertilizer + timely planting	2.3	192	2.2	183	2.2	183	2.4	200	2.1	175	2.2	183	2.2	183

Note

Resource endowed: current practice (i) fertilizer rate, 90 kg N ha^{-1}, 26 kg P ha^{-1}, 10 t ha^{-1} manure; (ii) area planted early or during normal window: 1.4 ha

Resource-intermediate: current practice (i) fertilizer rate, 35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure (ii) area planted early or during normal window: 0.9 ha

Adaptation option 1: increased fertilizer (i) fertilizer rate, 60 kg N ha^{-1}, 20 kg P ha^{-1}, 7 t ha^{-1} manure (ii) area planted early or during normal window, 0.9 ha

Adaptation option 2: timely planting (i) fertilizer rate, 60 kg N ha^{-1}, 20 kg P ha^{-1}, 7 t ha^{-1} manure; (ii) area planted early or during normal window, 1.2 ha

Resource-constrained: current practice (i) zero fertilization rate (ii) area planted during early and normal windows: 0.3 ha

Adaptation option 1: increased fertilizer (i) fertilizer rate, 35 kg N ha^{-1}, 14 kg P ha^{-1}, 3 t ha^{-1} manure (ii) area planted in early or during window, 0.3 ha

Adaptation option 2: timely planting (i) fertilizer rate: 60 kg N ha^{-1}, 20 kg P ha^{-1}, 7 t ha^{-1} manure; (ii) area planted early or during normal window, 0.6 ha

See Table 2.4, Chapter 2 for the calculations for the household food self-sufficiency (FSSR).

Soil fertility management studies have received considerable attention in smallholder farming systems of sub-Saharan Africa (Palm et al., 2001; Sanchez, 2002; Nezomba et al., 2010). This study has attempted to understand the importance of soil fertility against other suggested farm-level adaptive management options. My aim was to provide empirical evidence about the relative urgency of different options for efficient use of scarce resources in the face of climate change and increased climate variability. Chapters 3, 4 and 5 bring to the fore the underling importance of addressing soil fertility challenges that opens opportunities for reducing risks of crop failure and food insecurity, even as the quality of rainfall seasons deteriorates with climate change. Even farmers prioritized soil fertility management as a strategic option to buffer crop yields against climatic shocks (Chapter 2). Fraser et al. (2013) have also found fertilizer use to be positively related with adaptive capacity in tropical and arid countries.

Soil fertility management is therefore a major entry point for farmers of different resource endowments to stabilize their household food self-sufficiency in a changing climate. This means that the impact of a changing climate on crop production will strongly depend on the interaction with soil fertility management. Resource-endowed farmers, who apply sufficient amounts of fertilizers are normally food secure even under a changing climate with household food self-sufficiency of >200% for all four climate periods (Table 6.1). However towards the end of 21st Century maize yield is predicted to decline regardless of fertilization (Table 6.1) due to rising temperatures, which shorten crop maturation (Springate and Kover, 2014). This suggests that climate change impacts are likely to be greater than the influence of fertilization in future. To increase resource use efficiency and minimise loss to fertilizer investment, resource-endowed farmers might need to reduce the amount of fertilizer from about 90 kg N ha^{-1} to about 70 kg N ha^{-1}, towards of the end of the century (see also Chapter 5).

The intermediate resource group is food secure even with future change in climates but their household food self-sufficiency is marginal (Table 6.1). They need to increase rates of fertilizers use to about 60 kg N ha^{-1} to strengthen their household food stocks. Meanwhile resource poor farmers who currently apply little or no fertilizer are perennially food insecure (Table 6.1). This group needs to increase the amounts of fertilizers to about 35 kg N ha^{-1}, to increase their household food self-sufficiency (Table 6.1). The overall importance of soil fertility is to be expected given that the majority of soils in smallholder farming systems in Africa are inherently infertile. This is particularly relevant for Southern and West Africa where Arenosols and Cambisols predominate. These soils are typified by deficiencies in major nutrients and low available water capacity to support crop production (World Soil Resource Base, 1998; Hartemink and Huting, 2008).

Despite the importance of soil fertility, many smallholder farmers in southern Africa, have little or no access to both organic and mineral fertilizers (Mapfumo and Giller, 2001). Manure is a scarce resource as livestock numbers fell due to the drought in 1990-1992 and have yet to recover to their previous numbers. For example about 1.03 million (> 23% of the Zimbabwean national herd) cattle died during the 1991-1992 drought (Tobaiwa, 1993). Encroachment into grazing areas for arable farming and settlement also has negative impacts on livestock production (Rufino et al., 2011). The application of low amounts of fertilizer is mainly due to difficulty in accessing fertilizer coupled with the prohibitive costs of the commodity (Nyikahadzoi et al., 2012). It is therefore not surprising that farmers apply on average 3 t ha^{-1} manure per two years, against a recommended 10 t ha^{-1} year^{-1}; and less than 6 kg ha^{-1} for P and K against a recommended 30 kg ha^{-1} (Table 3.7, Chapter 3). This suggests that the current cropping system is actually mining the little nutrients available leading to soil degradation and poverty traps. Long-term field experiments have shown that when the soil is so degraded, it is difficult to restore its productivity, even when large amounts of manure, e.g. 25 t ha^{-1} $year^{-1}$, are applied (e.g. Rusinamhodzi et al., 2013).

It is important to note that the same strategy of improving soil fertility may work variedly in different seasons and agro-ecology. Although crop productivity in many parts of southern Africa is primarily limited by soil nutrients there is a strong interaction with rainfall, which varies in space and time. Chapters 3 and 4 have provided evidence that even if the soil is amended with a combination of manure and mineral fertilizer, poor yields can be obtained because of poor rainfall patterns. In drier areas, such as Zimbabwe's agro-ecological region V (where the rainfall is below 450 mm per year and the distribution is erratic), use of high rates of fertilizer has been reported to increase the risk of crop failure (Twomlow et al., 2010). Because fertilizer use is a prerequisite in these farming systems (Giller et al., 2011), perhaps a strategy of variable fertilizer application in response to rainfall patterns can help to minimize risk and increase the efficient use of fertilizer, as demonstrated by Piha (1993). Another strategy is to use low rates of fertilizer, as I demonstrated that farmers can currently achieve household food self-sufficiency with low amounts of fertilizer (Chapter 3), similar to the idea of micro-dosing presented by Twomlow et al. (2010).

6.2.2. Multiple planting dates as an adaptation option

Varying planting dates as well as use of multiple cultivars are well documented in literature as cost effective adaptation options that can buffer crop production against increasing climatic risk across the globe (IPCC, 2007). These adaptation options are rarely evaluated in the context of biophysical and socioeconomic conditions of farmers (Vermeulen et al., 2012). In Zimbabwe, smallholder farmers stagger planting dates mainly due to limited family labour that precludes planting all fields at the same time (Waddington and Hlatshwayo, 1991). It is recommended to plant with the first effective rains to avoid a 2.3% of grain yield decline per day delay in planting over the period October to mid-December (Shumba, 1989). Contrary to this established knowledge, this study has indicated that a relatively wide time window exists for planting before a yield penalty is caused by a delay based on field experimentation and simulation modelling (Chapters 3 to 5). Similarly, in southern Mali, Traore et al. (2014) reported that there was no significant yield difference between crops planted early or during what farmers considered the normal window. Only when crops are planted later than mid-December, did the yields declined drastically (Chapters 3 to 5).

In recent years, many parts of southern Africa experienced a late start to the rainy season even after mid-December (Tadross et al., 2009), but with no change in timing of the end of rainy season (Fig. 3.4; Chapter 3). This means when the rains start late, farmers automatically plant late and the season is shorter. Such delayed planting is often compounded by shortage of draught power leading to dramatic yield decline (Chapter 3). This scenario of delayed planting is particularly a problem for resource intermediate and resource-constrained farmers who currently plant a significant portion of their land in the late planting window due to limited access to draught power. The projections for household food self-sufficiency indicate that the two farmer groups should increase the area planted early or during the normal window, but this strategy will only increase maize yield providing soil fertility is improved. Without soil fertility management, the yield benefits of the adaptation option, timely planting, will be small (Table 6.1).

Overall there is a reasonably wide sowing window if the rains start on time, but if the start of the rains is delayed until after the beginning of December this advantage is lost and planting should be done as soon as possible. This is particularly true given that the soil is too hard for ploughing which could cause another delay. One approach to tackle the problem of delayed planting is winter ploughing. Many farmers used to practice winter ploughing to reduce draught power requirements and conserve soil water, to increase the success of early planting. The practice of winter ploughing has been practiced less over time due to many factors including the perceived increasing climatic risks, shortage of farm labour, shortage of draught power due to declining cattle production, and promotion of conservation agriculture (CA). Farmers also suggested various options such as *Humwe* as a means of sharing labour (see Table 2.7; Chapter 2), which can assist such households to access draught power on time (Chapter 2).

The crop cultivars currently available in Zimbabwe, and in many parts of sub-Saharan Africa, exhibit narrow differences in time to maturity (Chapter 3). Thus, in the current cropping system farmers can select any cultivar available on the market without a yield penalty. However, with climate change none of the available cultivars will be able to compensate for the decline in yield regardless of improved soil fertility management and timing of planting (Chapter 5). Breeding for early maturing cultivars with greater tolerance to more frequent droughts and deteriorating soil nutrient conditions, is generally seen to be necessary in future (e.g. Bänziger et al., 2006). An interesting recent finding of Traore (2014) was that short duration varieties seem more vulnerable to predicted increases in temperature than long duration varieties. Because of increased temperature the crop growth model used by Traore et al. (2014) predicted that the growing period of the short duration varieties is decreased so much that overall biomass and grain production is reduced. This suggests that although short duration varieties are perceived to be more climate robust because they are not dependent on a long growing season with ample rainfall, this stronger negative temperature response might counter-act that, and more detailed crop experimentation research is needed to investigate how these interactions work out in reality.

Bänziger et al. (2006) argued that crop breeding has greater chance of success if conducted with the participation of farmers, taking into account their ability and willingness to adopt new risks. Nevertheless breeding alone will unlikely stabilise crop production in a changing climate unless it is supported by improved agronomic management (Passioura, 2006). Chapter 3 has shown a huge yield gap between what is currently produced by farmers and what is achievable in well managed on-farm experiments. Tittonell and Giller (2013) argued that smallholder farmers are unable to benefit from the current yield gains offered by plant genetic improvement because farmers are faced with a plethora of biophysical and socioeconomic challenges such as lack of fertilizers.

6.2.3. Potential for substitution of maize with small grains

Substitution of climate sensitive crops such as maize with less sensitive ones such as small grains has been recommended as a viable adaptation option for smallholder farmers in southern Africa (Makadho, 1996; Lobell et al., 2008). This adaptation option is however controversial because the direction of climate change is uncertain, particularly rainfall patterns (Chapter 5). Even in southern Africa, which is generally projected to become drier (IPCC, 2013), changes in the rainfall patterns will be neither spatially nor temporally uniform across locations leading to varying consequences on different crops (Zinyengere et al., 2013).

My results clearly demonstrate that the belief that small grains will yield more than maize under variable rainfall conditions is contextual. Maize yielded more than finger millet and sorghum even when rainfall was poor (Chapter 4). Chidhuza (1993) working in northern Zimbabwe reported that maize out-performed sorghum and pearl millet on relatively fertile soils, but sorghum was superior in poorer soils. In southern Mali, maize out-competed sorghum and pearl millet under different rainfall conditions (Traore et al. (2014). Even long-term climate change impact studies on crop production have also indicated that different crops will be impacted variedly depending on location and other non-climatic factors such as soil type (Chipanshi et al., 2003; Zinyengere et al., 2013). Maize is also perceived to have a number of advantages by smallholder farmers. For example, the produce market and the low labour demands for weeding, harvesting and processing for maize have been attractive to farmers (Easterling et al., 1992). Furthermore, small grains; and particularly sorghum, are prone to bird damage (Chapter 4). These results suggest that maize is still competitive and replacing it with small grains will neither build a climate robust cropping system nor attract farmers' attention particularly those who are resource-endowed in sub-Saharan Africa. However, much more attention has been focused on maize than on sorghum and millet in terms of crop breeding and processing technologies.

To build a climate resilient cropping system, spreading different crops across landscape and time may be a key strategy not only to reduce the adverse impacts of the changing climate but also to improve human nutrition. Crop diversification has long been considered an option to spread climatic risk, and this study demonstrated that farmers are increasingly recognising the importance of this option in the face of a changing climate (Fig. 2.5; Chapter 2). Because finger millet can be stored in granaries for more than five years without significant damage from pests, it can strategically be used as a 'safety net' to complement maize for household food in times of droughts (Chapter 4). On top of reducing climatic risk, crop diversification can help to improve human nutrition given that about two hundred and eighty million people are under malnutrition in sub-Saharan Africa (FAO, 2011).

Although small grains such as sorghum and finger millet are generally known to be more drought tolerant than maize (Frere, 1984), this study has demonstrated that small grains are only superior over other cereals with regards to human diet, not in terms of production per unit land. In particular, finger millet is a strategic crop because of its high calcium content, which is ten times greater than maize (Table 4.5, Chapter 4). While sorghum can also help in balancing human diet, the crop is prone to birds making it difficult for farmers to increase area under sorghum. Breeding of sorghum cultivars that are resistant to bird damage and tolerant to poor soil nutrients may be necessary. It is important for each smallholder household to allocate a small portion of its farm to finger millet to enhance adaptation and nutrition security. The nutritional value of finger millet is mostly critical for poorer households, which often lack basic dietary requirements. Chapter 4 has also demonstrated that the use of high rates of fertilizer was financially attractive for maize production, while the use of low rates was financially attractive for small grains. Although wealthier farmers can focus more on maize production, switching to small grains is particularly important for poor farmers.

Although small grains demand less fertilizer than maize (Carter and Murwira, 1995), I have shown that the emergence of finger millet and sorghum was poor unless they are fertilized (Chapter 4). Application of manure alone will not address this challenge (Rurinda et al., 2014). This means that without farmers having access to affordable mineral fertilizers, the idea of reviving small grains into the current maize-based systems in southern Africa is unlikely to succeed. Legumes such as groundnuts (*Arachis hypogaea* L.) and cowpea (*Vigna* *unguiculata* [L.] Walp.) are other crops that are critical for improving human nutrition as well as buffering smallholder household food against increasing climatic risks (Rusinamhodzi et al., 2012).

6.2.4 Other adaptations options

6.2.4.1. Strengthen grain reserve systems

Many farming households would over rely on grain reserves to buffer their household food against bad seasons (Milgroom and Giller, 2013), but in southern Africa this strategy has deteriorated over time due to lack of supporting institutions (Mapfumo et al., 2013). Findings from this study demonstrating exposure to risk due to complete crop failure in rain-fed smallholder farming systems mainly due to droughts (Chapter 3), suggest that storing grain for future use is important to cushion households against hunger. Strengthening grain reserve systems has been proposed as a fall back mechanism with direct benefits to household food security in a changing climate (Mapfumo et al., 2013). However, the major challenge with this option is the post-harvest management of storage in granaries. Milgroom and Giller (2013) reported that maize grain stored in granaries can be heavily damaged by insect pests. Crops such as finger millet, which can be stored for multiple years with minimum damage from pests, can strategically be stored to buffer household food against droughts years (Chapter 4).

6.2.4.2. Improved management of natural resources

Research demonstrates that smallholder farmers are increasingly relying on depleting natural resources such as wild fruits for general livelihoods (Woittiez et al., 2013). This is particularly true for poorer households who strongly depend on natural resources for their household food and income (Chapter 2). In the 2007/8 agricultural season, many households in Makoni and Hwedza survived on the fruits of *Parinari curatellifolia* and *Uapaca kirkiana* because the field crops failed mainly due to drought. Thus wild fruits often serve as ‘safety nets’ to provide household food in times of food crisis often when crops fail. The changing climate is also negatively impacting the natural ecosystems causing changes in phenology and species composition (Watson et al., 2013). Thus the future contribution of natural resources for supporting livelihoods of smallholder farmers therefore is highly uncertain. Farmers revealed that establishing household and community woodlots, and strengthening of social safety nets could be possible options, which can help to increase the availability of natural resources (Chapter 2). There is a need for a detailed study to understand the changing use patterns of natural resources by gender among rural communities as climate changes.

6.2.4.3. Exploring other livelihood options outside agriculture

Due to limited opportunities within smallholder farming areas to expand farming operations and to engage in profitable enterprises, switching to alternative livelihood options outside agriculture may help to build a resilient livelihood systems. Many farmers have traditionally been investing part of their money generated from agriculture, in the education of their children or themselves. As such, education has mainly been the trajectory for farmers to move out of poverty. However, due to declining agricultural production in Zimbabwe because of multiple constraints including increased rainfall variability and lack of produce markets, farmers often fail to get sufficient income from agriculture to invest in education. In addition, livelihood opportunities outside agriculture have also declined in Zimbabwe due to economic melt-down. This has been demonstrated by the limited capacity of farmers to identify adaptation options outside agriculture (Chapter 2). Thus, farmers need external support (e.g. for job creation) to be able to broaden their adaptation options.

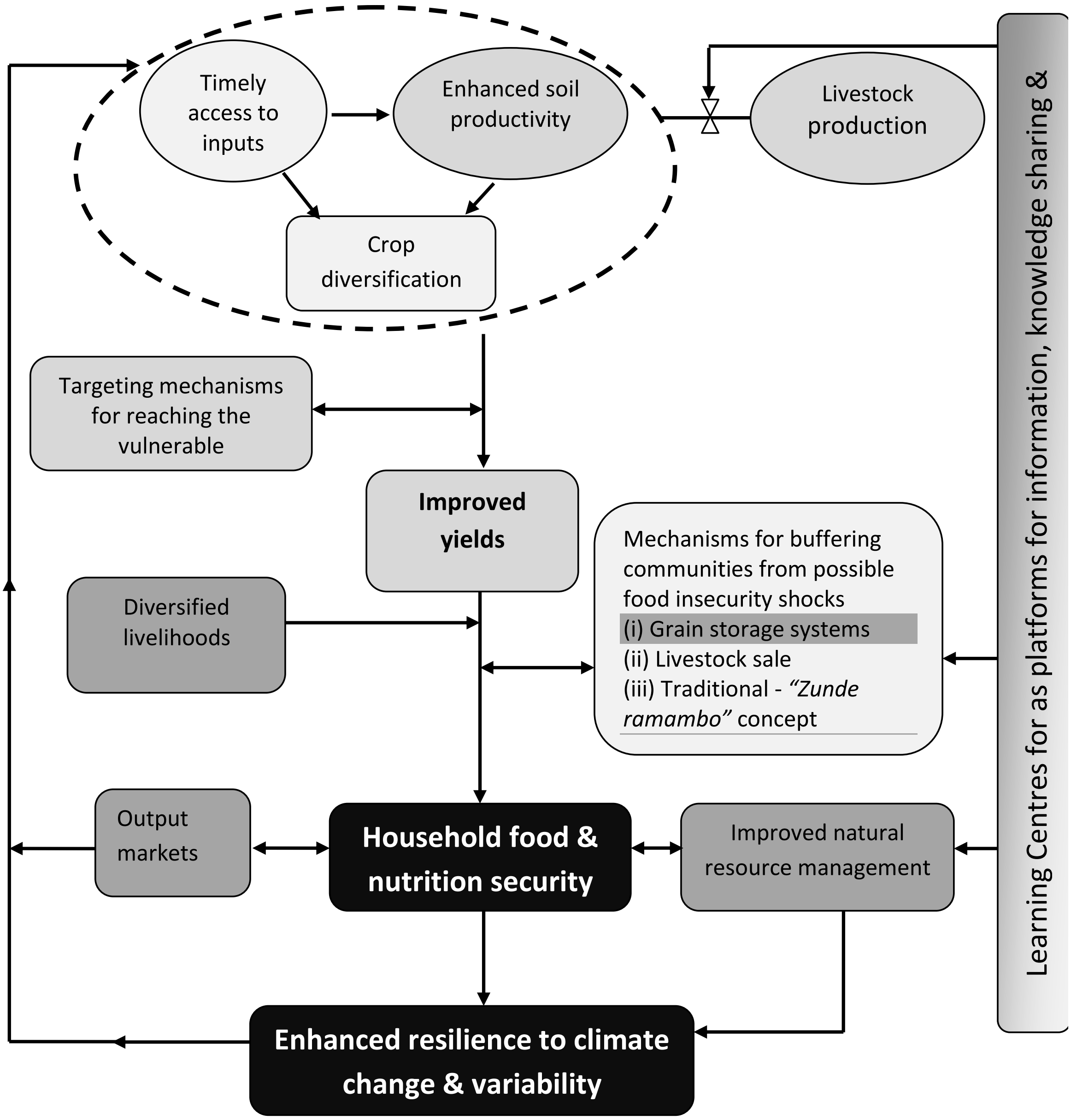

Fig. 6.2. Linkages among issues raised during visioning exercises on how to adapt to climate variability and change by a community in Nyahava ward, Makoni district of Zimbabwe. (*The intensity of the grey shades for each box indicate whether the issue can be addressed in the short term (light grey), medium term (medium grey) of long term (dark grey) leading to improved food security and enhanced resilience goals).* Adapted from Mapfumo et al., 2013.

6.3 Strategies for increasing adaptive testing of promising adaptation options

The adoption of climate adaptation options by farmers has been limited (Ajayi et al., 2007; Kristjanson et al., 2012) despite evidence that household food security would improve (Mapfumo et al., 2013). Farmers are faced with many biophysical and socioeconomic constraints to implement technologies or practices that can increase their adaptive capacity to impacts of climate variability and change. In particular, farmers lack financial resources for timely access to agricultural inputs such as fertilizers, labour and draught power (Chapter 3). They also lack institutional and policy support, and access to reliable sources of climate change information (Nyagumbo and Rurinda, 2012; Mapfumo et al., 2013).

Establishing co-learning platforms that can bring together farmers, local leadership, local extension, researchers, government institutions and private sector, is a critical step in addressing many of the above mentioned challenges. Such co-learning platforms not only help to raise awareness of climate variability and change, and their possible impacts on livelihoods, but also to experimentally test together with farmers the importance of promising adaptation options (Kristjanson et al., 2014). Such fora can also help farmers to learn and adjust their practices as climate changes, as well as to respond to unanticipated future climate shocks given the uncertainty of processes underpinning climate change (Dessai and van der Sluijs, 2007).

An example of a learning platform is the learning centre concept (Fig. 6.3) of Mapfumo et al. (2013). The concept recognises that the flow of knowledge on such issues as climate change, soil fertility management, agro-biodiversity and natural resource management is complex and non-linear. Gwandu et al. (2014) has assessed the performance of the learning centre and reported that such learning platforms are strong tools for sharing agricultural information and enhancing farmers' social capital. However, the learning platforms need to be supported by structured institutions such as innovation platforms (IPs) (Fig. 6.3). An IP is a coalition or strategic alliance of public and private agricultural researchers and extension officers, policy makers, agro-dealers, farmers, farmer organizations and NGOs who cooperate, collaborate, communicate and interact in pursuit of a common goal (Mapfumo, 2009). For effective information and knowledge sharing these IPs should be mobilized at different levels, from community to national (Fig. 6.3).

The learning centre and IP concepts, for example, can facilitate formation or strengthening of farmer groups. Formation of farmer groups for collective acquisition of inputs such as fertilizers has been suggested as a possible option to access fertilizer in time as farmers would share the cost of production (Chapter 2). The idea of farmer groups is not new (Gwandu et al., 2013). Perhaps the key research question is how farmer groups can be supported and sustained in a changing socioeconomic and political environment.

Provision of credit facilities has also been suggested as a possible option that can help farmers to access financial resources (Antwi-Agyei et al., 2013). However, many investors particularly the private sector are reluctant to extend credit because smallholder farmers are located in marginal environments where the risk of crop failure is high. As a result, many farmers would not be able to re-pay credit. Perhaps to attract the private sector to support staple cereal crops such as maize and finger millet, the national IP can facilitate the identification of guarantees, e.g. government, that can help farmers to re-pay credit in seasons of crop failure. The IP can also help farmers to develop improved output markets to motivate them to test and possibly adopt technologies and practices that can increase their adaptive capacity to the changing and increasingly variable climate.

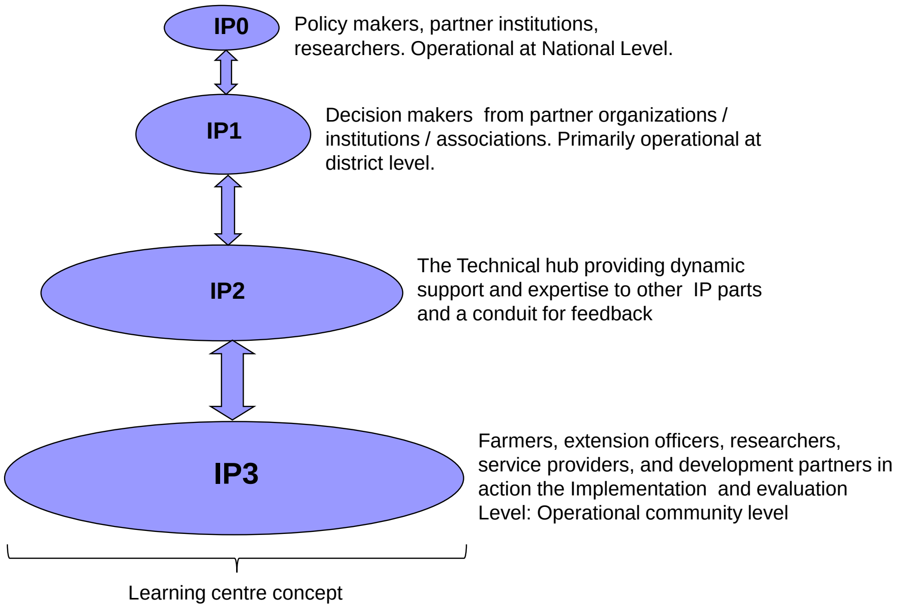

Fig. 6.3. The learning centre and innovation platform concept (adapted from Mapfumo et al., 2009).

6.4 Communicating uncertainties about climate variability and change

Given that information concerning climate change effects on crop yields and possible adaptation options, is urgently needed by both farmers and policy makers to plan about food security issues, dealing with uncertainties associated with climate impact studies on yields is critical for making robust decisions and building climate resilient cropping system (Rötter et al., 2011). There are many uncertainties associated with climate change impact and adaptation studies (Van der Linden and Mitchell, 2009).

Model outputs for many climate impact studies are more robust for changes in mean climate than for changes in climate variability (Chapter 5). Yet crop production in southern Africa is already largely determined by climate variability (Chapter 3), which is also anticipated to increase as climate changes (Chapter 5). This suggests underestimation of climate change effects on crop production. Rowhani et al. (2011) concluded that by 2050 in some parts of Africa the impacts of climate change on crop yields would be under-estimated by between 4% and 27% if only changes in climatic means are taken into account and climate variability is ignored. The increasing frequency of extreme events such as droughts, floods and hotter summers (Coumou et al., 2013), which are not taken into account in many climate impact studies (Chapter 5), can also lead to severe yield reductions. Dai (2013) has projected severe and widespread global warming-induced droughts by 2100 over many regions including southern Africa because of decreased precipitation and/or increased evaporation.

To enhance the quantification and reduction of uncertainties, the use of multiple-model ensemble technique similar to that of climate modelling community is recommended (Rötter et al., 2011). This is important as different models differ in structure and parameter values (Rötter et al., 2011). Asseng et al. (2013) reported that a significant proportion of uncertainty in climate impact projections was due to variations among crop models. Crop growth models such as DSSAT, which has also been evaluated for its usefulness in a range of environments including in southern Africa could complement APSIM to provide a range of possible impacts of climate change on crop yields.

Overall, to take into account these inherent uncertainties and those arising due to lack of knowledge, perhaps the best strategy is to strengthen learning platforms to capacitate/empower farmers to learn and adapt as climate, and other environmental and socioeconomic conditions, change. Other studies have recommended implementation of ‘no regrets’ adaptation options (e.g. Hallegatte, 2009). For example, results from this study indicated that integrated soil fertility management can be a key strategy for building a climate resilient cropping system in African smallholder farming systems. The adaptation process also needs to recognise that climate change may bring some opportunities such as altered rainfall patterns leading to additional rainfall given that in Zimbabwe the change in annual rainfall is less clear in future (Chapter 5). Capitalizing on such windows of opportunities will further strengthen the adaptive capacity of smallholder farmers.

Conclusions and recommendations

The impacts of rising temperatures and more frequent and severe droughts, on livelihoods of smallholder households vary from farmer to farmer, suggesting that one-size-fits-all adaptation model does not necessarily address all farmers. This study underscores the overall importance of soil fertility management as a key strategy for reducing the risk of crop failure and food insecurity even as rainfall season quality deteriorates and temperature increases, with climate change. In Zimbabwe and other parts of southern Africa, there is a reasonably wide planting window if the rains start on time, but if the start of the rains is delayed until after the beginning of December this advantage is lost and planting should be done as soon as possible. The influence of maize cultivar choice on yield is negligible now and in future shifts in climates. Breeding for drought tolerant cultivars maybe necessary in the future. The superiority of maize production over finger millet and sorghum even when the rainfall was poor means that the recommendation to substitute maize with small grains is unlikely to build a robust climate adaptation cropping system in southern Africa. Instead, spreading different crops on a farm and in time not only will help to spread the risk of crop failure and increase household food security, but also improve human nutrition given that lack of dietary requirements is a major problem in sub-Saharan Africa.

There is a large uncertainty in climate change impact studies. Opening up knowledge systems is critical to empower smallholder farmers to adjust their farming livelihood systems as climate changes and to be able to respond to a range of possible future climates including unanticipated climate shocks. In this study different options for adaptation were identified by farmers, but only those that were related to crop production were explored in detail. A more comprehensive adaptation study on livestock production, social safety nets and productivity of natural resources is required for detail understanding of the interactions between these sub-systems together with crop production for sustainable livelihoods of smallholder farmers in a changing and variable climate. Legumes can also play an important role in reducing climatic risk and improve human nutrition. There is need for further studies that assess the critical role legumes play within smallholder farming systems as climate continues to change. Because in this study the experimental data for sorghum and finger millet were not sufficient to assess yield response to long-term change in climate, this calls for further experimental studies to gather more data on the production of sorghum and finger to fill this research gap.

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Appendices

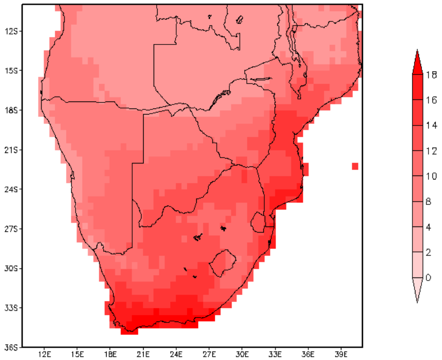
Appendix 1A. Average change in number of consecutive five dry days for three climate periods, against the baseline simulated climate data, for two radiative forcings: representative concentration pathways (rcp) of 4.5 W m^{-2} and 8.5 W m^{-2}, in Southern Africa

Appendix 1B. Average change in length of the longest period of consecutive dry days for three climate periods, against the baseline simulated climate data, for two radiative forcings: representative concentration pathways (rcp) of 4.5 W m^{-2} and 8.5 W m^{-2}, in Southern Africa

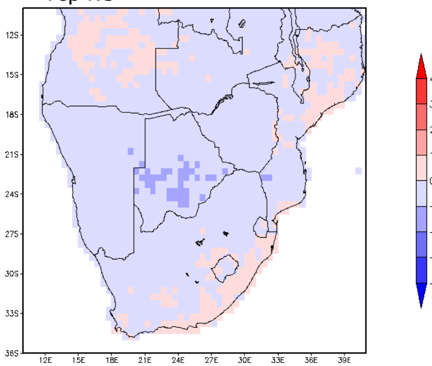
Appendix 1C. Average change in rainfall intensity (mm) for three climate periods, against the baseline simulated climate data, for two radiative forcings: representative concentration pathways (rcp) of 4.5 W m^{-2} and 8.5 W m^{-2}, in Southern Africa

Appendix 1A. Average change in number of consecutive five dry days (cdd) for three climate periods, against the baseline simulated climate data, for two radiative forcings: representative concentration pathways (rcp) of 4.5 W m^{-2} and 8.5 W m^{-2}, in southern Africa

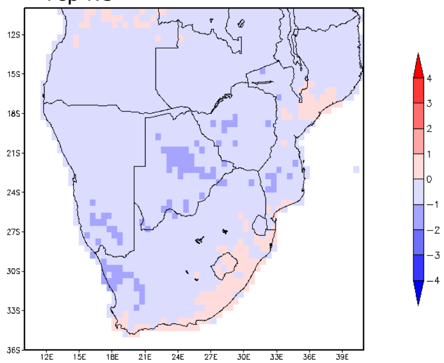
(a) Average number of cdd periods, 1975-2005



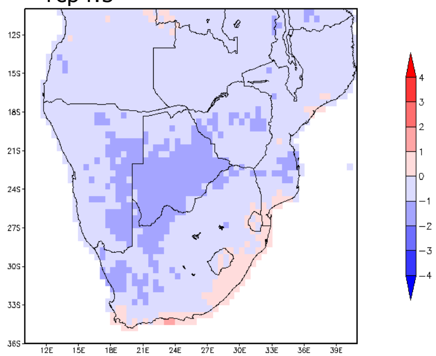
(b) Average change in number of cdd periods, 2010-2039 vs 1975-2005, rcp4.5



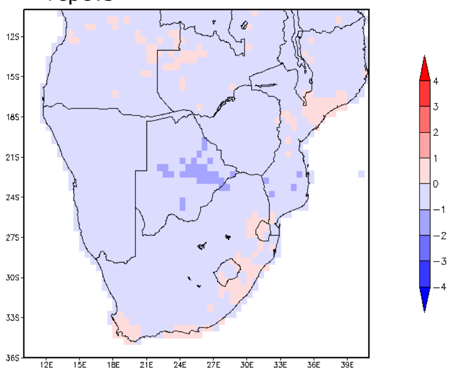
(c) Average change in number of cdd periods, 2040-2069 vs 1975-2005, rcp4.5



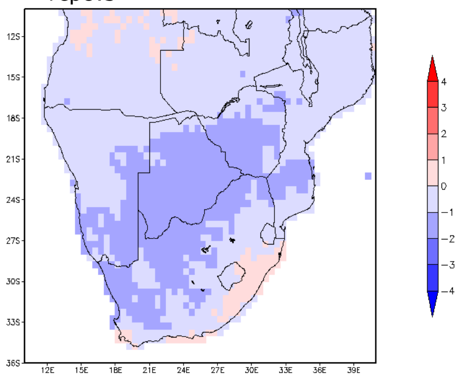
(d) Average change in number of cdd periods, 2070-2099 vs 1975-2005, rcp4.5



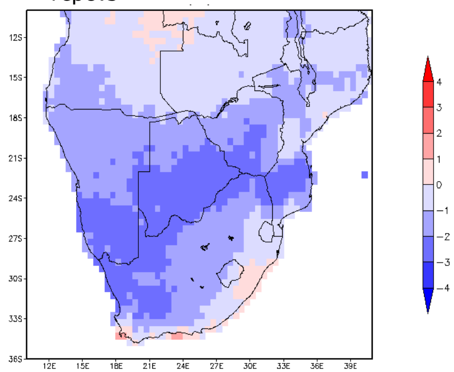
(e) Average change in number of cdd periods, 2010-2039 vs 1975-2005, rcp8.5



(f) Average change in number of cdd periods, 2040-2069 vs 1975-2005, rcp8.5

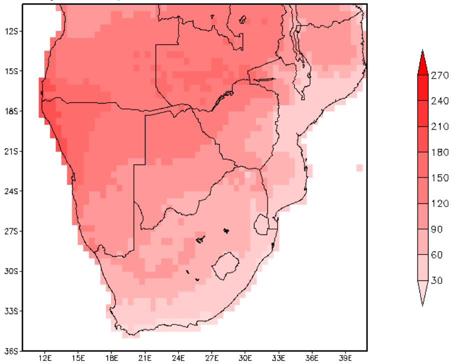


(g) Average change in number of cdd periods, 2070-2099 vs 1975-2005, rcp8.5

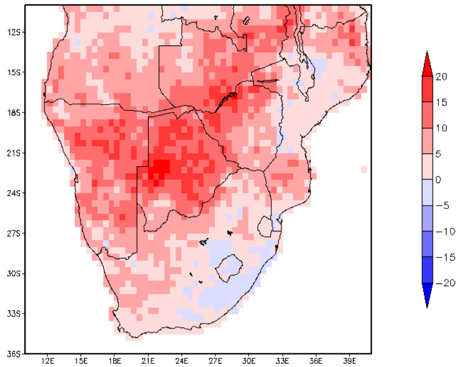


Appendix 1B. Average change in length of the longest period of consecutive dry days for three climate periods, against the baseline simulated climate data, for two radiative forcings: representative concentration pathways (rcp) of 4.5 W m^{-2} and 8.5 W m^{-2}, in southern Africa

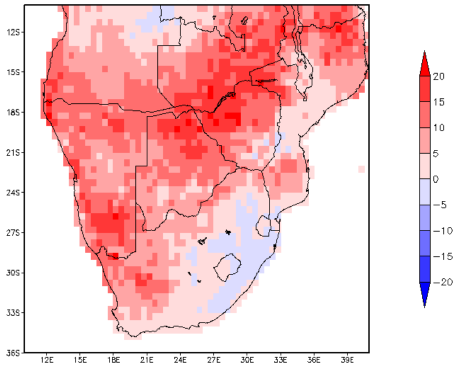
(a) Average length of largest cdd period, 1975-2005



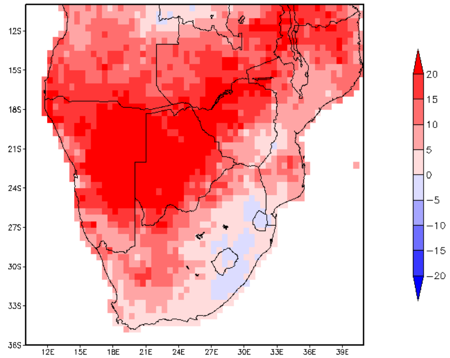
(b) Average change in length of largest cdd period, 2010-2039 vs 1975-2005, rcp4.5



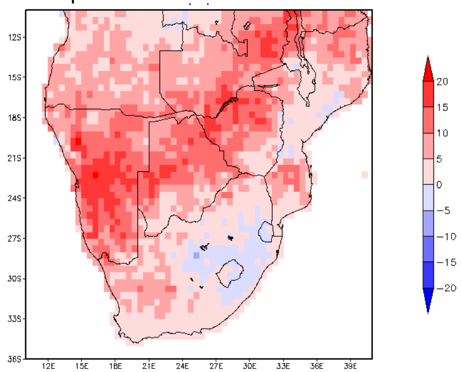
(c) Average change in length of largest cdd period, 2040-2069 vs 1975-2005, rcp4.5



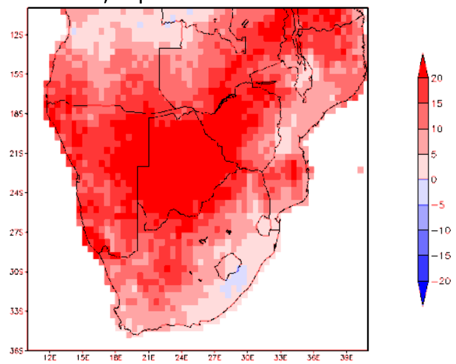
(d) Average change in length of largest cdd period, 2070-2099 vs 1975-2005, rcp4.5



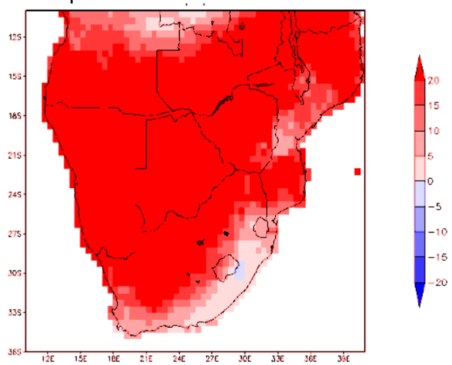
(e) Average change in length of largest cdd period, 2010-2039 vs 1975-2005, rcp8.5



(f) Average change in length of largest cdd period, 2040-2069 vs 1975-2005, rcp8.5

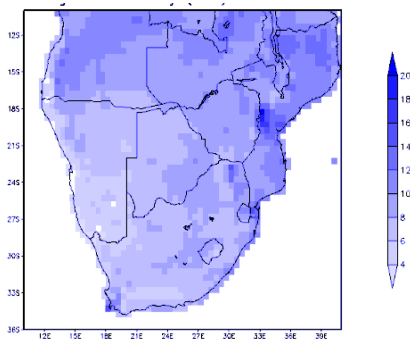


(g) Average change in length of largest period, 2070-2099 vs 1975-2005, rcp8.5

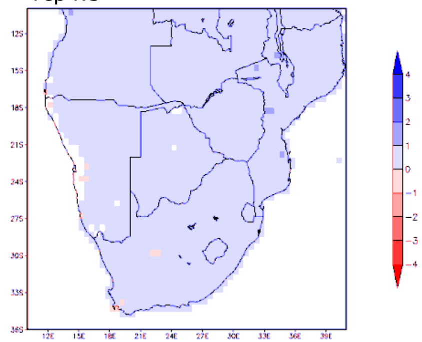


Appendix 1C. Average change in rainfall intensity (mm) for three climate periods, against the baseline simulated climate data, for two radiative forcings: representative concentration pathways (rcp) of 4.5 W m^{-2} and 8.5 W m^{-2}, in southern Africa

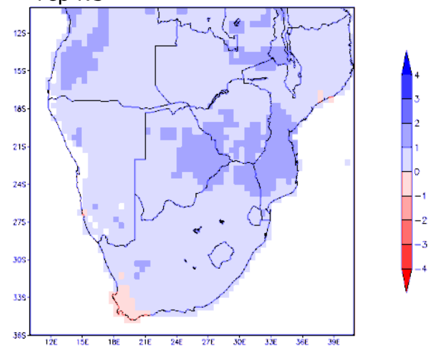
(a) Average rain intensity (mm), 1975-2005



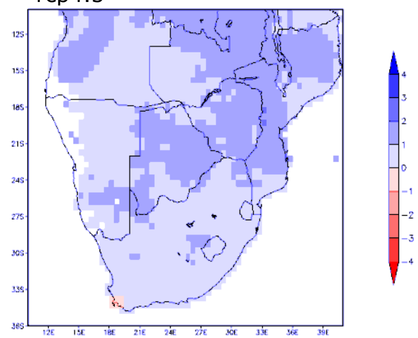
(b) Average change in rain intensity (mm), 2010-2039 vs 1975-2005, rcp4.5



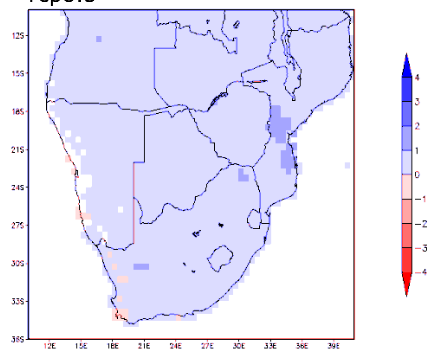
(c) Average change in rain intensity (mm), 2040-2069 vs 1975-2005, rcp4.5



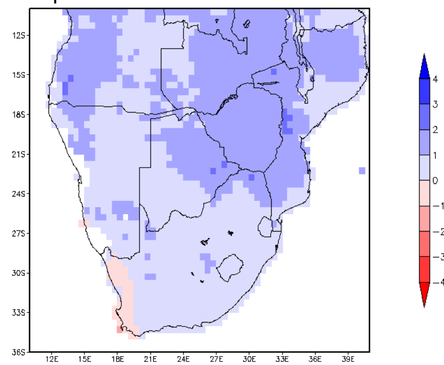
(d) Average change in rain intensity (mm), 2070-2099 vs 1975-2005, rcp4.5



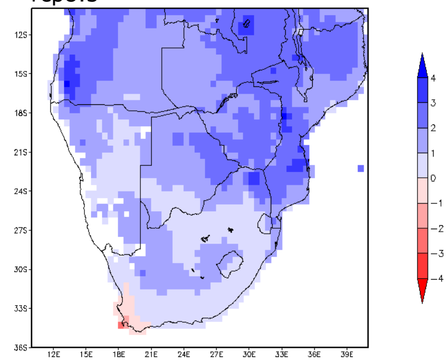
(e) Average change in rain intensity (mm), 2010-2039 vs 1975-2005, rcp8.5



(f) Average change in rain intensity (mm), 2040-2069 vs 1975-2005, rcp8.5



(g) Average change in rain intensity (mm), 2070-2099 vs 1975-2005, rcp8.5



Summary

Many climate projections and the associated impact studies suggest that southern Africa, including Zimbabwe, is a ‘vulnerable hotspot’ to rising temperatures, and more severe and frequent droughts. The vulnerability arises from the dominant rural livelihoods, which are focused on smallholder farming and have a low capacity to adapt. Smallholder farmers have struggled to achieve food security over the past decades, due to natural rainfall variability, weak markets and land degradation. The impacts of a changing climate are likely to interact with these existing stresses to further threaten food security. Although farmers have been adapting to climate variability, the predicted high rate and magnitude of climate change in the region suggest that farmers may not be able on their own to adjust their farming systems fast enough to match the rate of climate change. In an effort to increase the adaptive capacity of smallholder farmers to a changing climate, the main objectives of this study are first to identify and understand the nature and the sources of vulnerability of smallholder households and second, to use this knowledge to evaluate possible farm-level management options that can enhance the adaptive capacity of smallholder farmers in the face of climate change and increased climate variability.

This study focuses on smallholder farming systems in two districts, Makoni and Hwedza, in eastern Zimbabwe. The two locations have contrasting dry sub-humid and semi-arid tropical climates. Rainfall in Zimbabwe as in many parts of southern Africa is strongly seasonal and falls between October and April with the highest rainfall amounts received between December and February. Both sites have soils of poor fertility, Lixisols and Arenosols, which are representative for large areas of sub-Saharan Africa. For example, Arenosols cover about 13% of sub-Saharan Africa and more than 6.5 million ha of cropland in southern Africa.

To investigate the nature and sources of vulnerability, we analysed long-term climate data from the Meteorological Services Department of Zimbabwe and interviewed farmers individually and in groups. Participatory diagnostic studies were conducted to understand farmers’ perceptions of climate variability and change. The long-term rainfall analyses closely supports farmers’ perceptions that the mean annual rainfall has not changed, whereas marked changes in the pattern of rainfall within the season have occurred. The number of rain days has decreased, and the frequency of dry spells within the season has increased, which support farmers’ perceptions. The mean daily minimum temperature increased, by 0.2°C per decade in Makoni and by 0.5°C per decade in Hwedza, over the period from 1962 to 2000. The number of days with temperatures >30°C increased in Hwedza. The temperature is also projected to increase significantly in Makoni and Hwedza by 2100. Yet there is no clear evidence that the annual rainfall in in the two study sites will change by 2100 under both low and high emission scenarios.

The impacts of rising temperatures, and more severe and frequent droughts among smallholder households were highly differentiated. Smallholder households differing in resource endowments depend on varied sub-systems of the broader livelihood system namely cropping, livestock production, natural resources and social safety nets, which are exposed differently to the aspects of climatic risk. Livestock production was sensitive to drought due to lack of feed, affecting resource-endowed farmers, who own relatively large herds of cattle. Crop production was more sensitive to increased rainfall variability, affecting especially farmers with intermediate resource endowment. Availability of wild fruits and social safety nets were affected directly and indirectly by extreme temperatures and increased rainfall

variability, impacting the livelihoods of resource-constrained farmers. As such, there was no simple one-to-one relationship between vulnerability and farm types, suggesting that vulnerability to climate variability and change is not simply related to poverty.

On the other hand, farmers have access to different resources such as fertilizer and farm labour inputs. Consequently, they respond uniquely to the changing climate. For example, in Makoni and Hwedza, farmers revealed that timely access to fertilizer and draught power can buffer crop production against increased rainfall variability. Timely access to fertilizers and draught power can help farmers to synchronize their farming operations with seasonal rainfall pattern. Similarly, farmers who have access to cash for buying supplementary livestock feed or have strong social networks for transhumant movement, can reduce the impacts of droughts on livestock. Thus, alongside climate variability and change farmers were also faced with biophysical and socio-economic problems, and these challenges had strong interactions with adaptation options to climate change.

On-farm experiments were conducted to evaluate the impacts and interactions of field-level adaptation options namely planting date, fertilization and maize cultivar choice. These potential adaptation options were identified together with farmers. Initially, following experimentation, these adaptation options were examined in response to short-term rainfall variability as adaptation options that address short-term climate variability are likely to lead to short-term benefits and will help to deal with future changes in climate. The results from experiments showed that there were no significant differences in maize development or grain yield among cultivars. Greater maize grain yields were obtained with both the early and normal plantings, with no significant differences between these planting windows (e.g. on average 5 t ha^{-1} in Makoni, and 3 t ha^{-1} in Hwedza for the high fertilization rate). This suggests that there is a wide planting window for successful establishment of crops in response to increased rainfall variability. Regardless of the amount of fertilizer applied, yields were reduced strongly when planting was substantially delayed by four weeks after the start of the rainy season. Across the planting dates, fertilization led to a large increase in maize grain yield, but the yield increased much more with fertilization of the early and normal plantings. With fertilization the probability of achieving household food self-sufficiency was greater, > 0.8 when planting early or during the normal window, suggesting that resource endowed farmers who apply reasonable rates of fertilizers are often food secure. While without fertilization the probability of achieving household food self-sufficiency was low, less than 0.05, even when the crop was planted early. Soil nutrient management had an overriding effect on crop production, suggesting that although the quality of within-season rainfall is decreasing, nutrient management is the priority technical option for adaptation in rain-fed smallholder cropping systems.

Another on-farm experiment was conducted to assess whether small grains (finger millet and sorghum) perform as well as maize under variable soil and rainfall conditions, to inform farmers on cropping systems that can increase their food security in a changing climate. Maize yielded more than finger millet and sorghum even in the season (2010/11) with poor rainfall distribution. For example, maize yielded 2.4 t ha^{-1} compared with 1.6 t ha^{-1} for finger millet and 0.4 t ha^{-1} for sorghum in the 2010/11 rainfall season in Makoni. The emergence for maize was also greater regardless of the amount of fertilizer applied. In contrast, finger millet and sorghum crops failed to emerge unless fertilizer was applied. Sorghum failed to yield due to bird damage unless the panicles were protected. Breeding sorghum cultivars that are not prone to bird damage and increasing the marketing structure of the crop might attract farmers to increase area under sorghum. All three crops yielded significantly more with increasing rates of fertilization. Under high fertilization rate, maize yielded 5.4 t ha^{-1}, finger millet, 3.1 t ha^{-1} and sorghum 3.3 t ha^{-1}, against 2 t ha^{-1} and 0.5 t $ha^{-1}$for each crop for the low rate and control respectively, in Makoni in the 2009/10 season. The strong response to high amount of fertilizer by small grains, often regarded as less nutrient-demanding crops demonstrated that the soils are so poor in fertility that more investment in soil fertility management is a pre-requisite for increased yields. Marginal rates of return for maize production were greater for the high fertilization rate (> 50%) than for the low rate (< 50%). Whereas the financial returns for finger millet were more attractive for the low fertilization rate (> 100%) than for the high rate (< 100%).

Although the yields of maize were greater than those of small grains, finger millet and sorghum are important in the human diets in the region. Finger millet has a higher content of minerals, especially calcium, and dietary fibre than maize. Given that lack of nutritionally balanced diet is a major problem in sub-Saharan Africa, the production of finger millet is an option to improve human nutrition, particularly for the poorest farmers. Finger millet can be stored for up to five years with minimum damage form post-harvest pests. Thus finger millet could play a role in complementing maize in order to stabilize household food self-sufficiency particularly during drought years.

To provide evidence on the impacts of long-term change in climate on crop production, we assessed the response of maize yield to projected climate change and to planting date, fertilization and maize cultivar choice as three key management options, using the Agricultural Production Systems Simulator (APSIM). Three climate periods were selected to cover both near and long term climates: 2010-2039; 2040-2069; 2070-2099, against a baseline, 1976-2005. Future climate data for two Representative Concentration Pathways (RCPs): rcp4.5 with radiative forcing of 4.5 W m^{-2} and rcp8.5 with radiative forcing of 8.5 W m^{-2}, were generated from an ensemble of five global circulation models. The yield performance for all three cultivars is projected to be similar in future change in climates, consistent with results from the experiments. The simulations projected that the impact of climate change on maize yield will increase as time progresses and as temperature continues to increase as a consequence of future greenhouse gas emissions. Although maize production will decline in the near future when compared with the baseline climate, the yield decline will be relatively small (- 11%) until the middle of the 21st Century particularly for the low greenhouse gas emission scenario. Larger maize yield losses (≤ - 25%) are only projected for the more distant future i.e. towards the end of the 21st Century, and under the high radiative forcing scenario of 8.5 W m^{-2}.

The simulated average maize yield increased gradually with planting date from early November to mid-December. Then after mid-December the simulated maize yield decreased drastically. The similarity in yield among the planting dates until mid-December further reinforced the finding from our experimental studies that there is no yield difference between crops planted early (25 October - 20 November) or during what farmers considered the normal planting window (21 Novermber-15 December). Fertilization increased yield significantly under both the baseline and future climates particularly when planting before mid-December. The maize response to mineral nitrogen is projected to decline as climate changes, although effects only become substantial towards the end of the 21st Century. The simulation results indicate that maize yields in future might plateau at smaller mineral nitrogen additions than under current climate. This would mean that recommended application rates for southern Africa should be reduced in future, unless breeding can compensate for the reduced yields.

This study demonstrated that the maize cultivars currently on the market in Zimbabwe, and in many parts of southern Africa, exhibit too narrow differences in maturity time to respond differently to prolonged dry spells. In the current cropping system farmers can select any cultivar available on the market without a yield penalty. However, with climate change none of the available cultivars will be able to compensate for the decline in yield regardless of improved soil fertility management and timing of planting. In the long-term breeding for rapidly maturing maize cultivars may be an option although this will curtail potential yield in good seasons. Contrary to well established knowledge, there is a reasonably wide planting window if the rains start on time as long as soil fertility is improved, but if the start of the rains is delayed until after the beginning of December this advantage is lost and planting should be done as soon as possible. The better performance of maize over finger millet and sorghum in this study suggests that the recommendation to substitute small grains for maize as a viable adaptation option to a changing climate, will neither be the best option for robust adaptation nor attract farmers to increase area under small grains, in southern Africa. Alternatively spreading crops across the farm and in time could help to spread climate risk as well as improve human nutrition. Poor soil fertility constrained yield more strongly than rainfall and late planting. Soil fertility management is therefore likely to remain a key technical option for buffering crop yield against a changing climate. Because currently farmers lack access to mineral fertilizers due to prohibitive cost, strategies to increase farmers' access to mineral fertilizers are likely to strengthen the adaptive capacity of farmers.

Given that there is a large uncertainty in climate change impact studies, establishing learning platforms is important to empower smallholder farmers to adjust their farming livelihood systems as climate changes. Such co-learning process can also capacitate farmers to be able to respond to a range of possible future climates including unanticipated climate shocks. The adaptation framework needs to take into account that climate change might bring some opportunities which need to be capitalised on to strengthen the adaptive capacity of smallholder farmers.

Samenvatting

Veel klimaatvoorspellingen, en de daaraan geassocieerde studies over impact, suggereren dat zuidelijk Afrika, waaronder Zimbabwe, een "kwetsbare hotspot" is voor stijgende temperaturen, en ernstigere en vaker terugkerende droogteperiodes. De kwetsbaarheid komt voort uit de dominante landbouwgeoriënteerde levenswijze, die toegespitst is op kleinschalige familielandbouw en doorgaans weinig aanpassingsvermogen heeft. Kleine boeren worstelen al decennia met hun voedselzekerheid , die bedreigd wordt door grote natuurlijke variatie in neerslag, zwakke markten en landdegradatie. De effecten van een veranderend klimaat zullen de voedselzekerheid waarschijnlijk verder aantasten door interactie met bestaande stressoren. Hoewel de boeren al bezig zijn hun landbouwsysteem aan te passen aan klimaatschommelingen, is de voorspelde snelheid en grootte van de klimaatverandering in de regio zodanig dat men mogelijk niet in staat zal blijken de landbouwsystemen snel genoeg aan te passen om de klimaatverandering te kunnen bijbenen. In een poging het aanpassingsvermogen van kleine boeren aan een veranderend klimaat te vergroten zijn de belangrijkste doelen van deze studie in de eerste plaats om de aard en de bronnen van kwetsbaarheid bij kleine boeren te identificeren, en in de tweede plaats om deze kennis te gebruiken om management-opties, die het aanpassingsvermogen van kleine boeren ten opzichte van klimaatverandering en toegenomen variabiliteit in het klimaat kunnen vergroten, op bedrijfsniveau te evalueren.

Deze studie richt zich op kleinschalige landbouwsystemen in twee districten, Makoni en Hwedza, in het oosten van Zimbabwe. De twee locaties hebben verschillende tropische klimaten: de één droog sub-humide, en de tweede semi-aride. Regenval in Zimbabwe, zoals in veel delen van zuidelijk Afrika, is sterk seizoensgebonden, en is geconcentreerd tussen oktober en april met de hoogste regenval van december tot februari. Beide onderzoeksgebieden hebben arme bodems (Lixisols en Arenosols) die representatief zijn voor grote delen van sub-Sahara Afrika. Arenosols, bijvoorbeeld, beslaan ongeveer 13% van sub-Sahara Afrika en zijn te vinden in meer dan 6,5 miljoen hectare akkerland in zuidelijk Afrika.

Om de aard en de bronnen van kwetsbaarheid te onderzoeken hebben we het klimaat van Zimbabwe geanalyseerd aan de hand van langetermijngegevens van het Departement Meteorologische Diensten van Zimbabwe, en hebben we boeren geïnterviewd, zowel individueel als in groepen. We hebben participatief diagnostisch onderzoek uitgevoerd om de percepties van boeren wat betreft de klimaatverandering en -variabiliteit te begrijpen. De langetermijnanalyse van de neerslagdata onderschrijft de percepties van boeren dat de gemiddelde jaarlijkse neerslag niet is veranderd, maar dat zich duidelijke wijzigingen hebben voorgedaan in het neerslagpatroon gedurende het regenseizoen. Het aantal regendagen is afgenomen, en de frequentie van droge perioden in het regenseizoen is toegenomen, wat overeenkomt met de percepties van de boeren. De gemiddelde dagelijkse minimumtemperatuur is tussen 1962 en 2010 gestegen met 0,2 °C per decennium in Makoni en met 0,5 °C per decennium in Hwedza. Het aantal dagen met temperaturen >30 °C is gestegen in Hwedza. De oppervlaktetemperatuur zal in 2100 naar verwachting significant gestegen zijn in Makoni en Hwedza. Toch is er geen duidelijk bewijs dat de jaarlijkse neerslag in de twee studiegebieden zal veranderen tussen nu en 2100, onder lage noch hoge emissiescenario's.

De gevolgen van de stijgende temperaturen en de ernstigere en frequentere droogtes voor de kleine boeren waren zeer verschillend. Kleine boerenbedrijven, variërend in beschikbare middelen, zijn afhankelijk van verschillende subsystemen van het bredere rurale systeem, namelijk gewasteelt, veeteelt, natuurlijke hulpbronnen en sociale vangnetten, die op verschillende manieren worden blootgesteld aan klimaatrisico's. Dierlijke productie was gevoelig voor droogte door daaruit voortvloeiend gebrek aan voeder, wat bemiddelde boeren raakt die relatief grote kuddes vee bezitten. Plantaardige productie was gevoeliger voor variabiliteit in neerslag, wat vooral boeren van gemiddelde welvaart raakt. Beschikbaarheid van wilde vruchten en sociale vangnetten werd direct en indirect beïnvloed door extreme temperaturen en toegenomen variabiliteit in neerslag, met gevolgen voor het levensonderhoud van onbemiddelde boeren. Als zodanig was er geen eenvoudige een-op-een relatie tussen kwetsbaarheid en bedrijfstypen, wat suggereert dat kwetsbaarheid voor klimaatschommelingen en klimaatverandering niet enkel en alleen gerelateerd is aan armoede.

Aan de andere kant hebben de boeren in toegang tot verschillende hulpbronnen, zoals kunstmest en agrarische arbeid. Het gevolg is dat ze op unieke wijze reageren op het veranderende klimaat. Boeren in Makoni en Hwedza toonden bijvoorbeeld aan dat tijdige toegang tot kunstmest en trekkracht de gewasproductie kan beschermen tegen toegenomen variabiliteit in neerslag. Tijdige toegang tot kunstmest en trekkracht kan boeren helpen hun agrarische activiteiten beter af te stemmen op het neerslagpatroon van het seizoen. Een gelijksoortige situatie: boeren die toegang hebben tot geld voor de aankoop van aanvullend veevoeder of die sterke sociale netwerken hebben voor nomadische migratie kunnen de gevolgen van droogte voor het vee verminderen. Zodoende werden boeren niet alleen geconfronteerd met klimaatverandering en klimaatschommelingen maar ook met biofysische en sociaal-economische problemen, en deze problemen hadden weer een sterke wisselwerking met de mogelijkheden voor aanpassing aan de klimaatverandering.

Veldexperimenten op boerenbedrijven zijn uitgevoerd om de effecten en interacties van aanpassingsmogelijkheden op veldniveau te evalueren, door plantdatum, bemesting en maïscultivar te variëren. Deze aanpassingsmogelijkheden werden samen met boeren geïdentificeerd. Aanvankelijk, naar aanleiding van experimenten, werden deze aanpassingsmogelijkheden onderzocht in reactie op kortetermijnvariabiliteit in regenval, aangezien aanpassingsmogelijkheden die gericht zijn op kortetermijnvariabiliteit in het klimaat waarschijnlijk kortetermijnvoordelen zullen opleveren en zullen helpen bij het omgaan met toekomstige veranderingen in het klimaat. De resultaten van de experimenten toonden aan dat er geen significante verschillen in maïsontwikkeling of graanopbrengst waren tussen cultivars. Hogere maïsopbrengsten werden verkregen met zowel de vroege als de normale plantdata, zonder significante verschillen tussen deze plantperiodes (bijvoorbeeld gemiddeld 5 t ha^{-1} in Makoni, en 3 t ha^{-1} in Hwedza voor het hoge bemestingsniveau). Dit suggereert dat er een lange plantperiode is voor succesvolle vorming van gewassen bij toenemende neerslagvariabiliteit. Ongeacht de hoeveelheid kunstmest waren de gewasopbrengsten veel lager wanneer het planten aanzienlijk was vertraagd tot vier weken na het begin van het regenseizoen. Bemesting leidde tot een grote toename van de maïsopbrengst bij alle plantdata, maar de oogst was nog veel groter bij bemesting van de maïs geplant in de vroege en normale plantperiodes. Met bemesting was de kans op het bereiken van voedselzelfvoorziening op huishoudniveau groter, tot > 0,8 bij het planten in de vroege of de normale plantperiode, hetgeen suggereert dat bemiddelde boeren die redelijke hoeveelheden kunstmest gebruiken vaak voldoende voedsel produceren. Zonder bemesting was de kans op het bereiken van voedselzelfvoorziening op huishoudniveau klein, minder dan 0,05, zelfs wanneer het gewas vroeg werd geplant. Het management van voedingsstoffen in de bodem had een overheersend effect op de gewasproductie, wat suggereert dat dit de belangrijkste technische optie is voor aanpassingen in regenafhankelijke kleinschalige teeltsystemen, ondanks dat de kwaliteit van de neerslag in het seizoen afneemt.

Een ander veldexperiment op de boerderij werd uitgevoerd om te beoordelen of fijnzadige granen (vingergierst en sorghum) net zo goed presteren als maïs onder variabele bodem- en neerslagomstandigheden, om de boeren informatie te kunnen geven over teeltsystemen die hun voedselzekerheid in een veranderend klimaat kunnen vergroten. Maïs gaf meer opbrengst dan vingergierst en sorghum, zelfs in het seizoen (2010/11) met een slechte neerslagverdeling. Maïs leverde bijvoorbeeld 2,4 t ha^{-1}, vingergierst 1,6 ton ha^{-1}, en sorghum 0,4 t ha^{-1} in het regenseizoen van 2010/11 in Makoni. De maïs kwam ook beter op, ongeacht de hoeveelheid gebruikte kunstmest. Vingergierst en sorghum kwamen echter niet op tenzij kunstmest werd gebruikt. Sorghum gaf geen oogst vanwege vraat door vogels tenzij de pluimen werden beschermd. Het ontwikkelen van sorghumcultivars die niet gevoelig zijn voor vogelvraat en het verbeteren van de afzetmarkt van het gewas kan boeren aanzetten om de oppervlakte met sorghum te vergroten. Alledrie de gewassen leverden aanzienlijk meer op met toenemend gebruik van kunstmest. Onder hoge bemestingsregimes produceerde maïs, vingergierst en millet respectievelijk 5,4 t ha^{-1}, 3,1 t ha^{-1} en 3,3 t ha^{-1}, tegen 2 t ha^{-1} en 0,5 t ha^{-1} voor elk gewas voor respectievelijk de lage bemestingsgraad en de controle in Makoni in het seizoen 2009/10. De sterke reactie op de hoogste bemestingsgraad van de fijnzadige granen, die vaak worden beschouwd als minder veeleisend wat betreft voedingsstoffen, heeft aangetoond dat de bodems zo onvruchtbaar zijn dat grotere investering in management van bodemvruchtbaarheid een voorwaarde is voor hogere opbrengsten. Marginale meeropbrengsten voor de productie van maïs waren groter voor de hoge bemestingsgraad (> 50%) dan voor de lage (< 50%), terwijl de financiële opbrengsten van vingergierst beter waren bij de lage bemestingsgraad (> 100%) dan bij de hoge bemestingsgraad (< 100%).

Hoewel de opbrengsten van maïs groter zijn dan die van de kleinkorrelige granen zijn vingergierst en sorghum belangrijk voor het dieet van de bevolking in het gebied. Vingergierst heeft een hoger gehalte aan mineralen, vooral calcium, en voedingsvezels dan maïs. Aangezien gebrek aan evenwichtige voeding een groot probleem is in sub-Sahara Afrika, is de productie van vingergierst een mogelijkheid voor verbetering van het dieet, in het bijzonder voor de armste boeren. Vingergierst kan maximaal vijf jaar worden opgeslagen, met een minimum aan schade door insecten. Daardoor kan vingergierst een rol spelen als aanvulling op maïs om voedselzekerheid van het huishouden te stabiliseren, met name tijdens jaren van droogte.

Om bewijzen te leveren wat betreft de effecten van langetermijnveranderingen in het klimaat op gewasproductie hebben we de reactie van maïsopbrengst op de voorspelde klimaatverandering, en plantdatum, bemesting en de keuze van maïscultivar als de drie belangrijkste aanpassingsmogelijkheden, onderzocht met behulp van de *Agricultural Production Systems Simulator* (APSIM). Drie klimaatperiodes werden geselecteerd om zowel het klimaat op korte als op lange termijn mee te nemen: 2010-2039, 2040-2069 en 2070-2099, tegen een baseline: 1976-2005. Toekomstige klimaatgegevens voor twee *Representative Concentration Pathways* (RCP; rcp4.5 met een stralingsforcering van 4,5 W m^{-2} en rcp8.5 met een stralingsforcering van 8,5 W m^{-2}), werden gegenereerd uit een verzameling van vijf globale circulatiemodellen. De prognose is dat de opbrengstprestaties voor alle drie de cultivars vergelijkbaar zullen zijn onder toekomstige klimaatveranderingen, en dit is in overeenkomst met de resultaten van de experimenten. De simulaties voorspelden dat de effecten van de klimaatverandering op de opbrengst van maïs zullen toenemen naarmate de tijd vordert en de temperatuur blijft stijgen als gevolg van de toekomstige uitstoot van broeikasgassen. Hoewel de productie van maïs zal afnemen in de nabije toekomst in vergelijking met de klimaatbaseline zal de opbrengstdaling relatief klein zijn (- 11%) tot het midden van de 21e eeuw, met name voor het scenario van lage uitstoot van broeikasgassen. Grotere maïsopbrengstverliezen (≤ -25%) zijn alleen voorspeld voor de verre toekomst, namelijk aan het einde van de 21^{e} eeuw, en onder het scenario van een hoge stralingsforcering van 8,5 W m^{-2}.

De gesimuleerde gemiddelde opbrengst van maïs steeg geleidelijk met plantdatum van begin november tot half december, maar na half december daalde de gesimuleerde opbrengst drastisch. De vergelijkbaarheid van de opbrengst bij plantdata tot half december versterkte de bevinding van onze experimentele studies dat er geen verschil is in opbrengst tussen de vroeg-geplante gewassen (tussen 25 oktober en 20 november) en de gewassen die zijn geplant tijdens wat boeren beschouwen als de normale plantperiode (21 november tot 15 december). Bemesting verhoogde de opbrengst significant onder zowel de baseline als de toekomstige klimaatscenario's, in het bijzonder wanneer was geplant voor medio december. Het effect van minerale stikstof op maïs zal naar verwachting verminderen als het klimaat verandert, hoewel deze gevolgen pas significant zullen worden tegen het einde van de 21^{e} eeuw. De simulatieresultaten geven aan dat de opbrengsten van maïs in de toekomst misschien al zullen afvlakken bij lagere minerale stikstofgiften dan onder de huidige klimaat. Dit zou betekenen dat aanbevolen hoeveelheden bemesting voor zuidelijk Afrika in de toekomst moeten worden verminderd, tenzij plantenveredeling kan compenseren voor de daling van het productievermogen.

Deze studie heeft aangetoond dat de maïscultivars die momenteel op de markt zijn in Zimbabwe, en in vele delen van zuidelijk Afrika, te weinig verschillen wat betreft rijpingsperiode om anders te reageren op langdurige droogteperiodes in het regenseizoen. In het huidige teeltsysteem kunnen boeren iedere cultivar op de markt selecteren zonder aan opbrengst in te boeten. Met de klimaatverandering echter zal geen van de beschikbare cultivars in staat zijn om te compenseren voor de daling van de opbrengst, ongeacht verbeterd management van bodemvruchtbaarheid en het tijdstip van planten. Op de lange termijn kan ontwikkeling van vroegrijpende maïscultivars een optie zijn, hoewel dit de potentiële opbrengst in goede seizoenen zal verminderen. In tegenstelling tot wat algemeen wordt aangenomen is er een redelijk ruime plantperiode als de regens op tijd beginnen, mits de bodemvruchtbaarheid wordt verbeterd, maar als het begin van de regen is vertraagd tot na begin december gaat dit voordeel verloren en moet het planten zo spoedig mogelijk worden gedaan. De hogere opbrengsten van maïs, in vergelijk met die van vingergierst en sorghum in deze studie, suggereren dat de aanbeveling om fijnzadige granen te vervangen door maïs als haalbare mogelijkheid tot aanpassing aan een veranderend klimaat noch de beste optie zal zijn voor een robuuste aanpassing, noch de boeren in zuidelijk Afrika zal aantrekken. Als alternatief kan het spreiden van gewassen over het land en in de tijd helpen om klimaatrisico's te spreiden en het voedingspatroon te verbeteren. Lage bodemvruchtbaarheid beperkt de productie meer dan regen en late aanplant. Het is daarom te verwachten dat bodemvruchtbaarheidsbeheer een belangrijke technische optie blijft als buffer voor gewasopbrengst tegen een veranderend klimaat. Omdat de boeren momenteel geen toegang hebben tot kunstmest door te hoge prijzen zullen strategieën om de toegang van boeren tot kunstmest te verbeteren waarschijnlijk helpen het adaptieve vermogen van de boeren te versterken.

Gezien het feit dat er grote onzekerheid bestaat in studies over de effecten van klimaatverandering is de oprichting van 'leerplatforms' belangrijk om kleine boeren in staat te stellen hun landbouwsystemen aan te passen aan klimaatverandering. Dergelijke collectieve leerprocessen kunnen ook de capaciteiten van boeren vergroten om te reageren op een scala van mogelijke toekomstige klimaten, inclusief onverwachte klimaatschokken. In het kader van de aanpassingen dient men er rekening mee te houden dat klimaatverandering ook kansen kan bieden die benut moeten worden om het aanpassingsvermogen van kleine boeren te versterken.

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I apologize if I have forgotten anyone.

Curriculum vitae

About the Author

Jairos Rurinda was born in Masvingo, Zimbabwe on the 17th of April 1980. He attended secondary school at Chibi High School from 1994 to 1999, and in 1997 he won an award in the Zimbabwe Physics Challenge Competition. Jairos obtained a BSc honours degree in Applied Environmental Science in 2003 from the University of Zimbabwe. He did his internship at the Tropical Soil Biology Fertility (TSBF CIAT) from 2002 to 2003. After graduating he continued working for TSBF, as a research assistant. In 2004, he joined the University of Zimbabwe in the Department of Soil Science and Agricultural Engineering, as a teaching assistant. While he was a teaching assistant, he pursued a MSc in Environmental Policy and Planning at the same university and the MSc was completed in 2006. He was awarded a distinction in his MSc thesis entitled “Modelling flood hazard and risk in the lower Limpopo Basin of Zimbabwe”, which was done under the broader project “Land Use and Contingency Plans for Flood Management in the Limpopo Basin, funded by UNDP through UN-Habitat”. On completion of his MSc, he was upgraded to become a lecturer within the same department. In 2009, while he was a lecturer, he started his PhD project at the Plant Production Systems Group, Wageningen University under the leadership of Prof. dr Ken Giller. The PhD study focused on agricultural adaptation to impacts of climate change and increased climate variability, in Zimbabwe. The project was in collaboration with the University of Zimbabwe and was part of the bigger project “Lack of resilience in African smallholder farming: Exploring measures to enhance the adaptive capacity of local communities to pressures of climate change” implemented by the Soil Fertility Consortium for Southern Africa (SOFECSA). Jairos is married to Tafadzwa with two children: Tadiwanashe and Tanaka.

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List of publications

Peer reviewed journal articles

1. **Rurinda, J.**, Mapfumo, P., Van Wijk, M.T., Mtambanengwe, F., Rufino, M.C., Chikowo, R., Giller, K.E., Accepted. Sources of vulnerability to a variable and changing climate among smallholder households in Zimbabwe: A participatory analysis. Climate Risk Management.
2. **Rurinda, J.**, Mapfumo, P., van Wijk, M.T., Mtambanengwe, F., Rufino, M.C., Chikowo, R., Giller, K.E., 2014. Comparative assessment of maize, finger millet and sorghum for household food security in the face of increasing climatic risk. European Journal of Agronomy 55, 29– 41.
3. **Rurinda, J.**, Mapfumo, P., van Wijk, M.T., Mtambanengwe, F., Rufino, M.C., Chikowo, R., Giller, K.E., 2013. Managing soil fertility to adapt to rainfall variability in smallholder cropping systems in Zimbabwe. Field Crops Research 154, 211-225.
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1. Nyagumbo, I., Nyamangara, J., **Rurinda, J**., 2012. Scaling out integrated soil nutrient and water management technologies through farmer participatory research: Experiences from Semi-arid Central Zimbabwe. In: A. Bationo et al. (eds.), Innovations as Key to the Green Revolution in Africa-Vol. 1: Exploring the Scientific Facts, 1221 DOI 10.1007/978-90-481-2543-2_124, © Springer Science+Business Media B.V. 2011.

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8. Nyagumbo, I., Nyamangara, J. and Rurinda, J., 2007. Scaling out integrated soil nutrient and water management technologies through farmer participatory research: Experiences from semi-arid central Zimbabwe. AfNet conference paper 17- 12 0ctober 2007, Nairobi.

PE&RC Training and Education Statement

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)
- Vulnerability and adaptation to climate variability and change in smallholder farming systems in Zimbabwe

Writing of project proposal (4.5 ECTS)
- Exploring agricultural management options for improving adaptation to climate variability and change in smallholder farming systems in Zimbabwe

Post-graduate courses (6.8 ECTS)
- Photosynthesis, climate and change; PE&RC (2013)
- Tropical farming systems with livestock; PE&RC (2013)
- I-GIS; PE&RC (2013)

Deficiency, refresh, brush-up courses (3 ECTS)
- Systems analysis, simulation and systems management (2009)
- Basic statistics (2012)

Competence strengthening / skills courses (3 ECTS)
- Dealing with uncertainties; PE&RC (2012)
- Techniques for writing and presenting a scientific paper; PE&RC (2012)
- Reviewing a scientific paper; PE&RC (2012)
- Interpersonal communication for PhD students; PE&RC (2013)
- Information literacy PhD including EndNote; PE&RC (2013)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)
- PE&RC Weekend (2013)
- PE&RC Day (2013)

Discussion groups / local seminars / other scientific meetings (7.5 ECTS)
- SOFECSA-Zimbabwe Annual Review Meeting (2009)
- Participatory Action Research (PAR) workshops 1, 2 & 3; Harare, Zimbabwe (2009, 2010)
- SOFECSA Zimbabwe National Innovation Platform (IP) Meeting: towards efficient Production-Marketing models for improved performance of smallholder cropping systems in Zimbabwe (2010)
- Climate change IDRC funded workshop; Western Cape, South Africa (2011)
- Coping with Drought and climate change project: climate change adaptation symposium in Zimbabwe: Building Climate Resilient Rural Communities (2012)
- Sustainable Intensification of Agricultural Systems (2013)

- CGIAR/WUR Workshop on “Analysis of Trade-offs in Agricultural Systems “ (2013)

International symposia, workshops and conferences (7.1 ECTS)
- The NASAC-KNAW Scientific Conference on “The impact of and adaptation to climate change in relation to food security in Africa” (2011)
- The 5th TWAS-ROSSA Young Scientists’ Conference on “Exchanging knowledge on climate change impacts and vulnerability in Africa: the role of networking; Nairobi, Kenya (2011)
- Global Science Conference on Climate-Smart Agriculture (2011)
- Integrated Soil fertility Management in Africa: from microbes to markets; Nairobi, Kenya (2012)
- First International Conference on Global Food Security; Noordwijkerhout, the Netherlands (2013)

Lecturing / supervision of practical’s / tutorials (3 ECTS)
- Geographic Information Systems (GIS: AES 208); Department of Soil Science and Agricultural Engineering, University of Zimbabwe (2009-2012)
- Special Topics in Environmental Science (AES 301); Department of Soil Science and Agricultural Engineering, University of Zimbabwe (2009-2012)
- Special Topics in Soil Science (SL 316); Department of Soil Science and Agricultural Engineering, University of Zimbabwe (2009-2012)

Supervision of Mphil student (Christopher Chagumaira)
- Changing use patterns of natural resources supporting livelihoods of smallholder communities and implications on climate change in Zimbabwe

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