

**ASSESSING CLIMATE CHANGE IMPACTS AND AGRONOMIC ADAPTATION
STRATEGIES FOR DRYLAND CROP PRODUCTION IN SOUTHERN AFRICA.**

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We live, we learn, we grow.

ABSTRACT

Dryland farmers in southern Africa operate under harsh conditions; infertile soils, erratic rainfall regimes, sub-optimal input levels etc. Crop yields have generally been low, negatively affecting food security and livelihoods. Climate change is anticipated to aggravate these already existing challenges. In the recent past, a wide range of studies has sought to understand how climate change will affect crop production. However, there are only few detailed localised studies that focus on understanding climate change impacts and adaptation under heterogeneous conditions that dryland farmers in southern Africa operate. This study sought to understand how climate change will affect food crop production in southern Africa's drylands and to provide insight on the potential of on-farm agronomic management strategies for adaptation. The study focused on three locations representing some of the agro-ecological conditions of southern Africa i.e. Big Bend in Swaziland (low altitude, hot and dry), Mphahle's Hoek in Lesotho (high altitude, cool and wet and dry), and Lilongwe in Malawi (mid altitude, wet with moderate temperatures). The study was performed largely using a climate-crop model simulation approach supported by a review of similar approaches in the region, data collected from reported agricultural experimental trials, regional experts, downscaled climate projections (using up to 9 GCMs) and surveys.

The study showed that temperature is projected to increase 1.3-2.7 °C in the 2050s and rainfall change will be uncertain, with a range of change from -15% to 18%. Aggregate projections from large scale studies showed that climate change effects on crops will be progressively negative with a median decline of -18% in the 2050s and -30% by the end of the 21st century. While large scale projections potentially miss out on local differences in impacts and potential for adaptation, data limitations often hamper location specific study. In this study, location specific projections were performed using the DSSAT group of models, which was first tested for the simulation of crop yield response (maize, sorghum and groundnuts) under data limited conditions. The DSSAT group of models applied were found to perform well despite data challenges with simulated mean yields within $\pm 15\%$ of observed district wide yields, although the model's capture of seasonal yield variation was less accurate under extreme climates. Projections showed that the impact of climate change varies considerably from one place to the other and according to crops. Mean yields will decline by 20% and 16% for maize and sorghum in Big Bend and by 5% and 33% for maize and groundnut in Lilongwe, while in Mphahle's Hoek, maize and sorghum yields will increase by

an average 8% and 51% albeit with the highest uncertainty of all locations, owing to simulated GCM and agronomic scenarios.

On-farm agronomic strategies (fertiliser amount, planting date and planting density) were investigated for their potential for adaptation. It was found that adjustments in on-farm agronomic strategies have potential for adaptation in some places. In more arid locations such as Big Bend, there are limited options to adapt to climate change through on-farm agronomic adjustments. Future maize yield in Big Bend declined up to 33% with some on-farm agronomic changes. However, in cooler and moderate climates like Mohale's Hoek and Lilongwe respectively, more opportunities exist to adapt through on-farm adjustments. In Mohale's Hoek, planting late can dramatically increase future yields by up to 34%. Modest fertiliser applications of no more than 40kg N/ha could increase future maize yields up to 15% higher than if no on-farm adjustments were made in Mohale's Hoek and Lilongwe, albeit with the right timing of planting dates and appropriate planting densities. It was shown that investigating multiple agronomic practises simultaneously and accounting for the socio-economic conditions of farming communities provides better insight into potential adaptation for dryland farming systems.

The study concludes that climate change will have important impacts on dryland crop production in the region, with opportunities for adaptation through on-farm agronomic adjustments. Impacts and adaptation potential will vary considerably by location. As such, location specific climate change studies are better suited to inform adaptation in dryland systems of southern Africa as they allow for the investigation of relevant on-farm practices with consideration of the bio-physical and socio-economic challenges under which farmers operate. However, on-farm agronomic strategy adjustments are not the panacea for adaptation in the drylands of southern Africa. Adaptation will need to be supported by livelihoods diversification (e.g. livestock rearing in dry locations), access to improved infrastructure (electricity, communication, water supply, transport etc.), access to markets, improved public private partnerships and broad empowerment of dryland farmers.

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DEDICATION

To Hellen, Ivy and Juliana

CONTENTS

ABSTRACT	iii
ACKNOWLEDGEMENTS	v
DEDICATION	vi
CONTENTS	vii
LIST OF FIGURES	xi
LIST OF TABLES	xiv
CHAPTER 1	1
BACKGROUND	2
1.1 Introduction	2
1.2 Agriculture, food security and livelihoods in southern Africa	2
1.3 Climate change and variability and crop production: Challenges	5
1.4 Opportunities for adapting to climate change	7
1.5 Modelling climate change impacts and adaptation	8
1.6 Aims, objectives and thesis outline	10
1.6.1 Aims	10
CHAPTER 2	13
CROP RESPONSE TO CLIMATE CHANGE IN SOUTHERN AFRICA: A COMPREHENSIVE REVIEW	14
2.1 Introduction	15
2.2 Background	16
2.2.1 Global climate trends and projections	16
2.2.2 Future climate projections in Africa	17
2.3 Methods used to project crop response to climate change in southern Africa	19
2.3.1 Process-based crop modelling	20
2.3.2 Empirical crop modelling	21
2.3.2.1 Statistical	21
2.3.2.2 Ricardian	22
2.4 Results	23
2.4.1 Compiled independent projections	28
2.4.2 Overall projected impacts by process-based and statistical methods	30

2.4.3 Ricardian Approach	30
2.4.4 Adaptation to climate change in southern Africa	33
2.4.5 CO ₂ fertilisation effects.....	34
2.5 Discussion.....	35
2.6 Conclusion	38
CHAPTER 3	40
CROP MODEL USEFULNESS IN DRYLANDS OF SOUTHERN AFRICA: AN APPLICATION OF DSSAT.....	41
3.1 Introduction	42
3.2 Study Area	43
3.2.1 Southern Africa.....	43
3.2.2 Big Bend	45
3.2.3 Mohale's Hoek.....	45
3.2.4 Lilongwe	46
3.3. Materials and Methods	47
3.3.1 The DSSAT model.....	47
3.3.2 Input data	48
3.3.3 Calibration and validation.....	52
3.3.4 Yield bias correction	53
3.4 Results	54
3.5 Discussion.....	57
3.6 Conclusion	60
CHAPTER 4	62
LOCAL IMPACTS OF CLIMATE CHANGE AND AGRONOMIC PRACTICES ON DRYLAND CROPS IN SOUTHERN AFRICA	63
4.1 Introduction	64
4.2 Methodology.....	65
4.2.1 Study location	65
4.2.2 Scenario based impact assessment.....	66
4.2.3 Climate data and scenarios.....	66
4.2.4 Crops, soils and management practices	67
4.2.5 Confidence and uncertainty assessment.....	69
4.3 Results	70
4.3.1 Climate change projections.....	70

4.3.2 Projected impacts on crop yields	72
4.3.3 Uncertainty and confidence degrees	76
4.4 Discussion.....	79
4.4.1 Crop yield changes.....	79
4.4.2 Agronomic management strategies.....	80
4.4.3 Uncertainties and limitations	82
4.5 Conclusion	83
CHAPTER 5	85
UTILITY OF AGRONOMIC MANAGEMENT STRATEGIES FOR ADAPTING DRYLAND CROP PRODUCTION TO CLIMATE CHANGE IN SOUTHERN AFRICA	86
5.1 Introduction	87
5.2 Data and methods	89
5.2.1 Climate and socio-economics circumstances of each location	89
5.2.1.1 Climate	89
5.2.1.2 Household socio-economics.....	90
5.2.2 Climate data and scenarios.....	92
5.2.3 DSSAT CERES-Maize	93
5.2.4 Agronomic management strategies.....	94
5.2.4.1 Response of historical maize yields to agronomic management changes.....	96
5.2.4.2 Agronomic management strategies for adaptation.....	96
5.3 Results	97
5.3.1 Maize yield response to climate.....	97
5.3.2 Maize yield response to agronomic strategies	98
5.3.3 Effect of single factor agronomic strategy changes under climate change.....	100
5.3.3.1 Fertiliser amount	100
5.3.3.2 Planting date.....	102
5.3.3.3 Planting density	102
5.3.4 Effects of combined changes in management strategy under climate change...	103
5.3.4.1 Big Bend.....	104
5.3.4.2 Mohale's Hoek	105
5.3.4.3 Lilongwe.....	107
5.4 Discussion.....	110
5.4.1 Maize response to climate change	110

5.4.2 Maize response to agronomic strategies	111
5.4.3 Effects of management strategies under climate change	112
5.4.4 Adaptation options for households	114
5.4.5 Uncertainties and limitations	116
5.5 Conclusion	117
CHAPTER 6	119
SYNTHESIS, CONCLUSIONS & RECOMMENDATIONS	120
6.1 Introduction	120
6.2 Key findings	121
6.2.1 Summary	121
6.2.2. Aggregate impacts and modelling challenges.....	123
6.2.3 Location specific climate change impacts	124
6.2.4 Adaptation to climate change.....	125
6.3 Implication of findings	126
6.4 Uncertainties and limitations of the study	127
6.5 Recommendations for further study	128
REFERENCES	131
ANNEX.....	158
I. CO ₂ fertilisation	159
II. Sample farmer survey questionnaire	161
III. Publications and conferences.....	173

LIST OF FIGURES

Fig 1.1 Land use systems of southern Africa. (Adapted from Nachtergaele and Petri, 2008).	3
Fig 1.2 Mean rain fed maize (a) and sorghum (b) yields in southern Africa tonnes per hectare (t/ha) (Adapted from Hachigonta et al., 2013).	4
Fig 1.3 Annual average precipitation in southern Africa, 1950–2000 (millimetres per year) (Adapted from Hachigonta et al., 2013).	5
Fig 2.1 Reported highest percentage yield changes per study and crop using process based and statistical methods.	29
Fig 2.2 Projected yield variation for all crops and periods by method of research	31
Fig 2.3 Projected yields for the 21st century: Early (2020-2039), Mid (2040-2069) and Late century (2070-2100) for all crops and methods projecting yield change (process-based and statistical).	31
Fig 2.4 Projected change in farm net revenue in all farms and dryland for the 21 st century under uniform and GCMs scenarios based on the Ricardian approach.	32
Fig 3.1 Calibration simulations for crop yields (by adjusting varietal phenology and growth coefficients) for 1 season per district.	55
Fig 3.2 Relationship between observed and simulated crop yields for Lilongwe, Mohale's Hoek and Big Bend. Solid line shows 1:1 relationship.	56
Fig 4.1 Projected ensemble mean monthly rainfall and temperature for Big Bend (a-b), Mohale's Hoek (c-d), and Lilongwe (e-f) for two emission scenarios: low (B1) and high (A2).	71
Fig 4.2 Mean percentage values of coefficient of variation. A measure of interannual variability of projected crop yields per locations and CO ₂ emission scenarios B1 (low) and A2 (high), clustered by management strategy. Management references: see Table 4.4.	77
Fig 4.3 Mean percentage values of coefficient of variation. A measure of interannual variability of projected crop yields per locations and CO ₂ emission scenarios B1 (low) and A2 (high), clustered by GCMs. GCMs references: see Table 4.1.	78
Fig 5.1 Sensitivity of mean maize yields to perturbations of temperature and rainfall from historical climate (1971-2000) in Big Bend, Mohale's Hoek and Lilongwe. Agronomic practices were simulated at average historical common levels.	98
Fig 5.2 Boxplots showing simulated maize yields for baseline (1961-2000) (light grey)	

and future (2046-2065) (dark grey) for Big Bend (a), Mohale's Hoek (b) and Lilongwe (c) from four GCMs with changing fertiliser amounts (F1 – F7). In each box plot, outer horizontal lines represent from top to bottom, the 10th percentile, 25th percentile, median, 75th percentile and 90th percentile of all simulations per treatment. The maize yields are indicative and should not be read as absolute yields but as an indicative of yield change and variability. 101

Fig 5.3 Boxplots showing simulated mean maize yield for baseline (1961-2000) (light grey) and future (2046-2065) (dark grey) for Big Bend (a), Mohale's Hoek (b) and Lilongwe (c) from four GCMs with changing planting dates (S1 – S7). In each box plot, outer horizontal lines represent from top to bottom, the 10th percentile, 25th percentile, median, 75th percentile and 90th percentile of all simulations per treatment. The maize yields are indicative and should not be read as absolute yields but as an indicative of yield change and variability. 103

Fig 5.4 Boxplots showing simulated mean maize yield for baseline (1961-2000) (light grey) and future (2046-2065) (dark grey) for Big Bend (a), Mohale's Hoek (b) and Lilongwe (c) from four GCMs with changing planting density (D1 – D7). In each box plot, outer horizontal lines represent from top to bottom, the 10th percentile, 25th percentile, median, 75th percentile and 90th percentile of all simulations per treatment. The maize yields are indicative and should not be read as absolute yields but as an indicative of yield change and variability. 104

Fig 5.5 Frequency of occurrence of mean yields (contours) in Big Bend per combination of management strategies i.e. fertiliser amount (F), planting date (S), and planting density (D) under baseline (1961-2000) (upper panel) and future (2046-2065) (lower panel) conditions, averaged across all four GCMs. High frequencies of occurrence of mean yields are indicated by darker shades of grey and represent lower yield variability and therefore more stable yields across simulated scenarios 108

Fig 5.6 Frequency of occurrence of mean yields (contours) in Mohale's Hoek per combination of management strategies i.e. fertiliser amount (F), planting date (S), and planting density (D) under baseline (1961-2000) (upper panel) and future (2046-2065) (lower panel) conditions, averaged across all four GCMs. High frequencies of occurrence of mean yields are indicated by darker shades of grey and represent lower yield variability and therefore more stable yields across simulated scenarios. 108

Fig 5.7 frequency of occurrence of mean yields (contours) in Lilongwe per combination of management strategies i.e. fertiliser amount (F), planting date (S), and planting density (D) under baseline (1961-2000) (upper panel) and future (2046-2065) (lower panel) conditions, averaged across all four GCMs. High frequencies of occurrence of mean yields are indicated by darker shades of grey and represent lower yield variability and therefore more stable yields across simulated scenarios..... 109

LIST OF TABLES

Table 2.1 Summary of projected temperature (°C) changes per SRES scenario (B1, B2, A1B, A1T, A2, A1FI) by the end of the 21st century. In brackets are ranges of projected changes.	17
Table 2.2 Future projections of climate in Africa by the end of the 21st century. Output from 21 GCMs (IPCC, 2007a).	18
Table 2.3 Reviewed studies and tools applied for crop response projections for each area, crop and time period covered. See Table 2.1 for simulated emissions scenarios descriptions.	24
Table 3.1 Physical characteristics of study sites. Mean annual temperatures and rainfall. In parenthesis are averages over the growing season (October-April).....	44
Table 3.2 Soil class, seasons and references to some documents and reports used for DSSAT calibration and validation for study sites.	50
Table 3.3 Physical and chemical characteristics; Bulk Density (BD), Organic Carbon (OC), Clay content (C), Silt content (SI), pH, Lower Limit (LL), Drained Upper Limit (DUL), Saturation (SAT) of selected soils and simulated estimate agronomic practices of smallholder farmers.	51
Table 3.4 Observed and simulated district mean yields (kg/ha) before bias correction (b). Ranges are shown in parenthesis.	57
Table 3.5 Comparison of observed, simulated mean crop yields after bias adjustment, showing the coefficient of variation (CV), relative percentage difference (RD%), root mean square error (RMSE) and index of agreement (d) for a number of seasons per study district.	58
Table 4.1 Comprehensive Model Intercomparison Project 3 (CMIP3) Global Circulation Models (GCMs) from which climate scenarios were obtained.	67
Table 4.2 Showing simulated conditions; agronomic management (planting density, fertiliser application amount and timing and planting dates), soils (Bulk density (BD), Organic Carbon (OC), Clay content (CL), Silt Content (SI)) and mean crop yields per location and crop.....	68
Table 4.3 Mean change in projected climate between baseline (1961- 2000) and future (2046-2065) for two CO ₂ emission scenarios; low (B1) and high (A2) and the range (min-max) of projections across all nine Global Circulation Models	

(GCMs).	70
Table 4.4 Percentage mean maize and sorghum yield changes between baseline and future periods: Big Bend for nine Global Circulation Models (GCMs), four management treatments: early planting (EP), late planting (LP), common fertilizer (CF) and recommended fertilizer (RF), and two CO ₂ emission scenarios: low (B1) and high (A2). GCMs references; see Table 4.1.	73
Table 4.5 Percentage mean maize and sorghum yield changes between baseline and future periods: Mohale's Hoek for nine Global Circulation Models (GCMs), four management treatments: early planting (EP), late planting (LP), common fertilizer (CF) and recommended fertilizer (RF), and two CO ₂ emission scenarios: low (B1) and high (A2). GCMs references; see Table 4.1.	74
Table 4.6 Percentage mean maize and sorghum yield changes between baseline and future periods: Lilongwe for nine Global Circulation Models (GCMs), four management treatments: early planting (EP), late planting (LP), common fertilizer (CF) and recommended fertilizer (RF), and two CO ₂ emission scenarios: low (B1) and high (A2). GCMs references; see Table 4.1.	75
Table 4.7 Degree of coincidence (percentage of time series showing non-significant differences). Represents percentage yield projection uncertainty per location and crops based on differences in time series by management strategy and GCM scenarios. Management and GCMs references: see tables 4.1 and 4.4.	76
Table 5.1 A selection of household (HH) endowments and activities in Big Bend, Mohale's Hoek and Lilongwe based on demographics, assets, livelihood activities, access to production inputs, finance, information and coping strategies.	91
Table 5.2 Projected change in annual maximum (max) and minimum (min) temperatures and annual total rainfall (%) for Big Bend, Mohale's Hoek and Lilongwe between baseline (1961-2000) and future (2046-2065) periods from four GCMs under the SRES A2.	92
Table 5.3 Definition of considered management variables; fertiliser amount (F), planting date (S) and planting density (D) and historical agronomic conditions for Big Bend, Mohale's Hoek and Lilongwe.	95
Table 5.4 Single and combined effects of agronomic strategy perturbations on maize yields; shown as change in percentage mean yields from historical conditions (1971-2000) per perturbation.	99

Table 5.5 Mean yield changes between baseline (1961-2000) and future (2046-2065) per combination of agronomic management strategies i.e. fertiliser amount (F_i), planting date (S_j) and planting density (D_k). Yields were averaged across four GCMs. Mean yield change under “Business as usual scenarios” is shown next to site name. 106

CHAPTER 1

BACKGROUND

1.1 Introduction

This chapter provides a background to leading themes of this thesis. It describes the importance of agriculture (particularly dryland crop production) for food security and livelihoods in southern Africa, the challenges posed by climate change and opportunities to adapt to changes through on-farm agronomic strategies. A brief background of approaches used for climate change impact and adaptation studies is provided, leading into the objectives of this thesis, tools used to achieve them and an outline of the thesis structure.

1.2 Agriculture, food security and livelihoods in southern Africa

Southern Africa covers a total land area of 693 000 million ha (SADC, 2000) and has a very diverse set of land use systems, ranging from forests, crop lands, shrubs and grasslands (Figure 1.1). The north-eastern part of the region covering northern Zambia, the Democratic Republic of Congo (DRC) and parts of Angola is largely forested land and tree crops. The south and western region is arid and consists mostly of grassland and shrubs and is therefore dominated by pastoral and agro-pastoral systems. The dry area covers almost all of Botswana and Namibia, an estimated 50% of South Africa, and substantial parts of southern Angola, Mozambique, Tanzania, Zambia and western Zimbabwe. Of the total land area in southern Africa, 20% is arable. More than 50% of the agricultural land is allocated to cereal crop production, with maize (the main staple crop) accounting for more than 40% of the total harvested area (Hachigonta et al., 2013). Croplands dominate a belt stretching from central Tanzania and Malawi, southern parts of Zambia, northern Mozambique, Zimbabwe and the north eastern and south western regions of South Africa. This is where most of the region's food is produced.

Agriculture directly contributes up to 34% of GDP in sub Saharan Africa (SSA) (Osbaahr et al., 2008). The contribution to economies of southern Africa varies from over 30% of GDP in Malawi, Mozambique and DRC (World Bank, 2012), 18% in Zambia (ODI, 2002) and far

less (3%) in South Africa (South Africa GCIS, 2009). Agriculture directly contributes to livelihoods of up to 64% of the population of SSA (Osbar, 2008), with contributions as high as 80% in Zimbabwe (Reas et al., 2004). In recognition of the importance of agriculture in African economies and livelihoods, the Comprehensive Africa Agriculture Development Programme (CAADP) initiated in 2003 requires the allocation of at least 10% of national budgets to agriculture (NEPAD-CAADP, 2010) and has been ratified by at least 8 southern African countries.

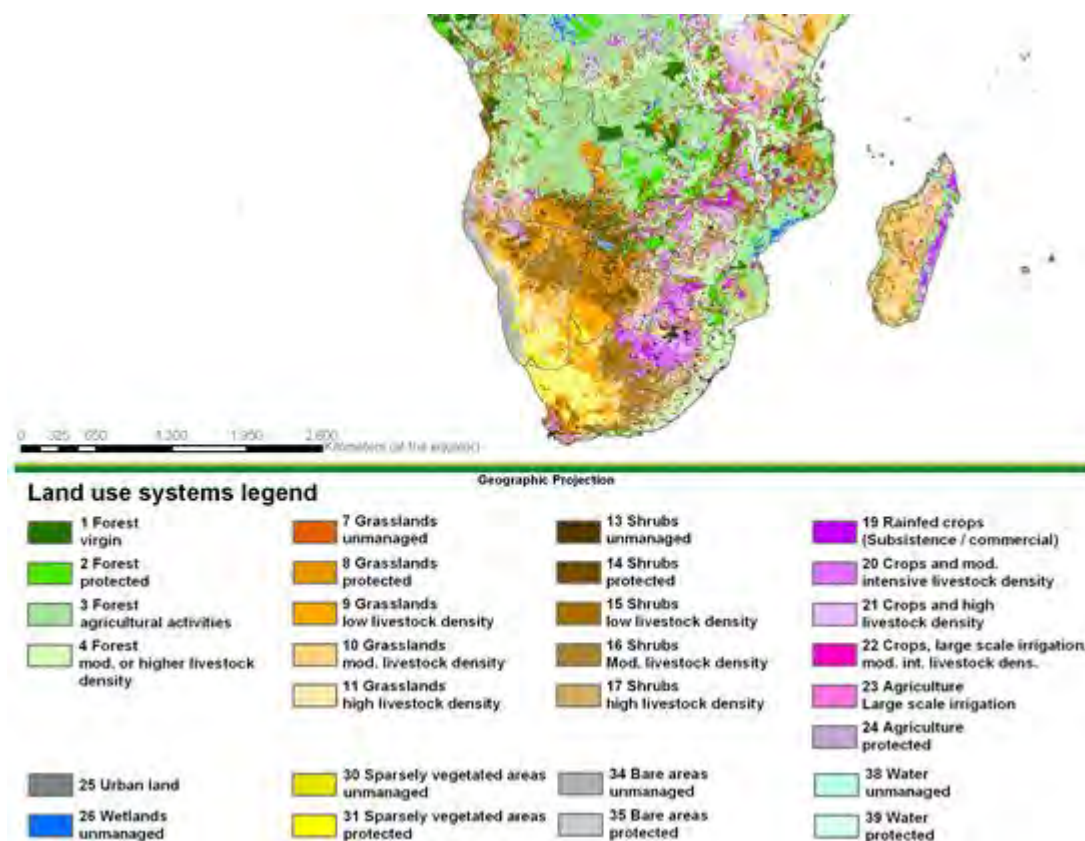


Fig 1.1 Land use systems of southern Africa. (Adapted from Nachtergaele and Petri, 2008).

The largest contribution to agriculture in southern Africa comes from smallholder farmers i.e. more than 60% for Zimbabwe, Zambia and Malawi (World Bank, 2009), with the exception of countries like South Africa where commercial farming dominates. Rain fed maize yields in smallholder systems in the region average below 1.5 t/ha annually in drier parts of the region and 2-3 t/ha in wetter parts of Zimbabwe, Zambia, Malawi and South Africa (Figure 1.2), although yields in South Africa can be much higher due to improved technology use. Over the last 40 years, maize yields in southern Africa increased from an average low of about 1 t/ha in 1961, marginally in the drier parts (e.g. Botswana, Namibia, and Angola) and at a

significant rate of above 2% per annum in the wetter parts of the region i.e. Zambia, Malawi, Tanzania and South Africa (Shi and Tao, 2014). The drier parts of southern Africa commonly grow the more water stress resistant sorghum in place of maize, it predominantly yields below 1 t/ha (Figure 1.2). Despite increases in some parts of the region, cereal crop yields in southern Africa are well below the global average (5 t/ha) and less than 30% of attainable yields (Edgerton, 2009; Mueller et al., 2012). The low yields in the region are attributable to poor investment in agriculture and low use of yield enhancing practices in the predominantly smallholder dryland systems of southern Africa (Cooper et al., 2008). Irrigated land is below 4% of the total crop land on the continent, compared to a world average of over 18%, while fertiliser use is at a minimal of 9 kg/ha compared to a global average of 100 kg/ha (Juma, 2011). Additional pressures on agriculture and livelihoods emanate from HIV/AIDS (highest global infections), unstable political and economic situations, unsecure land rights and high vulnerability to fluctuating world market prices (World Bank, 2009; Waha, 2012).

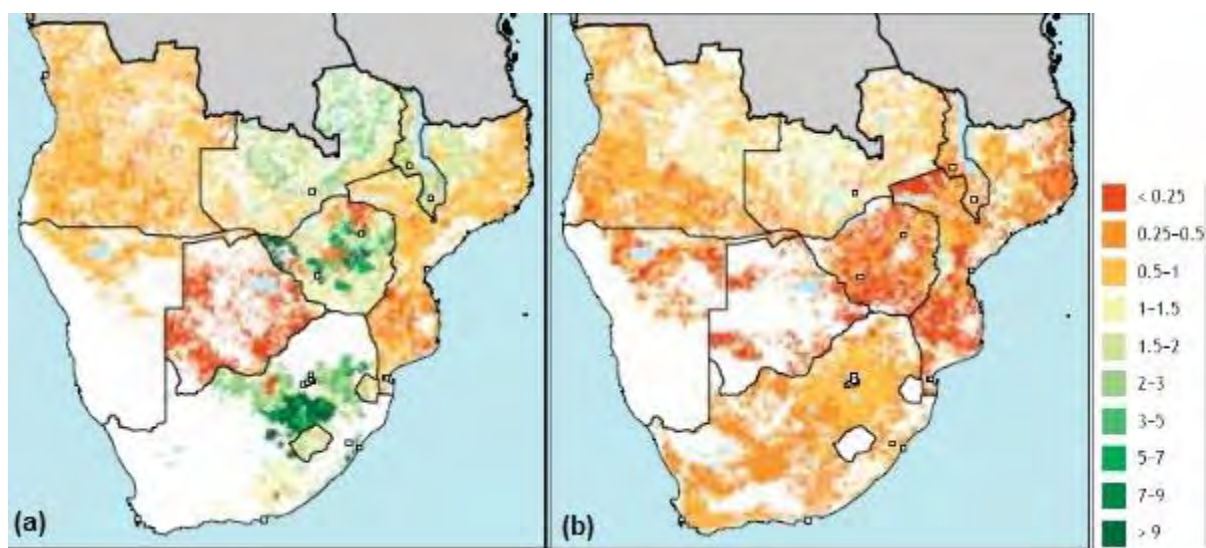


Fig 1.2 Mean rain fed maize (a) and sorghum (b) yields in southern Africa tonnes per hectare (t/ha) (Adapted from Hachigonta et al., 2013).

By the year 2050, the population in Africa is expected to double to 2.3 billion (PDDESA-UN, 2013). Southern Africa will make up almost 14% of that population (Hachigonta et al., 2013). There will be considerably more people to feed and livelihoods to sustain. In order to promote food security and livelihoods in southern Africa, food production will be required to increase from current levels. Yield increases of at least 2% per year until 2050 and thereafter are required to meet the food needs of a growing population and agribusiness demand in SSA

(FAO, 2003). There is growing concern that climate change and variability will intensify already existing agricultural challenges in southern Africa (Ziervogel et al., 2008), thereby making it hard to secure future food and livelihoods.

1.3 Climate change and variability and crop production: Challenges

Southern Africa is largely semi-arid, with high rainfall variability, characterised by frequent droughts and floods. It is considered one of the most vulnerable regions to climate change and variability owing to low coping and adaptive capacity, especially in poor smallholder communities that are highly dependent on dryland agriculture (IPCC, 2014). The combination of location and relief in southern Africa gives it different climate types and regimes across the region - coastal desert from about 32 degrees south of the equator to the border of Namibia with Angola, a temperate climate over the interior central plateau, a subtropical climate over the low-lying coastal regions of the southeast, and a Mediterranean climate in the southern part of South Africa (Davis, 2011). Precipitation in southern Africa shows an east-west and north-south trend, with the lowest rainfall amounts being received in the west and the south (Figure 1.3). Rainfall distribution within seasons and between years is highly variable (Reason et al., 2005, Cooper et al., 2008).

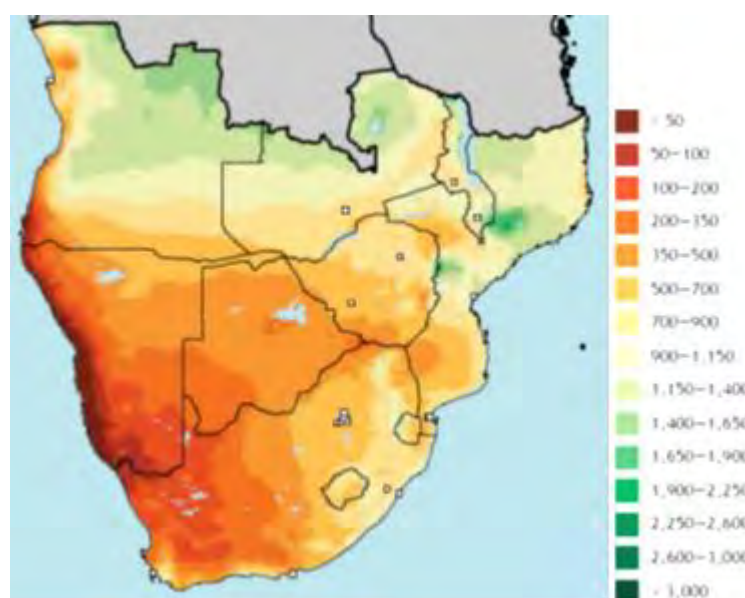


Fig 1.3 Annual average precipitation in southern Africa, 1950–2000 (millimetres per year) (Adapted from Hachigonta et al., 2013).

Climate variability in southern Africa is reflected in the varying levels of crop production over time in dryland systems. Seasonal rainfall variability increases disproportionately from wetter locations to the drier semi-arid regions (Cooper et al., 2008). This is particularly concerning for a region where large portions receive rainfall below 900 mm per year as shown in Figure 1.3. Within season, variability can also have a major effect on crop productivity. New et al. (2006) and Tadross et al. (2009) state that the length of in-season dry spells has been on the increase in large portions of southern Africa, with important impacts on crops. Devastating crop losses can also be expected during incidences of intense rainfall, which was detected to be on the rise in some parts of southern Africa (IPCC, 2007b). Climate variability in the region is also reflected in high variability in rainfall onset dates which have strong implications on dryland crop yields (Reason et al., 2005).

An analysis of temperatures across southern Africa reveals that annual minimum temperature increased at an average of 0.057 °C per decade and maximum temperatures increased at an average rate of 0.046 °C per decade between 1901 and 2009, with the largest rate of warming occurring in the second half of the 20th century (Davis, 2011). The Inter-governmental Panel on Climate Change (IPCC) assessment reports 4 (AR4) and 5 (AR5) agree that warming in the region is projected to continue and to be larger than the global annual mean warming in all seasons, averaging over 3 °C by the end of the 21st century (IPCC, 2007a; IPCC, 2014b). Projected rainfall changes vary across different models, however, southern Africa is one of the regions that will likely experience reduced precipitation. The Comprehensive Model Intercomparison Project 3 (CMIP 3) and 5 (CMIP 5) multi-model projections for the region show mean rainfall decline in the range of 0-20 % by the end of the 21st century (IPCC, 2007b; IPCC, 2014b). Projected for the end of the century (as the mean model estimate), with marked seasonal variations of significance to future crop production e.g. 13% decline in early season rainfall (IPCC, 2007b). The greatest impact on crop production is expected to be in the most marginal areas, where low and irregular rainfall is already experienced (Davis, 2011), a large portion of southern Africa experiences such conditions (Figure 1.3). Cereal crop yield changes in those areas show mild to strong negative impacts in response to projected future climate in southern Africa and as found in response to multiple GCM scenarios (IPCC, 2007b; IPCC, 2014b), mostly due to the effect on the growing conditions of crops. Thus, climate change will very likely increase the risks for regional food crises, and might also weaken socio-economic stability (Scheffran and Battaglini, 2011). Various studies

show that climate change will have significant effects on crop production especially in vulnerable dryland systems thereby requiring adaptation (Jones and Thornton, 2003; Lobell et al., 2008; Thornton et al., 2011; Waha et al., 2013; Folberth et al., 2014). An in-depth review of literature on the projected impacts of climate change on crops in the region and the gaps in such studies is presented in Chapter 2.

1.4 Opportunities for adapting to climate change

There is arguably little scope for substantial improvements in food security and livelihoods under climate change in the region without adaptation (Schlenkler and Lobell, 2010). Farmers and societies can adapt to climate change through autonomous incremental changes based on long experience in dealing with a highly variable climate (Vermeullen et al., 2013). The nature of adjustments required will depend on the degree of climate change, ranging from small on-farm adjustments e.g. water management, soil management, appropriate timing of activities etc., to more advanced activities such as change in crops, new livestock breeds, larger scale irrigation and off-farm diversification, to more complex transformational activities e.g. new production systems, migration and change in livelihoods (Smit et al., 1999; Dolan et al., 2001; Howden et al., 2010; Vincent et al., 2013). Howden et al., (2010), state that opportunities exist to adapt through making use of the coping strategies that farmers have been applying all along and tailoring them to suit a changing climate. Of the variety of autonomous actions common in southern Africa, the adjustment of on-farm agronomic practices (planting time, crop varieties, tillage practices etc.) is the most immediate response for dryland farmers partly because of their year to year flexibility, ease of access and low costs (Nhemachena, 2009). These strategies have provided farmers in the region with opportunities to deal with unfavourable climatic conditions through mitigating the negative impacts of poor seasons and exploiting the positive opportunities of average and better than average seasons, although the latter has been known to be mostly under estimated (Cooper et al., 2008). Quantitative studies that seek to understand the effects of climate change and various on-farm agronomic practices on important food crops in southern Africa are lacking. Yet, this is a vital step towards identifying potential adaptation options and promoting future food security and livelihoods. This partly emanates from the challenges presented by the tools and approaches required to carry out climate change impacts and adaptation studies.

1.5 Modelling climate change impacts and adaptation

One of the leading methodologies for assessing climate change impacts and adaptation on crop production is process-based bio-physical modelling, using General Circulation Models (GCMs) and dynamic crop growth simulation models. Notable early studies that used such methods included global studies by Rosensweig and Parry (1994) and Fischer et al. (1996), a southern Africa region study by Schulze et al. (1993) and a national study by Muchena (1994) in Zimbabwe. Some of the earliest challenges in these studies lay with the scale mismatch of large scale GCMs and field scale crop models. Crop responses were generally extrapolated to gain a perspective of how climate change would affect large swathes of land that differed in terms of soils, climate and agronomic practices. These early studies rarely made attempts to model agronomic strategies for adaptation assessment. Statistical approaches have been applied as alternatives to process-based bio-physical approaches by using historical data of crop yields and climate to develop statistical relationships for predicting future yield changes (Lobell et al., 2008; Lobell and Burke, 2010). They have been favoured for their simplicity (they do not require extensive data for calibration) and transparent assessment of uncertainties (Hertel and Rosch, 2010). However, statistical approaches have a number of challenges that include the extent of spatial and temporal scale, non-climatic trend removal, colinearity existing in climate variables and non-consideration of adaptations (Tao et al., 2013). Recent studies have gone on to suggest that climate impact studies should seek to combine statistical and process based crop models for assessments to obtain a fuller picture of impact and uncertainty (Estes et al., 2013).

Climate models and bio-physical crop models remain the central tools in climate change studies in crop production. Crop models simulate the interactions of the atmosphere-crop-soil continuum to determine crop growth and development (Van Ittersum et al., 2003). They are originally designed to operate at the field scale and require information that describes photosynthetic potential and water availability (daily rainfall and maximum and minimum daily temperatures), soil moisture capacities and mineral properties, plant phenological development requirements and agronomic practices to calculate yield. Some of the major models used include EPIC (Williams et al., 1989); CropSyst (Stöckle et al., 1994); APSIM (Keating et al., 2003); DSSAT (Jones et al., 2003); STICS (Brisson et al., 2003); Infocrop

(Aggarwal et al., 2006). These have been applied in recent times in various studies e.g. Jones and Thornton (2003); Challinor et al., 2007; Laux et al., 2010; Berg et al., 2013; Ruane et al., 2013; Folberth et al., 2014. Although crop models have been described as tools to facilitate climate change impact assessment and support adaptation decisions, relatively few instances of their use in adaptation studies are found in the literature (Webber et al., 2014). Webber et al. (2014) highlight that the appropriate scale to evaluate adaptation decisions is a major concern in data poor, limited capacity regions like SSA. Most studies have been performed at large scales because of the fewer parameters and low input requirements of models at such scales. However, these do not lend themselves easily to adaptation assessments although recent attempts have been made in SSA, including parts of southern Africa (Waha et al., 2013; Folberth et al., 2014). Dryland farmers in regions like southern Africa operate at the local scale, making decisions on best management strategies depending on local conditions (environmental and socio-economic). Therefore, while large scale impacts and adaptation studies provide an important perspective on regional limits of agriculture under climate change, they may not be reliable for understanding impacts and adaptation needs of farming communities at local scales.

In order to understand impacts of climate change and adaptation options at local scales, crop models would need more detailed location specific inputs to characterise local soils, climate, agricultural practices, crop cultivars etc. (Lobell et al., 2008; Thornton et al., 2011). The shortage of such data regularly hampers detailed location specific climate change impact and adaptation studies. The few local impacts studies that have sought to include and model agronomic strategies for adaptation assessment in southern Africa e.g. Abraha and Savage (2006) and Walker and Schulze (2006), have been limited in terms of crops investigated, and the diversity of bio-physical conditions (climate scenarios, soil types, etc.) and agronomic management strategies investigated. Furthermore, other conditions that could inform local adaptation e.g. socio-economics, which Nuijten (2011) suggests can triangulate modelling results and broaden understanding of potential adaptation through complementary knowledge have been largely neglected. The above challenges and gaps present several avenues for further study, part of which this thesis addresses.

1.6 Aims, objectives and thesis outline

1.6.1 Aims

This thesis aims to provide an assessment of the impacts of climate change and the potential of agronomic strategies practiced in dryland cropping systems of southern Africa for adapting to the impacts of climate change. It seeks to highlight the importance of localised impact and adaptation assessments for decision making under climate change.

1.6.1 Objectives and outline

The thesis achieves its aims through the following objectives:

1. To examine the effect of climate change on crops under diverse local conditions in southern Africa.
2. To demonstrate how data limitations (soils, climate, and agronomy) affect the modelling of crop yield responses to climate and agronomic practices in southern Africa.
3. To assess the effect of agronomic practices on crop yields and determine how useful on-farm agronomic adjustments may be for adapting to climate change in southern Africa.
4. To assess if simulating multiple combinations of agronomic strategies under socio-economic contextualisation provide further insight into adaptation potential of drylands in southern Africa.

The above objectives were addressed by a climate-crop modelling approach, supported by survey data, literature and reported agricultural trial data. The study explicitly investigated three crops (maize, sorghum and groundnuts), using the DSSAT group of crop models for the mid-21st century (2050s). The focus of the study was southern Africa. Three distinctly

different locations (bio-physical and socio-economic) were selected as cases for location specific assessments: Big Bend in Swaziland; Mohale's Hoek in Lesotho; and Lilongwe in Malawi. Some locally practised agronomic strategies were included in impact and adaptation simulations i.e. fertiliser applications, planting dates and planting densities. Downscaled climate scenarios from up to nine General Circulation Models (GCMs) were used to provide multiple local climate projections so as to consider changes and adaptation options that are robust across a range of possible future climates, a significant approach for assessing future risk.

1.6.3 Outline

Chapter 1 provides a background and introduction to all concepts and ideas integral to the thesis. It specifies the structure and sets the aims and objectives of the thesis.

Chapter 2 sets the stage for understanding the impacts of climate change on crop production in southern Africa and the region's adaptation needs through a review of studies carried out over a decade (2001 and 2011). The review highlights the nature of impact studies in the region and the tools commonly applied and compiles a summary of projected impacts of climate change thereby partly addressing *objective 1* of the study.

Chapter 3 deals with the setting up of crop models for simulating the effects of climate and agronomic practices on crop yields under data limitations common in southern Africa. Through an exercise to parameterise and validate the DSSAT group of crop models for maize, sorghum and groundnut, the chapter highlights weaknesses, limitations and opportunities for crop model use for impact assessments in data limited environments like southern Africa. The chapter therefore addresses *objective 2*.

Chapter 4 assesses location specific impacts of climate change and local agronomic strategies on crops in southern Africa by using statistically downscaled climate change projections (9 GCMs/CMIP3, A2 and B1 emission scenarios), a crop model (from the DSSAT group of models) and two agronomic practises (fertiliser application and planting dates). Results show the differences in impacts of climate change across different possible climates, crops (maize, sorghum and groundnut), locations and agronomic practices. The results thereby highlight the importance of location specific assessments and of including agronomic practices in change impact assessments. The chapter partly addresses *objective 1* and *3*.

Chapter 5 investigates how useful different on-farm agronomic management strategies are under climate change. The DSSAT CERES-Maize model, downscaled climate scenarios from four GCMs (CMIP3), and A2 emission scenarios were used. Multiple options of fertiliser amount applications, planting dates and planting densities were simulated separately and in combination (294 combinations) with each other to identify those that had adaptation benefits. Survey data was applied to provide a socio-economic context for adaptation. The chapter partly addresses *objectives 1, 3 and 4* by exploring local differences (physical and socio-economic), and investigating multiple combinations of agronomic strategies.

Chapter 6 provides a summary of the findings, makes recommendations, concludes the thesis and proposes future work which will be beneficial to undertake in the future in this area of study.

Chapters 2, 3, 4 and 5 are presented as papers submitted for publication in international peer reviewed scientific journals and are included in this thesis at various stages of publication as follows:

Chapter 2: Zinyengere N., Crespo O., Hachigonta S., 2013. Crop response to climate change in southern Africa: A comprehensive review. *Global and Planetary Change* 111: 118–126.

Chapter 3: Zinyengere N., Crespo O., Hachigonta S., Tadross M., 2015. Crop model usefulness in drylands of southern Africa: An application of DSSAT. *South African Journal of Plant and Soil* 32(2): 95-104.

Chapter 4: Zinyengere N., Crespo O., Hachigonta S., Tadross M., 2014. Local impacts of climate change and agronomic practices on dryland crops in southern Africa. *Agriculture, Ecosystems and Environment* 197: 1-10.

Chapter 5: Zinyengere N., Crespo O., Tadross M., Hewitson B., 2015. Utility of agronomic management strategies for adapting dryland crop production to climate change in southern Africa. *Agricultural Systems*. Under review.

CHAPTER 2

CROP RESPONSE TO CLIMATE CHANGE IN SOUTHERN AFRICA: A COMPREHENSIVE REVIEW.

Concern over future food security in southern Africa has led to various studies that assess the impact of climate change on crops in the region. This study reviewed and consolidated results from 19 studies which quantitatively project the impact of climate change on crops for the 21st century in southern Africa. Results were used to provide a general understanding of the potential impact of climate change on yields, tools and methodologies used, and to identify potential adaptation options and areas for further study. Results varied according to the different crop modelling techniques applied, which included process-based, statistical and economic (Ricardian) modelling. The aggregate impact of climate change on crops in southern Africa was shown to be negative. Maize yields were projected to decline on average by 18%. The collective impact of climate change on all crop yields showed a median decline of -11% and -19% respectively under process-based and statistical methodologies, albeit with a dispersion that ranged from -68% to 27%. Median impacts showed progressively declining crop yields through the 21st century i.e. no significant change in the near future (2020-2039), -18% for the mid-century (2040-2069) and -30% for late century (2070-2100). The Ricardian approach gave very contrasting results, despite projections of a median decline in revenue in the 21st century. Although the study could be limited by sparse quantitative data in southern Africa and a possible bias towards reported methodologies and studies, results highlight the considerable effect that climate change has on crop yields and the need for research into locally appropriate adaptation options for dryland farmers.

2.1 Introduction

Southern Africa is one region that has been shown to be highly vulnerable to climate related risk due to the region's low coping and adaptation capacity (IPCC, 2007a). Over 60% of the region's livelihoods depend on agriculture in one way or the other (Cooper et al., 2008). Agriculture is mostly practiced under rain fed conditions (Twomlow et al., 2008), thereby making crop production in southern Africa particularly prone to climate change and variability (Ziervogel, 2008). This has led extensive research on the potential impact of climate change on crop production in southern Africa (Chipanshi et al., 2003; Gbetibouo and Hassan, 2005; Fischer et al., 2005; Abraha and Savage, 2006; Liu et al., 2008; Thornton et al., 2011).

Climate change impact studies make use of simulation models to project how crops will respond to future climate. Considering the inherent complexity of systems being simulated, numerous uncertainties arise during the simulation process. These uncertainties emanate from incomplete data, limited knowledge of systems being modelled, methods and tools. Scientists however make use of available data, tools and methods in the best possible way to attempt to make informed projections. The last decades have a substantial body of work on climate change impacts on crops whose results vary considerably across regions and within southern Africa (Jones and Thornton et al., 2003; Rosenzweig and Iglesias, 2003; Parry et al., 2004; Walker and Schulze, 2006; Jain, 2007; Lobell et al., 2008; Thornton et al., 2009; Nelson et al., 2010; Roudier et al., 2011). These studies suggest that the production of major crops is under threat from climate change and that efforts to adapt food crop production systems to climate change should be explored in order to promote future food security.

Impact studies in southern Africa produce different results based on applied methodologies, tools and location of study within the region. While these studies are useful individually, a collective assessment would allow consistent information to be extracted. It would increase confidence in study results, especially towards adaptation planning. This study attempts to provide a collective insight of climate change impacts on crops in southern Africa by reviewing and analysing recent literature. A review of studies which quantitatively assess the impact of climate change on various food crops in southern Africa is done. Results from these studies are consolidated and presented according to the tools and methods used in order to describe the magnitude and direction of climate change impacts on crops. Tools and methods

used in the reviewed studies are described thereby placing projected climate change impacts within the context of their strengths and weaknesses. Results are discussed and linked to adaptation strategies suggested in literature. Despite the limitations of this review, this study can help to better understand the range of impacts projected by various studies, point out more or less confident projections and what the implications are for the adaptation of vulnerable crop production systems in southern Africa.

2.2 Background

2.2.1 Global climate trends and projections

The Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (AR4), states that global temperatures are on the rise. Instrumental records of temperature over the period of 100 years ending 2005 clearly show an average global increase of 0.74 °C with a doubling of the rate of increase in the 2nd half of the century (IPCC, 2007a). Continental average temperatures over the same period also rose similarly. Notably, global and continental temperature rise is clearly attributable to human activity. The IPCC (2007a) reports an 80% rise in annual carbon dioxide (CO₂) emissions since 1970. This and longer term greenhouse gases (GHGs) emission rise is reportedly a result of fossil fuel burning and land use changes among other human activities.

While global temperature projections are consistent over time, rainfall varies temporally, spatially and across models, such that no general trend is apparent on a global scale. However, there has been an increase in the parts of the world that are continuously being affected by excessive and insufficient rainfall (Porter and Semenov, 2005). Of concern in low income regions like Africa and some parts of Asia is the fact that regionally important food crop producing areas have been experiencing changes in rainfall variability and intensity.

Table 2.1 Summary of projected temperature (°C) changes per SRES scenario (B1, B2, A1B, A1T, A2, A1FI) by the end of the 21st century. In brackets are ranges of projected changes.

	B1	B2	A1B	A1T	A2	A1FI
Temperature (°C)	+1.8	+2.4	+2.8	+2.4	+3.4	+4.0
	(1.1 -2.9)	(1.4 -3.8)	(1.7 -4.4)	(1.4 -3.8)	(2.0 -5.4)	(2.4 -6.4)

Projecting into the future, most climate models agree on global temperature rise, albeit with varying degrees of warming (IPCC, 2007a). As shown in Table 2.1, mean temperatures are consistently projected to rise by the end of the 21st century. Mean temperature projections range from increases of 1.8 °C to 4.0 °C, according to the different CO₂ emissions scenarios defined in the special report on emission scenarios (SRES). On the other hand, future rainfall projections are not consistent. This poses a challenge when simulating the impact of climate change on crop development and devising adaptation strategies in Africa where a large portion of the population relies on rain fed crop production for food.

2.2.2 Future climate projections in Africa

A general warming higher than the global mean warming is predicted for all seasons across Africa. These projections are summarised in Table 2.2. All 21 General Circulation Models (GCMs) in the IPCC AR4 agree on warming across Africa. However, the degree of warming projected varies from one region to the other within the continent. Higher mean temperatures are projected for the Sahel compared to other regions. Projected temperature changes also vary from one season to the other within regions. Projections of future rainfall are more uncertain. Climate models do not agree on the magnitude or direction of rainfall changes. Mean annual rainfall is projected to increase in West Africa (+2%) and East Africa (+7%). Mean annual rainfall is projected to decrease in Sahel (-6%) and southern Africa (-4%). Marked variations are projected within seasons. These variations are significant for future crop production and food security.

Table 2.2 Future projections of climate in Africa by the end of the 21st century. Output from 21 GCMs (IPCC, 2007a).

Region	Season	Temperature change			Rainfall change (%)		
		Min	Mean	Max	Min	Mean	Max
Sahel	DJF	2.4	3.2	5	-47	-18	31
	MAM	2.3	3.6	5.2	-42	-18	13
	JJA	2.6	4.1	5.8	-53	-4	74
	SON	2.8	3.7	5.4	-52	6	64
	Annual	2.6	3.6	5.4	-44	-6	57
West Africa	DJF	2.3	3	3.5	-16	6	23
	MAM	1.7	3.5	3.6	-11	-3	11
	JJA	1.5	3.3	3.7	-18	2	13
	SON	1.9	3.3	3.7	-12	1	15
	Annual	1.8	3.3	3.6	-9	2	13
East Africa	DJF	2	3.1	3.4	-3	13	33
	MAM	1.7	3.2	3.5	-9	6	20
	JJA	1.6	3.4	3.6	-18	4	16
	SON	1.9	3.1	3.6	-10	7	38
	Annual	1.8	3.2	3.4	-3	7	25
Southern Africa	DJF	1.8	3.1	3.4	-6	0	10
	MAM	1.7	3.1	3.8	-25	0	12
	JJA	1.9	3.4	3.6	-43	-23	-3
	SON	2.1	3.7	4	-43	-13	3
	Annual	1.9	3.4	3.7	-12	-4	6

In southern Africa, projected climates have potentially negative implications for crop production and livelihoods. Major crop production systems which support most of the

livelihoods in southern Africa are located in the dry sub-humid and semi-arid zones. These regions are already experiencing high temperatures with a significant portion experiencing below 1000 mm of annual rainfall (Nhemachena, 2009). Projections of temperature increase or rainfall decline could translate into widespread crop failure. Table 2.2 shows that southern Africa is expected to have notably high temperature increase (3.7 °C) in the early summer season months of September, October and November (SON) compared to other regions. High warming rates are projected over the semi-arid southwestern parts of the sub-region covering north-western South Africa, Botswana, and Namibia. High temperatures are particularly significant for crop production especially where they coincide with the beginning of summer cropping in the region. While there is model disagreement on the average future changes in rainfall over southern Africa, seasonal projections show consistent decline in rainfall in the winter months of June, July and August (JJA) and in the 1st half of the summer cropping season (SON) (Table 2.2.). The recent CMIP5 models also project a *very likely* decrease in mean annual precipitation over areas of southern Africa beginning in the mid-21st century and expanding substantially in the late 21st century (IPCC, 2014b). Downscaled projections indicate wetter conditions in the southeast of South Africa (Hewitson and Crane, 2006). The projected decline in early summer rainfall is potentially unfavourable for crop production in southern Africa especially given the projected high rise in mean early summer temperatures. However, climate projections also suggest that increases in late summer rainfall (total and number of rain days) can be expected over southern Africa (Tadross et al., 2009). Therefore, climate change may not only be damaging to crop production but may present opportunities that can be exploited through adaptation. However, it is important to note that climate projections are made in the context of still developing regional modelling science, which is still not fully understood. They are therefore uncertain.

2.3 Methods used to project crop response to climate change in southern Africa

In assessing the impact of climate change on crops, climate scenarios are used to drive crop models. This section discusses the two crop modelling techniques which have been commonly employed to perform climate change impact assessments for crop production in southern Africa. These methods include process-based and empirical crop modelling

(statistical and Ricardian economic approach). Strengths and weaknesses of each method are also discussed.

2.3.1 Process-based crop modelling

The predominant tool for assessing the impacts of climate change on agricultural productivity is the process-based crop growth simulation model (Hertel and Rosch, 2010). Process-based crop models were developed to simulate crop responses to environmental conditions at the plot and field level. They do this by computing crop dynamics based on deterministic (cause and effect) equations and simulation of underlying processes at time scales of minutes to days (Tubiello and Ewert, 2002). Many impact studies in southern Africa have employed process-based models to project the impacts of climate change on crops at regional scale (tens to a couple of hundred kilometres) (Chipanshi et al., 2003; Jones and Thornton, 2003; Liu et al., 2008; Fischer et al., 2005; Thornton et al., 2011). This is despite the fact that crop models were made for finer spatial scales where parameter demands can be fulfilled better with fairly homogeneous data as done by Abraha and Savage (2006) and Schulze and Walker (2006). This is one of the immediate challenges of using process-based models for projecting crop response to climate change. They do not directly provide information on climate impacts at larger scale (Roudier et al., 2011). Yet climate models typically operate at large scale. Climate data therefore needs to be downscaled to the scale of a crop model or a crop model matched to the scale of climate model output (Challinor et al., 2007). The spatial mismatch introduces additional uncertainty in crop response projections. Process-based models are also limited by the bio-physical processes they are based on. Some models are based on the concept of radiation-use efficiency (RUE), whilst others are based on water-use or nitrogen-use efficiency, which are all determined by the aims for which the models are developed (Challinor et al., 2009a).

The Decision Support System for Agro-technology Transfer (DSSAT) model, referred in this thesis as the DSSAT group of crop models since it integrates single crop models into a modular framework, is the most widely applied process-based model in reviewed studies. Among others, it includes CERES-maize (Jones and Thornton, 2003; Walker and Schulze, 2006), SOYGRO for soybean (Parry et al., 2004), and CANEGRO for sugarcane (Knox et al., 2010), which were individually used in reviewed studies. Apart from DSSAT group of crop

models, Liu et al. (2008) use the Erosion Productivity Impact Calculator (EPIC) in combination with a Geographic Information System (GIS) called GEPIC while Fischer et al. (2005) incorporate GIS into their model called Agro-Ecological Zone (AEZ) model to make impact assessments. Abraha and Savage (2006) use the cropping system simulation model (CropSyst). All process-based models are invariably short of the complexities of the real world crop production systems (White et al., 2011). Despite these challenges, process-based models allow us to carry out near-life experiments to infer current and future responses of crops to climate and the environment thereby allowing us to plan ahead. This is one of the reasons this method is popular with climate change impact analysts.

2.3.2 Empirical crop modelling

2.3.2.1 Statistical

Statistical models use historical data on crop yields and climate to develop statistical relationships (Lobell and Burke, 2010). They were intrinsically designed to operate at the multi-seasonal, regional scale, and are thus best suited for analysing inter-annual variability of regional production (Hertel and Rosch, 2010). This makes them an attractive alternative to process-based methods when assessing climate change impacts at a coarse spatial scale. Recent impact studies performed in southern Africa using statistical methods include Lobell et al. (2008); Burke et al. (2009); Schlenkler and Lobell (2010). The main advantages of statistical models are their limited reliance on field calibration data, and their transparent assessment of model uncertainties through the use of coefficients of determination and confidence intervals (Hertel and Rosch, 2010). However, statistical models are not based on cause and effect and so rely on predicting future responses based on past relationships (White et al., 2011). These past relationships may not hold in the future. Furthermore, past relationships are hard to validate in regions like southern Africa where extensive historical data may not exist. Another limitation of statistical models for future crop response projection is the absence of adaptation responses. Changes in varieties grown, planting and harvesting dates, etc., are not taken into account (Lobell and Burke, 2010). Recent studies have however sought to use assumptions of historical behaviour of farmers over the long-run in response to climatic challenges to develop response functions and account for adaptation (Moore and Lobell, 2014). The adaptation limitation of statistical models has historically been overcome

by introducing economic models which allow for analyses of adaptation in the context of farm-level revenues. One of these directly translates crop response to climate into economic outcomes and has been extensively applied in southern Africa in the recent past. It is described hereafter.

2.3.2.2 Ricardian

The Ricardian approach (Mendelson et al., 1994) focuses on the economic impact of climate change on agriculture. The method considers that farmers are economically prudent and therefore select farming activities which give the highest return on any given piece of land. The method relates climate variation or change with fluctuations in land value. The Ricardian approach has been adapted for impact studies in or including southern Africa by Gbetibouo and Hassan (2005), Kurukulasuriya and Mendelson (2006a), Mano and Nhemachena (2006), Benhin (2008), Jain (2007), Seo and Mendelson (2008), Kurukulasuriya and Mendelson (2008), and Nhemachena (2009). In southern Africa, net revenues are used instead of land values because of the poorly developed land markets. The major advantage of this empirical approach is that it not only includes the direct effect of climate on productivity but also the adaptation response by farmers to local climate by accounting for the cost of different adaptation pathways (Kurukulasuriya and Mendelson, 2007). Like all empirical approaches, the Ricardian approach is limited by the use of current or past relationships which may not exist in the future. These relationships are also constrained by a lack of historical data in southern Africa. The method also assumes that prices are constant. This is an oversimplification as prices fluctuate significantly depending on global markets. This leads to the over estimation of gains and underestimation of losses. However, the fact that the Ricardian approach offers the simplicity of empirical methods and the opportunity to analyse the effect of adaptation options makes it an attractive method. In this review, Ricardian studies are analysed separately from the other methods because they consider monetary impacts not yield. Furthermore, they are given in summary since they mostly come from similar studies under a World Bank/Global Environmental Facility commissioned study in Africa (Kurukulasuriya et al., 2006b).

2.4 Results

The paper reviews studies on climate change impacts on crop production in southern Africa. The studies reviewed were done in the decade 2001-2011. Impact studies were reviewed through an analysis of major on-line databases. The review was limited to studies that clearly quantified changes in crop production or revenues between a present/past and future period either numerically or graphically. In total, 19 studies were reviewed and presented. The economic results emerging from the Ricardian approach come from studies carried out over particular countries in southern Africa (e.g. Zambia, Zimbabwe and South Africa) and other studies that cover southern Africa and/or sub-Saharan Africa (SSA) as a whole, thereby resulting in potential overlaps. Table 2.3 shows reviewed studies according to climate scenarios, crop modelling methods, area coverage, crop type and projected time period within the 21st century (Early (2020-2039), Mid (2040-2069) and Late (2070-2100)). It also shows whether a study included carbon dioxide (CO₂) effects, or adaptation.

Table 2.3 Reviewed studies and tools applied for crop response projections for each area, crop and time period covered. See Table 2.1 for simulated emissions scenarios descriptions.

Study	Climate model	Crop model	Simulated scenarios	Area coverage	Time period	Crops covered	Adaptation ?	CO ₂ Effect?
Jones and Thornton (2003)	HadCM2	CERES-maize	N/A	SSA & Latin America	Mid	Maize	No	No
Chipanshi et al. (2003)	CCC, OSU,	DSSAT	+2 °C, +3 °C	Botswana	N/A	Maize and Sorghum	No	Yes
Parry et al. (2004)	HadCM3	CERES and SOYGRO	A1FI, A2, B1, B2	Global	Early, Mid, Late	Maize, wheat, rice, Soybean	Partially	Yes
Gbetibouo and Hassan (2005)	Uniform scenarios	Ricardian	-5%, -20% +2 °C, +3 °C	South Africa	Late	All major crops	Yes	No
Fischer et al. (2005)	5 GCMs	AEZ model	A1FI, A1B, A2, B1, B2	SSA	Late	All cereals	Partially	Yes
Walker and Schulze (2006)	C-CAM, Uniform scenarios	CERES-maize	-10%, +10% +1°C, +2°C, +3°C	South Africa	Late	Maize	Yes	Yes

Mano and Nhemachena (2006)	Uniform, HadCM3	PCM, Ricardian	-7% +2.5°C,	Zimbabwe	Mid, Late	All cereal crops	Yes	No
Abraha and Savage (2006)	(ClimGen), Uniform scenarios	CropSyst	+10%, +20% +2 °C,+4 °C	South Africa	N/A	Maize	Yes	Yes
Kurukulasuriya and Mendelson (2006)	Uniform and CCC, CCSR, PCM	Ricardian	A1, -7%, -14% +2.5 °C, +5 °C	SSA	Early, Mid, Late	All field crops	Yes	No
Jain (2007)	Uniform scenarios	Ricardian	-20% +1 °C	Zambia	N/A	All cereal crops except wheat	Yes	No
Benhin (2008)	CSIRO2, HadCM3, PCM	Ricardian	A2 +1 °C	South Africa	Mid, Late	All major crops	Yes	No
Liu et al. (2008)	HadCM3	GEPIC	B2, A2, A1FI, B1	SSA	Early	Maize, wheat, sorghum, millet, rice, cassava	Partially	Yes
Seo and Mendelson (2008)	Uniform & CCSR, PCM	Ricardian	A1	SSA	Mid	All crops	Yes	No
Lobell et al. (2008)	20 GCMs	Statistical	-10%, +5% +1 °C	Global	Early	Maize, wheat, sorghum, rice, cassava, soybean, groundnut, sugar cane	No	No

Kurukulasuriya and Mendelson (2008)	Uniform, CCC	PCM, Ricardian	+1 °C, +1mm	SSA	Late	Multiple crops	Yes	No
Nhemachena (2009)	Uniform, CCC	PCM, Ricardian	A1,+2.5 °C, +5°C, -7%, -14%	SSA	Late	All field crops	Yes	No
Knox et al. (2010)	HadCM3	CANEGRO	A2, B2	Swaziland	Mid	sugarcane	Yes	Yes
Schlenkler and Lobell (2010)	16 GCMs	Statistical	A1B	SSA	Mid	Maize, millet, groundnuts, Sorghum, cassava,	No	No
Thornton et al. (2011)	14 GCMs	DSSAT	A1B, A2, B1	SSA	Late	Maize, beans	No	No
+5 °C								

SSA-sub-Sahara Africa

HadCM2-UK Hadley Centre's second generation climate model (Johns et al., 1997)

HadCM3-UK Hadley Centre's third generation climate model (Johns et al., 2003)

CCC-Canadian Climate Centre model (Boer et al., 2000)

CCSR-Centre for Climate Systems Research (Emori et al., 1999)

C-CAM-Conformal-Cubic Atmospheric Model (McGregor and Dix, 2001)

PCM-Parallel Climate Model (Washington et al., 2000)

CSIRO2-Commonwealth Scientific and Industrial Research Organisation (Gordon et al., 2002)

OSU-Oregon State University model (Schlesinger and Zhao, 1989)

AEZ-Agro-Ecological Zone model (Fischer et al., 2002)

CropSyst-Cropping Systems simulation model (Stockle and Nelson, 2000)

CERES-Crop Estimation through Resource and Environment Synthesis (Ritchie and Otter, 1984)

DSSAT-Decision Support System for Agro-technology Transfer: Within it is Ceres-maize, CANEGRO, SOYGRO (Jones et al., 2003)

GEPIC-An Environmental Policy Integrated Climate (EPIC) model with a Geographical Information System (GIS) (Liu et al., 2007)

2.4.1 Compiled independent projections

Jones and Thornton (2003) projected that maize yields will likely decline in most countries in southern Africa by an average of 10% by mid-21st century under rain fed small scale production. Their study was performed across two continents, sub-Sahara Africa (SSA) and Latin America. Thornton et al. (2011) concluded that given 5 °C of future warming, maize and bean production in southern Africa could decline by 16% and 68% respectively by late 21st century. Liu et al. (2008) estimated that, climate change will lead to 18% lower yield for wheat, 7-27% higher yield for millet, up to 7% higher yield for rice, 4% higher yield for maize, and negligible change in sorghum and cassava in the early 21st century. For all crops as a whole, they estimated a slight increase in crop yields of 1.6-3.3%. A global study by Parry et al. (2004) concluded that total crop yield in Africa may decrease up to 30% in the late 21st century. They made this assessment for wheat, maize, rice, and soybean. Cereal yields for southern Africa showed up to 5% decline for all scenarios without CO₂ fertilisation for the early century, 5-30% decline in mid-century and a consistent 10-30% decline for late century. In a study for SSA, Fischer et al. (2005) showed a potential 5-50% declined in cereal yields for most parts of southern Africa by late century. Chipanshi et al. (2003) examined the response of maize and sorghum in Botswana to uniform future climate scenarios. The country was split into two regions, the sand veldt and hard veldt. Simulated yields declined by 36% for maize and 31% for sorghum in the sand veldt region and 10% for both maize and sorghum in the hard veldt.

Some studies have been done at finer spatial scales, thereby allowing for the assessment of potential adaptation strategies. Knox et al. (2010) assessed the impact of climate change on sugar cane in Mhlume, a district in Swaziland. They projected a decline in sugarcane yields of up to 13% by mid-century. They also showed that with appropriate irrigation, sugarcane yields would increase over the same period. Walker and Schulze (2006) examined the response of smallholder maize production in Potshini village, Kwazulu Natal, South Africa to late 21st century climates. They projected a decline in average maize yields of 30% but also demonstrated that varying fertiliser and manure applications is a viable management strategy to adapt to climate change. The positive effect of adjusting management agronomic strategies was also confirmed by Abraha and Savage (2006) in a site study (Cedara, Kwazulu Natal, South Africa) on the effect of shifting planting date on maize yields in a changing climate. Projected maize yields increased from baseline yields by 10-12%. They concluded that

shifting planting dates could be a useful adaptation to climate change. However, reviewed literature shows that these kinds of adaptation studies are limited in southern Africa.

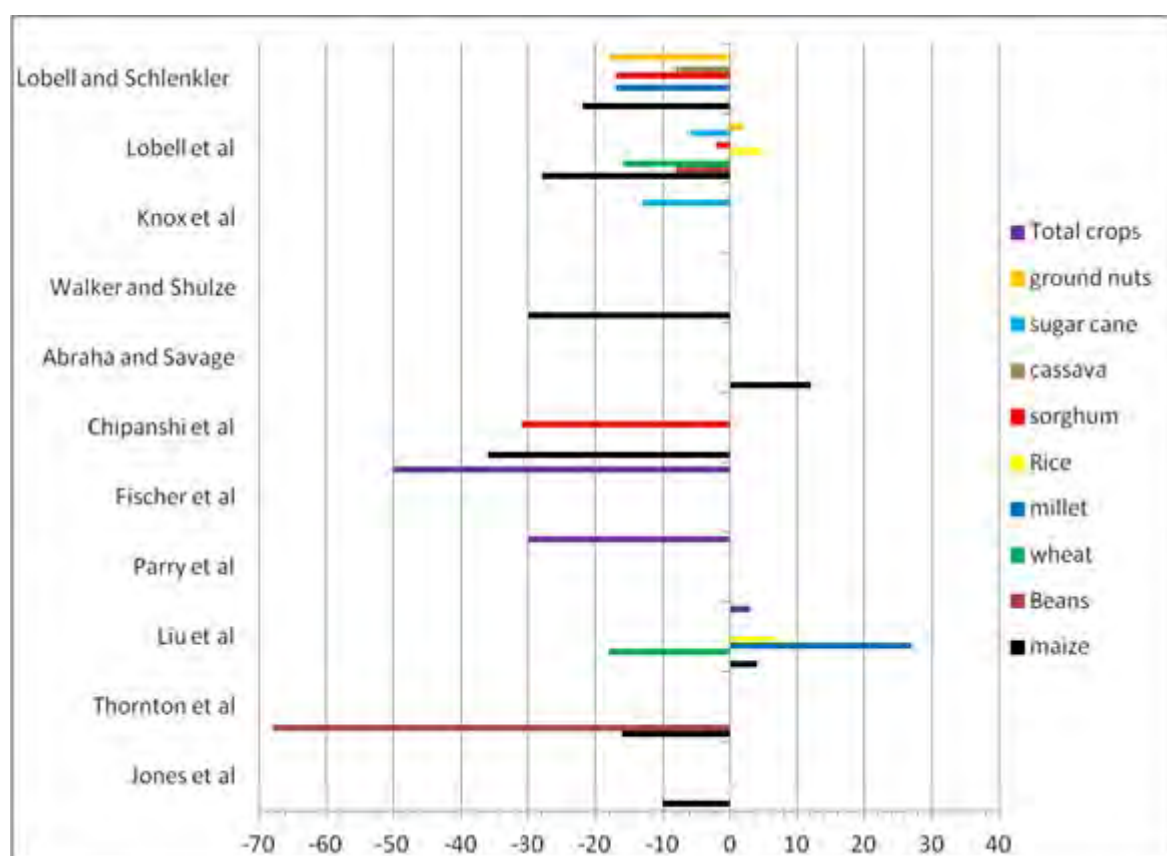


Fig 2.1 Reported highest percentage yield changes per study and crop using process based and statistical methods.

In a global study which projected crop response to climate in the early 21st century using statistical methods, Lobell et al. (2008) showed that without sufficient adaptation measures, southern Africa will likely suffer negative impacts on crops (Figure 2.1). The study projected an average decline in maize, wheat, soybean, sugar cane, and sorghum yields of 28%, 16%, 8%, 6%, and 2% respectively. Cassava was unchanged while rice yield was projected to increase by 5% and groundnut by 2%. Schlenkler and Lobell (2010) used panel statistical models to investigate crop response to climate change in SSA in the mid-21st century. They projected negative impacts of warming for all models used and crops investigated. The median impacts showed a 22%, 17%, 17%, 18%, and 8% decline in yields for maize, sorghum, millet, groundnut, and cassava, respectively. Severe cases showed a yield decline of 27-32% for all crops except cassava. Burke et al. (2009) also used statistical methods to show, without quantifying yield changes, that maize, sorghum and millet in southern Africa

will by mid-century experience climates which are significantly different from those of the present. They concluded that this warrants investment in adaptation measures.

2.4.2 Overall projected impacts by process-based and statistical methods

A comparison of projected crop response to future climate for southern Africa using process-based and statistical-based methods is summarised in Figure 2.2. Although the two methods are different in nature, they all predict a median decline in southern African crop yields (process-based: -11%; Statistical-based: -19%) under climate change for all projected future time periods combined. The process-based method however has a much larger range of crop yield changes (-68% to 27%) than the statistical method. The combined crop yield response projections for the process-based and statistical methods separated by time periods in the 21st century are summarised in Figure 2.3. A decline in crop yields is projected to increase with time i.e. median change of 0%, -18% and -30% for early, mid and late 21th century, with a range of -18% to 17%, -5% to -32% and -5% to -50% respectively. The early 21st century shows almost equal projections of yield increase as yield decline. However, projected percentage crop yield changes for mid and late 21st century consistently show decline.

2.4.3 Ricardian Approach

The Ricardian approach is commonly used for studying the impact of climate change on crop production in southern Africa. These results are assessed separately from the other methods because of the different units of measurement i.e. monetary as opposed to the production (yields/ha) applied by the other approaches. Some Ricardian studies reviewed used uniform future climate scenarios by varying temperature and rainfall by constant amounts e.g. +1 °C or +10% increase in rainfall (Gbetibouo and Hassan, 2005; Mano and Nhemachena, 2006; Jain, 2007). The general trend for projections made using uniform climate scenarios is a decline in farm net revenues across all farm types and dryland farms in southern Africa. Figure 2.4 shows median decline in farm net revenues of 12% for dryland farms and 14% for all farm types. The range of projections for dryland farms is negative while that of all farms combined ranges from negative to positive change in revenue.

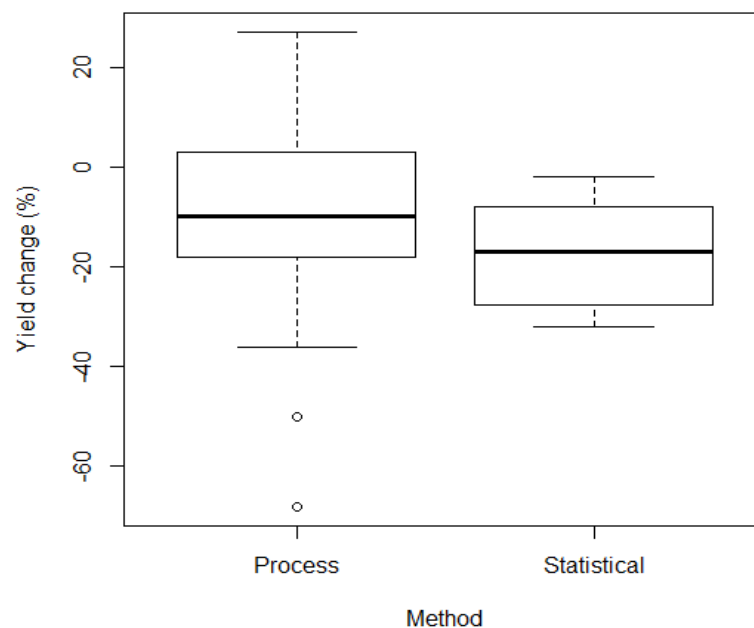


Fig 2.2 Projected yield variation for all crops and periods by method of research

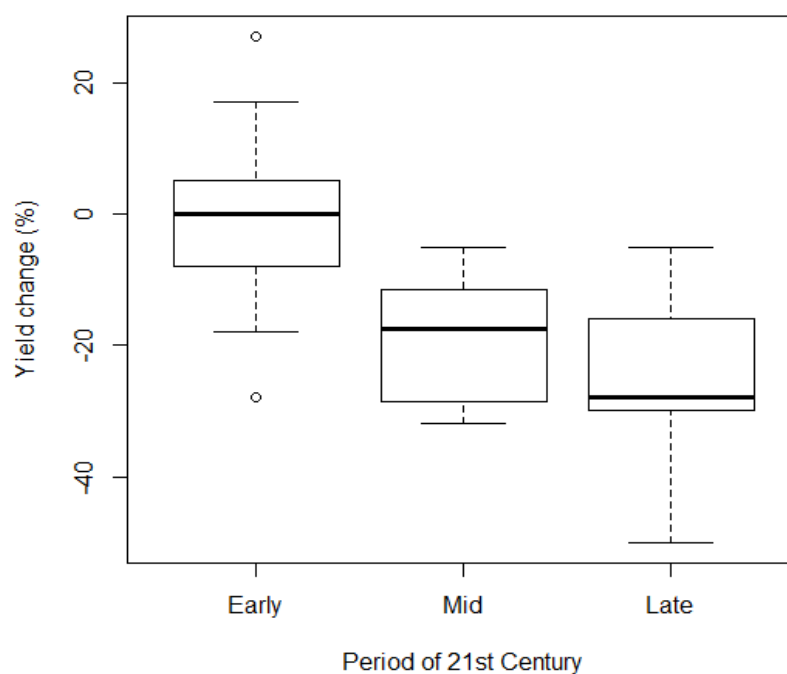


Fig 2.3 Projected yields for the 21st century: Early (2020-2039), Mid (2040-2069) and Late century (2070-2100) for all crops and methods projecting yield change (process-based and statistical).

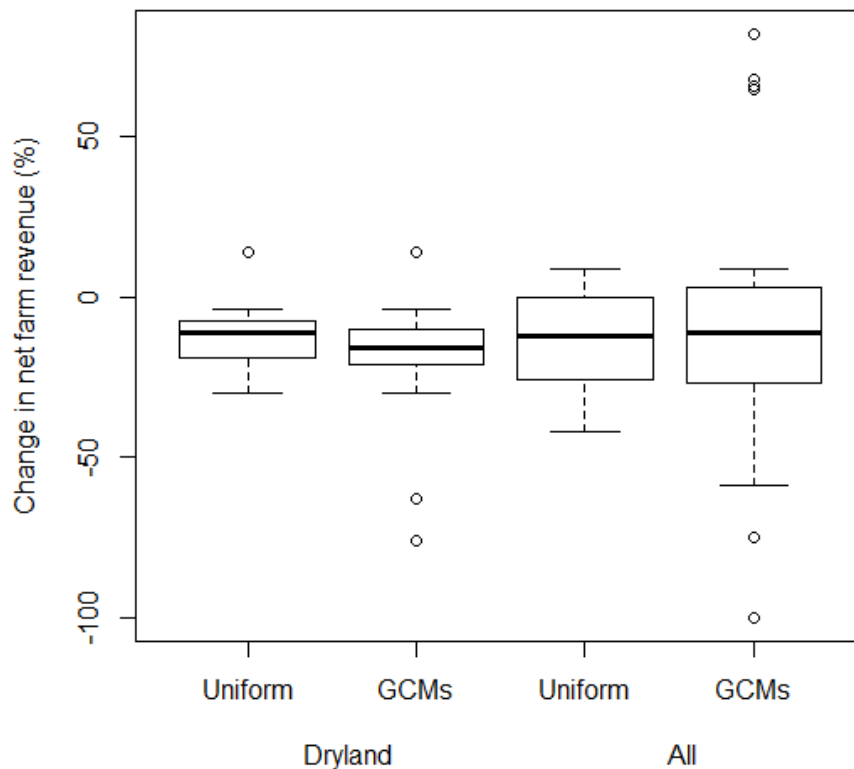


Fig 2.4 Projected change in farm net revenue in all farms and dryland for the 21st century under uniform and GCMs scenarios based on the Ricardian approach.

The percentage change in farm revenue from the Ricardian approach based on GCMs scenarios gave more contrasting results compared to the uniform scenarios of temperature and rainfall. These contrasting results could be found across and within reviewed studies, leading to extreme positive and negative revenue changes as shown in Figure 2.4. In some reviewed studies, farm revenue was found to decline by up to 100% for all farm types and up to 75% for dryland farms. At the same time, farm revenue also increased by up to 82% for all farms. Figure 2.4 also shows that while the dispersion of projected revenue change increases with the effect of GCM scenarios, the median change in farm net revenue is negative for all climate projections and farm types.

2.4.4 Adaptation to climate change in southern Africa

Adaptation is an important component of climate change impact studies. A number of reviewed studies suggest that adaptation of crop production systems in southern Africa is essential under climate change. However, the levels at which adaptation has been considered varies (Table 2.3). Some studies do not consider adaptation. Others consider it partially e.g. through general assumptions over a large study area or in full e.g. through assumed complete adaptation (Ricardian). However, all studies include adaptation options as part of their discussions, conclusions or recommendations. This section presents the different levels of engagement with adaptation by the impact studies along with their suggestions for adapting to modelled future impacts of climate on crops in southern Africa.

Studies that don't consider adaptation however suggest a number of potentially useful adaptation options by extrapolating from the impact study. Chipanshi et al., 2003 and Jones and Thornton (2003) did not include adaptation in their impact assessments but suggested that changing of on-farm management strategies and engagement in off-farm income generation were potential future adaptation options in southern Africa. Thornton et al., 2011 suggested the development and use of suitable crop varieties. Despite statistical methods inherently excluding adaptation in their projections, Lobell et al., 2008 and Schlenkler and Lobell (2010) agree that the development of irrigation technologies and new and improved crop varieties will be a useful way of adapting crops to future climates.

Other researchers consider adaptation in their impact studies. Fischer et al., 2005 considered farm-level adaptation (changing crop calendar and changing cropping systems) and regional and global markets adjustments. They concluded that adaptation could reduce negative impacts of climate change on crop production. Parry et al. (2004) performed an impact study by considering current irrigation and farm-level adaptation. They concluded that current adaptation practices may not be able to reduce the negative effect of future climate on crops. Liu et al. (2008) considered changing cropping dates as an adaptation and concluded that investment in research towards improved crop varieties as well as adjusting management strategies (crop varieties, water and fertiliser management) were potentially useful for adapting to future climates. All crop projections made using the Ricardian approach considered adaptation. Recurrent suggestions for suitable adaptation options to future changes in climate include irrigation, breeding and use of appropriate crop varieties, farmer access to extension services and markets as well as off-farm income generation.

The above mentioned studies performed impact assessments at a coarse spatial scale (national to regional). A few studies projected crop responses to future climates at finer spatial scales (district and site). This allowed them to assess adaptation more explicitly with a focus on local relevance and application. Walker and Schulze (2006) assessed the impact of climate change on maize with various treatments of tillage practices and fertiliser applications at village level in Kwazulu Natal, South Africa. They recommended conservation tillage and the application of optimal fertiliser levels as potential adaptation options for smallholder farming communities. They also suggested rainwater harvesting and supplementing incomes through off-farm employment. Abraha and Savage (2006) assessed the effect of various planting dates. They acknowledged the usefulness of adjusting planting dates for adapting to climate change at the local level. Knox et al., 2010 considered irrigation in their assessment of the impact of climate change on sugarcane yields in Mhlume district, Swaziland. They concluded that current irrigation levels will need to increase by 20-22% in order to maintain current optimal production levels.

2.4.5 CO₂ fertilisation effects

Rising CO₂ levels have been found to be the driving force behind global warming and climate change. However, depending on crop physiology (C3 or C4 pathways) increasing CO₂ levels in the atmosphere can also increase crop yields through CO₂ fertilisation (IPCC, 2007b). Knox et al. (2010) noted that CO₂ fertilisation offset the impacts of climate change and led to higher yields in Swaziland. Projected sugarcane yields increased by 15% with doubling CO₂ by 2050. Walker and Schulze (2006) found that a doubling CO₂ increased maize yields in Potshini, South Africa. They concluded that with a doubling in CO₂ levels, the potential positive and negative drivers of maize yield changes would be self-cancelling, leading to maize yield increase thereafter. Abraha and Savage (2006) noted that given non-limiting conditions of water, the effect of CO₂ was such that maize yields increased with doubling CO₂ and 2 °C temperature rise. However when temperature rises by 4 °C, the positive effect of CO₂ fertilisation is offset. Liu et al., 2008 partly attribute the projected overall increase in crop yields (1.6-3.3%) to CO₂ fertilisation in the early 21st century. Contrary to other studies, Parry et al. (2004) concluded that the effect of rising CO₂ in the region is unable to counteract the projected cereal yield decline. Maize yields still fall by 30% despite the rising CO₂ levels under the A1FI climate scenario. Chipanshi et al., 2003 concluded that the positive effects of

rising CO₂ are unlikely to be realised on maize and sorghum in Botswana. Statistical crop response projections made by Lobell et al., 2008 and Schlenkler and Lobell (2010) do not consider the effect of CO₂. Economic impact projections based on the Ricardian approach also exclude the effect of CO₂.

2.5 Discussion

Most studies reviewed assess the impact of climate change on maize, which is the staple food crop in the region. With the exception of Abraha and Savage (2006) and Liu et al., 2008, projections of maize yield response to climate change show a decline. A decline of maize production would significantly stress food security in the region. The overall effect of climate change on the yield of all crops put together based on projections by the process-based and statistical methods is also negative. This strengthens the suggestion of stress on food security due to climate change and limits adaptation options such as crop shifts. However, there is high variation in yield projections based on the process-based methods compared to the statistical methods (Figure 2.2). This is partly due to process-based methods simulating the physiological response of crops to various environmental factors and thus capturing a wide range of possible non-linear crop responses, while the statistical methods are limited by established historical relationships between crop yields and climate. Furthermore, some projections by process-based methods take CO₂ and adaptation into account, thereby allowing for potential benefits of CO₂ fertilisation and adaptation strategies while statistical methods inherently exclude them.

Projections of crop response by time period (Figure 2.3) show no change in median crop yields in the early 21st century for all crops combined. The range of projections for the early 21st century shows uncertainty about the direction of crop response, there is almost an equal projection of increase in yields as decrease. The uncertainty is common in both process-based and statistical methods in the early century e.g. Lobell et al., 2008 and Liu et al., 2008 as shown in Figure 2.1. This is partly due to the moderate climate change projections for the early part of the century where only an increase of 1-2 °C is projected for temperature in the region (IPCC, 2007a). The positive effects of CO₂ and adaptation strategies could still offset the potential negative effects of future climate as shown by positive yields projected by Liu et al. (2008). The positive effect of CO₂ and adaptation was also confirmed through increased

maize yields by Abraha and Savage (2006). However, it is important to note that the modelling of the direct effect of elevated CO₂ on crop growth and yield is highly debated. Some studies suggest that CO₂ has strong positive effects on crop yields (Long et al., 2006;; Ainsworth, 2008; Ainsworth and Ort, 2010; Taub, 2010), while others suggest that crop models overestimate the effect of CO₂ on plant growth and yield (Tubiello et al., 2007; Challinor et al., 2009a). Parry et al. (2004) also suggests that the effect of CO₂ and presently practiced adaptation strategies (irrigation and farm management practices) may have no noticeable effect on early century crop yields. Hence care needs to be taken when crediting CO₂ fertilisation for positive crop yields. Further into the century (mid and late), the effect of climate becomes more severe as temperature increases and rainfall becomes more variable such that crop responses projected by both methods during these periods are negative (Figure 2.3). The fertilisation effect of CO₂ at this time may be unable to compensate higher temperatures and unsuitable rainfall. Due to the associated climate physical processes and predictors, temperature projections are more robust than rainfall projections. Therefore whatever the rainfall change, high temperatures in the mid to late century can negatively affect crop yields through water stress from high evapotranspiration and by reducing crop growth periods. Changes in rainfall variability in the mid to late century can lead to changes in rainfall distribution, more frequent and intense extremes (e.g. dry-spell duration, rainstorms). Even where rainfall change projections are insignificant, these perturbations of climate could be highly detrimental to crop production.

Projected crop response to uniform climate scenarios under Ricardian studies show 12-14% decline in net revenues (Figure 2.4). This consistent mean decline in revenues under uniform scenarios could be a result of the exclusion of CO₂ fertilisation effects that is inherent in the Ricardian studies. The variation in projected revenues is much less than that projected using GCM scenarios especially for all farm types. This is partly because uniform scenarios applied by some studies were moderate e.g. +1 °C and +7%, -10%, +1 mm rainfall and therefore do not capture a wide range of possible climatic variations as done by GCMs. Dryland farms are shown to have less increase in revenue under GCM driven scenarios compared to all farm types combined probably because of the lack of irrigation. Dryland farms in southern Africa are also commonly known to have poor soils from years of nutrient mining (Twomlow et al., 2008), this can contribute to reduced economic benefits even with expectations of favourable future climate. The effect of different GCM projections and the sensitivity of the Ricardian approach to rainfall make revenue changes to future climate highly variable. This makes it

hard to make firm conclusions about crop responses to climate change in southern Africa using this method. However, median revenue projections are negative, regardless of the climate scenarios used. This suggests that despite the broad range of projections, crop production systems in southern Africa may suffer future economic losses as a result of climate change.

All studies reviewed suggest that adaptation of crop production systems to climate change in southern Africa is essential. Various adaptation options have been identified across the different studies and methodologies. The development and appropriate use of climate adapted crop varieties is a frequently suggested adaptation option. Variety selection for drought resistance and heat tolerance is likely to reduce the negative impacts of a warmer future climate with variable rainfall. Jones and Thornton (2003) suggest that given the history of cereal yield increases owing to crop breeding and technological development, moderate yield losses such as a 10% decline in maize yields could be compensated through the use of climate adapted varieties. Many studies also recommend the diversification of household income through off-farm employment. Such a strategy could be useful to over 60% of smallholder farmers in southern Africa who rely on rainfed crop production and natural resources for food and livelihoods (Ziervogel, 2008; Cooper et al., 2008). Reducing the reliance of livelihoods on rainfed crop production could cushion smallholder communities from unfavourable future climate and crop losses. Increased access to markets as suggested by several studies may help to improve on-farm profitability. Farmers would be able to save and to intensify farming, thereby increasing their capacity to cope with unfavourable impacts of climate change while also readily exploiting opportunities that may arise.

Most studies emphasise on-farm adaptation options, mainly through the adjustment of farm management strategies (planting dates, changing crop types, appropriate water and fertiliser management and irrigation). Since smallholder dryland farmers in southern Africa have been known to historically cope with variations in climate through adjusting management strategies (Twomlow et al., 2008), such an option could be a natural choice for dryland farming communities to adapt to future climate. Suggested improvements in climate forecasting and dissemination of forecasts, complemented by enhanced access to extension services would better prepare farmers to make use of these management strategies especially given increased future rainfall variability. Farmers would be better able to use irrigation and in-field water harvesting timely and appropriately thereby reducing the negative impact of

dry spells and exploiting the potential benefits of increased rainstorms. Farmers would also be able to time planting and fertiliser application well, in so doing avoid crop losses resulting from insufficient moisture for germination at the beginning of the season and the leaching of nutrients. All suggested adaptation options will most likely include various stakeholders like governments, private organisations, non-profit organisations and farmers themselves. Climate change adaptation strategies should therefore be developed and recommended within the context of stakeholders and their different roles.

2.6 Conclusion

This study reviewed and consolidated 19 climate change impact studies on crop production in southern Africa over a decade (2001-2011). The review combined results from studies across several methods and tools of projecting crop response to future climate. These results suggest that aggregate impacts of climate change on crops in southern Africa will be negative. Maize yields are on average projected to decline by 18% in the 21st century. This has unfavourable implications for food security in southern Africa where maize yields are a common determinant of food security especially in smallholder farming communities. The collective impact of climate change on all crops reviewed shows a yield decline of -11% and -19% respectively based on process-based and statistical methodologies. Median impacts show progressively stronger negative responses through the 21st century i.e. no significant change in the near future (2020-2039), -18% for the mid-century (2040-2069) and -30% for late century (2070-2100). Future crop yield projections are variable. This can be attributed to the large dispersion in future climate projections as a result of CO₂ emission pathways, climate model structure and data limitations for calibration and validation of climate and crop models. Hachigonta (2011) suggests that climate scenarios from GCMs are the major source of uncertainty in the region. That effect is even more notable for revenue change projections made under Ricardian studies. Revenue changes projected by GCM driven scenarios ranged from a revenue decline of -100 % to an increase of +82 % of revenues. However, overall projections under Ricardian studies showed a median decline in net revenues. Uniform scenario driven projections showed median revenue decline of 12% and 14% in dryland farms and all farm types respectively.

This review helps determine the range of impacts that climate change will have on various

crops in southern Africa, especially food crops. This is a first step to developing suitable adaptation measures to reduce such impacts and promote future food security. Reviewing studies that are based on varying assumptions, tools and methodologies is difficult. The study is limited by a lack of quantitative data in southern Africa and a bias towards reported methodologies and tools. However, it is clear that climate change will significantly affect crop production in southern Africa. There is a compelling need for adaptation especially for vulnerable smallholder farmers. Research into locally appropriate adaptation options is essential. Smallholder farmers' past and current coping capacity (Twomlow et al., 2008) suggests research could build on this knowledge. Though uncertainty is and will remain significant, prediction tools are useful for the exploration and evaluation of local adaptation alternatives. Such research could be approached through the use of downscaled climate projections such as those produced by the Climate System Analysis Group (Hewitson and Crane, 2006). Multiple GCMs and CO₂ emissions scenarios can be used to sample climate uncertainty. Furthermore, judicious calibration and validation of crop models for use at the local scale is also important (Challinor et al., 2009a). However, setting up crop models satisfactorily at local levels may be challenging in southern Africa where historical data is usually insufficient. Adapting crops to climate change in southern Africa will have to be accompanied by broad investments, the integration of new and appropriate technologies with local knowledge and a coordinated engagement of public and private stakeholders.

CHAPTER 3

CROP MODEL USEFULNESS IN DRYLANDS OF SOUTHERN AFRICA: AN APPLICATION OF DSSAT.

Crop models are useful tools for simulating impacts of climate and agricultural practices on crops. They have to demonstrate the ability to simulate actual crop growth response in particular environments before they can be applied. Data limitations in southern Africa frequently hinder adequate assessment of crop models before application. The DSSAT group of models was used to test the usefulness of crop models under data limited dryland conditions of southern Africa by validation using data from experimental trial reports and district-wide crop yield estimates. Two crops each were selected in three locations to represent varying cropping and physical conditions in southern Africa i.e. maize and sorghum (Mohale's Hoek - Lesotho and Big Bend - Swaziland) and maize and groundnut (Lilongwe - Malawi). Results showed that the DSSAT group of models performs well in simulating crop yields obtained from experimental trials. District wide simulated mean crop yields were acceptable (relative difference was within $\pm 15\%$). However, the model's capture of seasonal yield variation for some locations and crops was uncertain, due to climate extremes. It was concluded that satisfactory crop model testing before application is possible and that crop models are usefulness despite data limitations, especially for studies that focus on long term yield responses.

3.1 Introduction

Crop growth simulation models are valuable tools for assessing the impacts of climate change and variability on crop production. A lot of research has been done using crop models to assess impacts of climate change and variability on crops in southern Africa (Zinyengere et al., 2013). However, most of these studies obtain confidence to apply crop models from generalised validation procedures, where the model is considered suitable because it has been applied successfully in similar environments (Jones and Thornton, 2003; Liu et al., 2008; Knox et al., 2010, Thornton et al., 2011) or through point based validations obtained from experimental trials (Chipanshi et al., 2003). Generalised validations do not account for the fact that modelled conditions vary from one place to the other with respect to climatic and soil characteristics, land use and management practices (Gaiser et al., 2010). Experimental trials on the other hand while providing location specific validations are commonly done under well managed settings uncharacteristic of dryland conditions under which smallholder farmers in southern Africa operate (Twomlow et al., 2008). Dryland farmers in the region operate under sub-optimal conditions that range from heavily weathered and infertile soils, erratic and unreliable rainfall, poor water management, poor fertiliser use and untimely sowing (Whitbread et al., 2010). In most instances, these conditions differ from those under which most crop models have been developed and tested. It is therefore essential that crop models are tested under these particular conditions to capture their location specificity and variation in the region.

A persistent challenge to adequately testing crop models for use in impact studies under varied conditions which dryland farmers operate in southern Africa is data limitations. Data are seldom available in the quantity and quality that is easily adaptable to drive crop models. This is partly why crop models have occasionally been applied with inadequate validation. In cases where resources and time have permitted, experimental trials have been performed for the purpose of validating crop models in different locations in southern Africa. For example, in South Africa (Du Toit et al., 1997; Durand and Du Toit, 2000; Whitbread and Ayisi, 2004; Mabhaudhi et al., 2014) and as summarised by Singels et al. (2010), in Malawi (Kamanga, 2002), and in Zimbabwe (Dimes et al., 2002). Some studies have gone a step further by engaging smallholder farmers to model actual on-farm conditions and yields. For example, Thornton et al. (1995) assessed CERES-maize in Malawi with smallholder farm data and Ncube et al. (2006) did the same with the Agricultural Production Systems sIMulator

(APSIM) in Zimbabwe. These experiments are invaluable for modelling dryland systems in the region but are uncommon, such that researchers that seek to simulate effects of various biophysical factors on dryland systems in most parts of southern Africa will not have access to similar resources and data. Still, model performance assessment remains vital despite the data constraints, especially if crop models are to be used for assessments such as climate change impacts where uncertainty is inherent.

The main objective of this study was to test the potential of crop models to simulate crop yields under a range of biophysical conditions found in data limited drylands of southern Africa. In the process, the study sought to highlight the challenges and opportunities in carrying out crop model set up and assessing usefulness under data limited conditions common in the region. It was hypothesised that despite data challenges, satisfactory assessments of crop models can be performed in the region before they are applied in impact studies. The DSSAT group of models was tested for usefulness as a sample crop model through validation under various dryland conditions of southern Africa for simulating two crops each in three locations i.e. maize and sorghum (Mohale's Hoek in Lesotho), maize and sorghum (Big Bend in Swaziland) and Maize and groundnut (Lilongwe in Malawi). The three locations were selected for their diverse climatic and agroecological characteristics that include hot and dry low veld conditions (Big Bend), cold high altitude conditions (Mohale's Hoek) and moderate warm and wet mid altitude conditions (Lilongwe).

3.2 Study Area

3.2.1 Southern Africa

Southern Africa is a predominantly semi-arid region with high rainfall variability. It is known as one of the most vulnerable regions to climate change and variability with a low adaptive capacity combined with high dependence on rain fed agriculture (IPCC, 2007b). In general, the region is dominated by summer rainfall. In most parts of the region, including the focal areas of this study, October to April represents the main rainy season, reaching a peak between December and February when about 80 - 90 % rainfall is received. The rainfall season commonly starts earlier in the northern parts of southern Africa (September–October), whereas rains arrive later (November–December) in the central regions (Tadross et al. 2005).

Long-term rainfall records in southern Africa indicate that inherent variability in seasonal rainfall totals increases disproportionately from wetter locations to the semi-arid regions that receive between 250 and 600 mm of seasonal rainfall (Usman and Reason; 2004; Twomlow et al., 2008). The distribution of rainfall, both within the season (intraseasonal) and over years, is subject to high variability (Reason et al., 2005), with the El Niño Southern Oscillation (ENSO) playing an important role (Tadross et al., 2009).

Agriculture, especially maize production in southern Africa plays a critical role in sustaining rural livelihoods and food security and is directly dependent on climatic variables such as temperature and rainfall (Porter and Semenov, 2005). Crop yields vary with rainfall variability such that low rainfall usually results in low productivity (Twomlow et al., 2008). Agricultural productivity in dryland systems of southern Africa is also threatened by population pressure, declining soil fertility, poor technological inputs, weed invasion, decreasing farm size, disease, lack of or poor access to markets, etc. (Cooper et al., 2008). Changes in climatic variables may exert more pressure on agriculture resulting in crop production becoming less viable for rural livelihoods (Davis, 2011). Three districts in southern Africa i.e. Mphahle's Hoek in Lesotho, Lilongwe in Malawi, and Big Bend in Swaziland were used as case studies. Details of the physical characteristics of these districts are in Table 3.1.

Table 3.1 Physical characteristics of study sites. Mean annual temperatures and rainfall. In parenthesis are averages over the growing season (October-April).

District	Longitude	Latitude	Elevation (m)	Temperature (°C)			Rainfall (mm)
				Mean	Maximum	Minimum	
Big Bend	-26.85	31.92	138	22 (24.7)	29 (30.6)	14.9 (20.7)	608 (517)
M' Hoek	-30.15	27.47	1620	15.6 (18.9)	22.7 (25.7)	8.4 (13.4)	700 (602)
Lilongwe	-13.78	33.77	1229	19.9 (21.8)	25.5 (26.6)	14.8 (17.1)	826 (810)

Climate summaries were made from weather records obtained from national meteorological institutions in Lesotho (1980-2005), Malawi (1980-2009) and Swaziland (1985-2011), through the Climate System Analysis Group and FANRPAN under the SECCAP project.

3.2.2 Big Bend

Big Bend is located in the south east of The Kingdom of Swaziland. The country has an area of 17 370 km² and lies 100 - 1 800 m above sea level in south-eastern Africa. It is a landlocked country surrounded to the north, west and south by the Republic of South Africa and to the east by the Republic of Mozambique. The country is divided into 4 agroecological zones, the high veld, middle veld and low veld and Lubombo, experiencing average annual rainfall of 950 mm, 700 mm, 475 mm and 600 mm respectively (Government of Swaziland, 2000). Almost 15 % of the middle veld has arable soil of fair to good quality, about 20 % of the low veld has fair to good arable soils (Murdoch, 1970).

About 80 % of Swaziland's population is rural-based. Cereal crops are the major food crops grown with maize as the main crop. An estimated 90 % of the maize is grown by smallholder farmers under dryland conditions and yields are about 1.5 - 2 t/ha (Manyatsi et al., 2013). Other crops, such as sorghum, groundnuts, beans, and cowpea, are grown on a small scale. Dryland agriculture is mostly practiced in the middle veld and low veld of Swaziland. Big bend is located in the low veld, the driest part of the country. Big Bend receives highly variable rainfall averaging about 600 mm annually. Mean annual temperature is around 22 °C. Summer temperatures regularly reach 35 °C resulting in high evapotranspiration. The region is not usually suitable for maize production under dryland conditions but small grains like sorghum, yet maize is still the dominant crop (Manyatsi et al., 2013). Irrigated sugarcane is also commonly grown in the district.

3.2.3 Mohale's Hoek

Mohale's Hoek is located in Lesotho, a small country of 30 000 km², landlocked by South Africa. Lesotho has a harsh environment because of its highly variable terrain and climate. The altitude ranges from 1 400 to 3 500 m above sea level. Mean annual rainfall ranges from 450 mm in the lowlands to 1 100 mm in the highlands. The high altitude means that Lesotho experiences some of the lowest temperatures in southern Africa, with a significant proportion of the country experiencing mean annual temperatures below 10 °C. Except in the western

lowlands where maximum temperatures can reach 32 °C, mean daily maximum and minimum temperatures do not exceed 25 °C and 12.5 °C, respectively (Gwimbi et al., 2013).

Only around 15 % of the country is arable and the rest is composed of rocky land as well as steep slopes. Maize is by far the dominant crop grown in Lesotho, accounting for 77 % of the country's cereal production mainly through dryland smallholder subsistence farming. Average yields of maize are 0.72 t/ha (Mbata, 2008). Other principal crops are sorghum and wheat accounting respectively for 13.6 % and 9.4 % percent of cultivated land in 2008 (Gwimbi et al., 2013) and yielding respectively 0.74 t/ha and 0.68 t/ha on average (Mbata, 2008). The main agricultural activities in the country are confined to the lowlands where the elevation is about 1 500 - 1 700 m above sea level. This is where Mohale's Hoek is located. Temperatures in the lowlands reach 32 °C in the summer and as low as -7 °C in the winter. Annual temperatures in Mohale's Hoek average 15.6 °C. Rainfall received during the agricultural season (October- April) averages 500-700 mm (Masiatile, 2011). The lowlands account for 17 % of the land area and 80 % of the productive arable land (Ministry of Natural Resources, 2007).

3.2.4 Lilongwe

Lilongwe is located in central Malawi, a landlocked country located in the eastern part of southern Africa. Malawi has two distinct seasons, namely, rainy season (October - April) and dry season (May - September). Mean annual rainfall ranges from 500 mm in the dry and hot rift valley areas where temperatures can reach 35 °C, to 2 500 mm over highlands where temperatures are moderate. Precipitation is most frequent along the northern coast of Lake Malawi, where the annual average is above 1 600 mm. 70 % of the country averages 750 - 1 000 mm annually. 95 % of Malawi's cultivable land is under dryland crop production (Saka et al., 2013).

Lilongwe district is located in Lilongwe Agricultural Development Division (LADD) in the mid altitude region. The mid-altitude zone (1 000 - 1 500 m above sea level) experiences high annual average rainfall of 800 - 1 200 mm (Saka et al., 2013). LADD produces about 40 % of cereal grain in Malawi (Environmental Affairs Department, 2005). Most crop production is practiced by smallholder rural farmers and is vulnerable to climate variability. Maize is the

staple crop and produces on average 1.5 - 3 t/ha in yield under dryland conditions. The major food crops grown in Malawi are maize, groundnuts and beans on 45 %, 7.6 % and 7.5 % of the arable land respectively (Saka et al., 2013).

3.3. Materials and Methods

3.3.1 The DSSAT model

The Decision Support System for Agrotechnology Transfer (DSSAT) group of crop models was used in this study as a sample crop model to illustrate needs, challenges and opportunities in simulating dryland farming systems under data limitations in southern Africa. Among a limited number of biophysical crop models, DSSAT group of models was selected for its global use and proved performances in impact studies (White et al., 2011), as well as its regional repeated uses for climate variability and change impact studies in southern Africa (Jones and Thornton, 2003; Chipanshi et al., 2003; Walker and Schulze, 2006; Knox et al., 2010; Thornton et al., 2011). Furthermore, It takes into account a wide range of management practises e.g. tillage, fertilisation, residue and organic matter application, rotation etc., that are found in dryland systems of southern Africa and are known to be strong determinants of productivity (Cooper et al., 2008).

DSSAT is a simulation model for crops that describes daily phenological development and growth in response to environmental factors (soil, weather and management). The basis of DSSAT is a cropping system model (CSM) designed in modules in which components are separated along scientific disciplines. These include climate, crop and soil modules. It requires daily weather values of maximum and minimum temperatures, precipitation and solar radiation. Soil information needed includes details of soil characteristics; drainage, runoff, evaporation and soil water holding capacity, and rooting preference coefficients for multiple soil layers and initial soil water content (Jones et al., 2003). Crop characteristics are determined through crop and cultivar specific genetic coefficients. The DSSAT group of models has separate plant modules that simulate growth and yield for individual species e.g. CERES (Maize, Sorghum, Wheat, Rice etc.), SubStor (Potato), CANEGRO (sugar cane) etc. and CROPGRO for computing crop growth processes of soybean, peanut, dry bean, chickpea, cowpea, faba bean, tomato, Macuna, etc. The DSSAT group of models also have a

management module that determines when field operations are performed by calling sub modules. These operations can be specified by users and include planting, harvesting, applying inorganic fertilizer, tillage, irrigating and applying crop residue and organic material (Jones et al., 2003).

3.3.2 Input data

An assessment of a crop model's performance involves comparison of model outputs with real data and a determination of suitability for an intended purpose. This can be seen as a documentation of its accuracy for specific predictions in specified environments, with a consideration of possible errors in input variables or data (Grassini et al., 2015). Minimum data for the purpose includes a complete record of the data required to run the model and field information on the aspects for which the model was being tested (Aggarwal, 1995). In this study, this included a complete climate record, soil characteristics for the locations under study, a complete description of the crops being tested and management operations. While this information is usually available at experimental station level, experiments are hardly made for crop model set up and therefore data on climate, soils, crops and management are often not continuous in time and may be qualitative when the crop model requires quantitative values (Tingem et al., 2009). As such, data is not always easily adaptable to crop modelling. These challenges increase at scales beyond the experimental. Studies have sought to investigate what makes up a satisfactory crop model set up to improve inputs (Rotter et al., 2011; Grassini et al., 2015), while others have sought to set up crop models with available data (Angulo et al., 2013; Bilonis et al., 2015). In this study, we seek to set up a crop model under data scarcity through a mix of data obtained from reports of on-site experiments, published literature (crop types, varieties and yields, agronomic management, soils, etc.), government records and international databases (soils) and national meteorological departments (climate). Where data were particularly incomplete or scattered, expert judgement based on available information was used to build appropriate data sets for satisfactory crop model set up and testing.

Climate: While rainfall data is recorded frequently in the region, temperatures are often missing and solar radiation records hardly exist. In both cases, data is often riddled with gaps and inaccuracies, needing further processing. Furthermore, climate stations are sparse. For

this study, meteorological stations located in each study district that had a consistent set of historical climate data were used to collect daily precipitation, maximum and minimum temperature data. Daily solar radiation was estimated according to the minimum and maximum temperatures, Julian day, latitude, altitude and an empirical parameter following Allen et al. (1998) approach. Details of stations used for climate information are shown in Table 3.1. Climatic data was accessed and processed at the Climate System Analysis Group (CSAG) at the University of Cape Town through standing relationships with national meteorological services departments in Lesotho, Malawi and Swaziland.

Soil: In each location, a minimum description of the first 30 cm of the soil profile with relevant physical and chemical parameters existed from various sources e.g. government publications and local, regional and international soil databases. These soil data sources were used to find complete soil profiles within the DSSAT WISE database (Gijssman et al., 2007) that had similar physical and chemical characteristics. Two soil profiles were developed in each study district based on identified dominant soil types. A summary description of the two soils is shown in Table 3.2. Details of the soil characteristics e.g. lower drained limit, upper drained limit and saturation, essential parameters required for running the model and based on generic parameters identified in the WISE database is shown in Table 3.3. Other soil parameters, including the soil albedo, a soil water drainage rate constant and runoff curve number, were also based on soil texture estimates in the WISE database.

Crop varieties and management: Data on crops and management practices was obtained from reported experimental trials. These data included planting dates, planting densities, fertiliser application amounts and timing. Selected crop varieties were those reported in experimental trials as shown in Table 3.3. Detailed phenological and genotypic details of each crop variety were obtained from seed house pamphlets. Apart from experimental trials, information on crop management practices of dryland farmers in study districts were obtained from grey literature and local expert agronomists. These are summarised in Table 3.3.

Table 3.2 Soil class, seasons and references to some documents and reports used for DSSAT calibration and validation for study sites.

Study site	Soils	Seasons (calibration)	Seasons (validation)	Station	District	References
Big Bend	Sandy Clay Loam	90/91	89/90; 94/95	90/91-93/94;95/96;97/98;98/99; 02/03	00/01- 02/03	Mkhabela et al. (2001), ARD (1991); ARD (1992); Murdoch (1970)
	Clay Loam	87/88	88/89; 89/90	92/93; 93/94; 95/96; 97/98; 02/03		
Mohale's Hoek	Silty Loam;	88/89	86/87;87/88; 88/90	89/90 - 02/03		ARTI (1986); ARTI (1996); Massey et al. (1991); Massey et al. (1992a); Carroll and Bascomb (1967); Massey et al. (1992b); Ebenebe (1998)
	Sand Clay Loam	89/90	88/90; 90/91	89/90 - 02/03		
Lilongwe	Sandy Clay Loam	90/91	92/93; 95/96	96/97 - 02/03		Benson and Kumwenda (1998); Chigowo and Saka, 2001; Munthali and Chiremba (1999); Hildebrand and Bock (1990); Mwale et al. (2011); CRS (2008);
	Sandy Clay Loam	96/97	97/98; 98/99	96/97 - 06/07		

Table 3.3 Physical and chemical characteristics; Bulk Density (BD), Organic Carbon (OC), Clay content (C), Silt content (SI), pH, Lower Limit (LL), Drained Upper Limit (DUL), Saturation (SAT) of selected soils and simulated estimate agronomic practices of smallholder farmers.

Study site	Soils								Crop Variety	Fertiliser (kg/ha)	Planting density (plants/ha)	Planting date
	BD (g/cm ³)	OC %	CL (%)	SI (%)	pH	LL (cm ³ /cm ³)	DUL (cm ³ /cm ³)	SAT (cm ³ /cm ³)				
Big Bend	1.6	0.3	30	11	7.7	0.22	0.30	0.39	Maize PAN473	0-200	30 000, 33 000	10 Nov, 25 Nov, 10 Dec
	1.6	1.6	39	24	8.2	0.18	0.35	0.37	Sorghum DC75	0-150	50 000, 60 000	1 Dec, 15 Dec, 30 Dec
Mohale's Hoek	1.49	1.74	38	23	4.3	0.20	0.37	0.41	Maize PAN473	0-100	25 000, 30 000	15 Oct, 30 Oct, 15 Nov
	0.9	7.3	10	49	5.2	0.15	0.34	0.47	Sorghum PAN854	0-100	50 000, 60 000	15 Nov, 10 Dec, 25 Dec
Lilongwe	1.56	0.8	38	6	5.1	0.22	0.31	0.39	Maize MH17	0-300	33 000, 37 000	10 Nov, 25 Nov, 10 Dec
	1.4	1.7	28	21	5.5	0.19	0.32	0.43	G' nut Malimba	0	45 000, 55 000	10 Nov, 25 Nov, 10 Dec

3.3.3 Calibration and validation

DSSAT (v4.5) was calibrated to simulate maize at all study sites and sorghum in Mohale's Hoek and Big Bend and groundnut in Lilongwe and then validated with data sets derived from reported experiments in each study site (Table 3.2). These experiments described a variety of assessments of the effect of different agroecological factors such as nitrogen, season, weather, sowing dates and variety on growth and yield of studied crops. Parameterisation of DSSAT was based on typical values obtained from literature, default values from the model user manual and local expert advice. Tingem et al. (2009) suggested crop model set up can be performed using "loose" parameterisation, with the understanding that if a crop model's performance can be satisfactory with limited parameterisation, then performance could be even better if more data were available. The parameterisation performed in this study was limited by data scarcity, a common challenge in the region. In each location, a minimum description of the first 30 cm of the soil profile with relevant physical and chemical parameters existed from various sources e.g. soil survey data, government publications and local, regional and international soil databases. Crop cultivar specific parameters were achieved through tuning phenology and growth coefficients of each crop variety respectively through repeated iteration by minimizing the differences between observed and simulated crop yields until a close match was obtained. Only one season was used for calibration at each research site due to a lack of observed trial data. However one season could be considered sufficient under such limitations especially if calibration is performed across various sites (Fraisie et al., 2001; Akponikpe et al., 2010) or validation is done over two or more seasons (Rezougg et al., 2012; Mourice et al., 2014). Effort was made to select a season with well distributed rains and high nitrogen applications to simulate near non-stress conditions. Initial soil water was estimated by running the model 3 months prior to planting date. Crop varieties calibrated were identified from reported trials. The coefficients were adjusted from varieties already found in the DSSAT database to suit identified local cultivars which were not available in the database. The established cultivar parameters were applied for model validation.

For model validation, an independent data set from separate seasons listed in Table 3.2 was used. A twofold validation was performed. First, a validation based on reported station

experimental trials. These were limited to two or three seasons based on availability of records (Table 3.2). Since the reported experimental trials were carried out at agricultural research stations, usually well managed, which is uncommon in smallholder dryland systems, an assessment of the model for conditions more representative of the dryland systems was necessary. Therefore, a second validation was performed based on district-wide crop yields, which were considered to represent yields obtainable under sub-optimal conditions common in smallholder dryland production. In the validation, management inputs reflected common smallholder farming practices in each district (Table 3.3). All other input data (climate, soils, and agronomic practices) were used to represent conditions over the district. The validation was performed over several seasons to assess model performance in capturing seasonal mean crop yields and their temporal variation in response to climate.

A caveat in using district-wide yields as a proxy for yields attainable by smallholder farmers in drylands is that they operate under varying conditions even in the same district. Therefore reported district-wide yields average these vast conditions (climate, soils, crop varieties, time of sowing, planting densities, fertiliser application, etc). It would be difficult to estimate the different conditions and practices of farmers over an entire district. Modelling over a large production area cannot take into account the level of detail found at the field or farm scale. A reasonable approach is needed to capture heterogeneity over the production environment. In this study, a range of conditions were simulated to sample soils and common dryland agronomic practices. Two soils, three planting dates (consisting a one month window ranging from early to late planting), three fertiliser amounts (split between basal at planting and top dressing 4-6 weeks after planting) and two planting densities were simulated per district and crop as summarised in Table 3.3. In total, 36 treatments were simulated per season and crop (12 for groundnuts). The average yield from all treatments represented simulated crop yields per season.

3.3.4 Yield bias correction

Generally, the simulated yields would be expected to be considerably different from averaged district yields. This results from bias and errors due to differences in the actual and estimated environmental (soils, climate, etc.) and management conditions (planting dates, fertiliser application, etc.), site-specific constraints not specifically accounted for by the crop model

(e.g. pests and diseases, weeds, etc.), as well as errors due to methods used by responsible agencies to arrive at the reported district yield value. The model simulated yields would need to be corrected for such bias and errors for each crop and district. The simulated yields at district level were corrected against the observed district yields for a more representative assessment of model performance. Ideally, a large series of district yield data and a detailed description of the variation in physical and management conditions over space and time would help to compute bias satisfactorily. In this study, bias was computed from the linear relationship between observed and simulated district yields over multiple seasons (Table 3.2). The slope with a zero intercept was used as the yield bias correction factor to adjust simulated mean yields for each location and crop. The bias adjusted district mean yields were used to assess crop model performance in simulating mean crop yields and yield variation using the relative percentage difference (RD %), the co-efficient of variation (CV) (Loague and Green, 1991), root mean square error (RMSE) and index of agreement (d) (Willmott et al., 1985).

3.4 Results

A common crop variety in each district (Table 3.3) was calibrated by adjusting the phenological and growth coefficients of a selected variety from the DSSAT database respectively through repeated iterations until the difference between observed and simulated yields were minimised as shown in Figure 3.1. The same coefficients were used in subsequent validations. The results presented in Figure 3.2 show the performance of DSSAT in simulating crop yields recorded from experimental trials held at a research station (no bias correction). The figure shows that DSSAT was able to simulate observed maize yields well for Lilongwe ($R^2 = 0.72$), Mohale's Hoek ($R^2 = 0.96$) and Big Bend ($R^2 = 0.996$). DSSAT performance in simulating groundnut yields in Lilongwe ($R^2 = 0.89$), sorghum yields in Big Bend ($R^2 = 1$) and Mohale's Hoek ($R^2 = 0.70$) was also satisfactory. However the relationship between simulated and observed Mohale's Hoek sorghum yields was poor due to only two trial results including a 10% mean yield over estimation for the 1990/91 season.

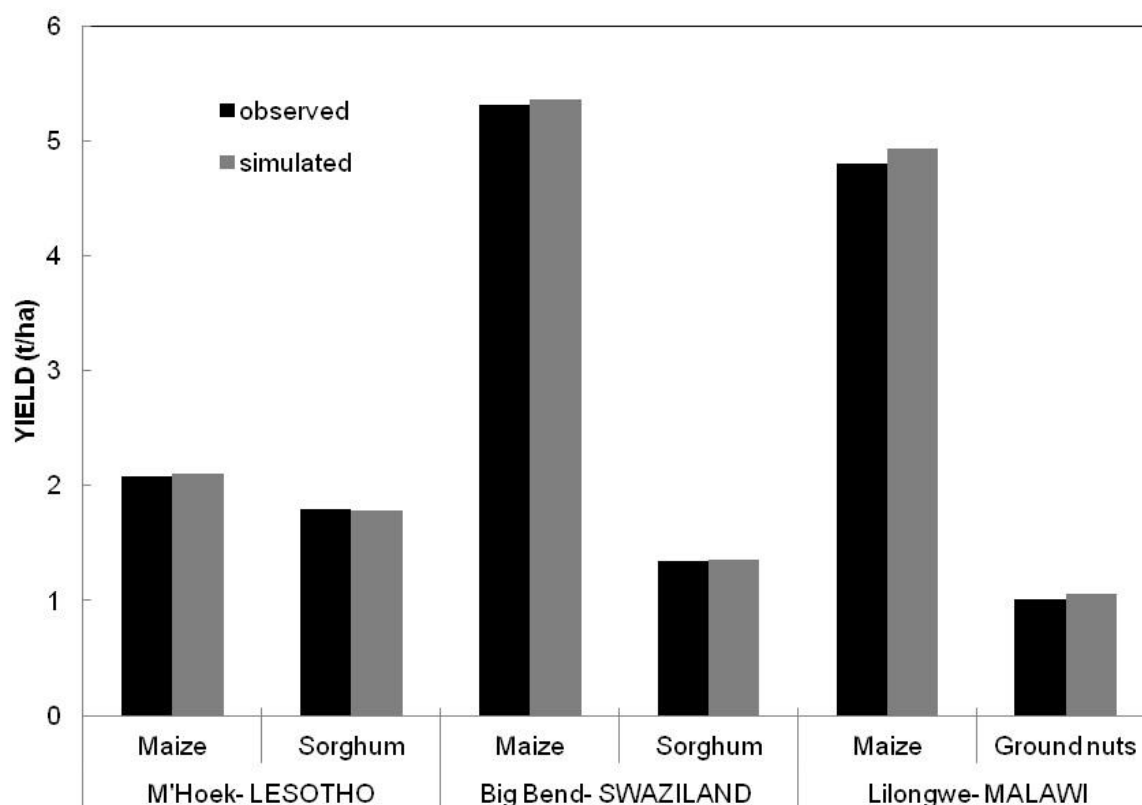


Fig 3.1 Calibration simulations for crop yields (by adjusting varietal phenology and growth coefficients) for 1 season per district.

A second validation where the crop model was tested for performance in simulating district yields as a proxy for yields attainable by smallholder farmers operating under dryland conditions was carried out. Table 3.4 shows the initial simulations before yield bias correction and the bias correction factors determined thereafter. It shows that simulated mean crop yields were generally higher for maize and sorghum than the recorded district yields for each study site. Simulated yields ranged from 1.5 - 3.5 times more than the observed yields. Mohale's Hoek had the largest difference between simulated and observed yields, while Big Bend showed the least difference. Simulated sorghum yields for Mohale's Hoek had the largest range of simulated yields. Simulated groundnut yields for Lilongwe were similar to observed yields. The model outputs were bias corrected with district yields in order to translate the effect of factors not modelled (see section on yield bias correction).

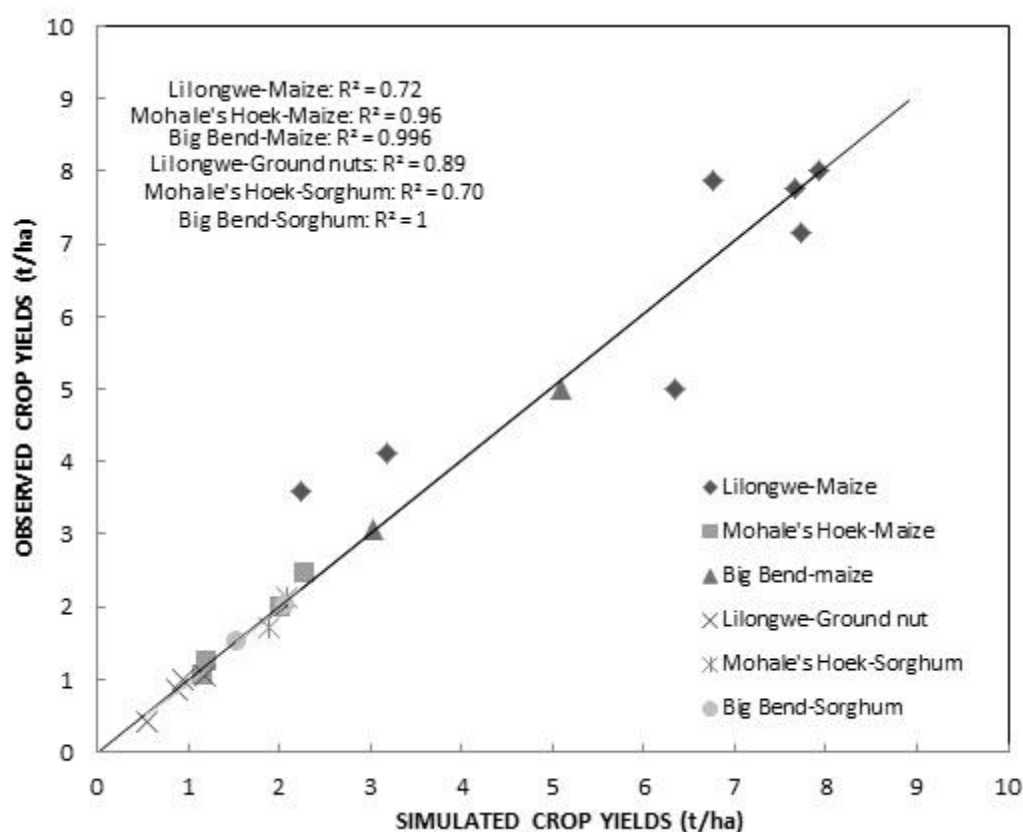


Fig 3.2 Relationship between observed and simulated crop yields for Lilongwe, Mohale's Hoek and Big Bend. Solid line shows 1:1 relationship.

Table 3.5 shows results of DSSAT performance in simulating district-wide mean crop yields and yield variation over several farming seasons after bias correction. Simulations were performed based on estimated and reported management practices of dryland farmers in the respective study districts. Model performance varied across study sites and crops. DSSAT estimated well the observed mean crop yields, estimating mean yields within 15 %, 10 % and 3 % of observed yields for Big Bend, Mohale's Hoek and Lilongwe respectively. The model captured accurately the mean yield variation of maize (CV of 0.2) but not of groundnut in Lilongwe. The low RMSE shows the model was able to capture season to season yield changes well in Lilongwe. However, as shown by the weak index of agreement (0.38 - 0.41), the amplitude of change was not well captured. For Mohale's Hoek, mean sorghum yield variation for all seasons together was well captured while less than a quarter of the maize yield variation was accounted for. Conservative indices of agreement (0.5 and 0.63) for Mohale's Hoek and high RMSE (43 %) indicate that the capture of season to season yield variation under extreme conditions was uncertain. Stronger indices of agreement for Big Bend (0.60 and 0.78) indicated a good capture of seasonal yield changes. Yield change

amplitudes were well represented for maize (RMSE: 24 %) and less so for sorghum (64 %). The capture of yield variation in Big Bend varied with crop.

Table 3.4 Observed and simulated district mean yields (kg/ha) before bias correction (b). Ranges are shown in parenthesis.

District	Crop	Observed	Simulated	b
Big Bend	Maize	1228 (600 – 1653)	1834 (1420 - 2640)	0.59
	Sorghum	742 (332 - 1680)	1591 (1032 - 1914)	0.48
Mohale's Hoek	Maize	741 (191 - 1813)	2538 (2101 - 3150)	0.30
	Sorghum	664 (220 - 1220)	2092 (753 - 4238)	0.29
Lilongwe	Maize	1202 (914 - 1569)	3288 (1864 - 3740)	0.36
	Groundnut	815 (658 - 1143)	861 (737 - 923)	0.93

3.5 Discussion

This study sought to test the usefulness of a crop model under limited spatial and temporal data, as common in drylands of southern Africa. Point validations were based on one or two sites in a district with only two or three years of trials. At the same time, validation with district wide data was done over six to fourteen cropping seasons with limited information on the spatial variation of climate, soils, and management practices. However, despite the data limitations, a satisfactory test of crop model usefulness for capturing crop yields in study locations was carried out. DSSAT was able to produce good estimates of mean crop yields as reported through location specific experimental trials as well as district-wide yield estimates in all study locations. Relative percentage difference (RD %) between observed and simulated mean yields was within ± 15 %. This gives indication towards good usefulness for studies that seek to apply the model for climate change studies that usually focus on long term responses of crops.

Table 3.5 Comparison of observed, simulated mean crop yields after bias adjustment, showing the coefficient of variation (CV), relative percentage difference (RD%), root mean square error (RMSE) and index of agreement (d) for a number of seasons per study district.

District	Crop	Seasons		Mean (kg/ha)	CV	RD (%)	RMSE (%)	d
Big Bend	Maize	6	Observed	1228	0.4			
			Simulated	1078	0.25	-12.2	24.4	0.78
	Sorghum	6	Observed	742	0.8			
			Simulated	764	0.24	2.9	63.9	0.60
Mohale's Hoek	Maize	14	Observed	741	0.53			
			Simulated	763	0.12	2.98	43.4	0.50
	Sorghum	14	Observed	664	0.42			
			Simulated	611	0.41	-8.1	43.1	0.63
Lilongwe	Maize	7	Observed	1202	0.2			
			Simulated	1169	0.2	-2.74	23.8	0.41
	Groundnut	11	Observed	815	0.17			
			Simulated	861	0.08	2.36	17.7	0.38

DSSAT also demonstrated an ability to simulate season to season yield variation albeit with varying degrees of accuracy between locations and crops. Seasonal yield variation was captured particularly well for maize in Big Bend and Lilongwe and Sorghum in Mohale's Hoek. The capture of yield variation was less accurate for sorghum in Big Bend, maize in Mohale's Hoek and groundnut in Lilongwe. For Big Bend and Mohales' Hoek, this was caused by the model not fully capturing high and low yields caused by extreme weather during some seasons as demonstrated by the high RMSEs (RMSE is sensitive to large individual difference between observed and simulated yields, therefore amplifies the effect of extremes). RMSEs for Lilongwe were small, indicating that the simulations were less affected by extreme weather. Big Bend and Mohale's Hoek experience more extreme climate and are much more prone to extreme yield changes than Lilongwe which commonly experiences a moderate climate. These results suggested that while the model can perform well in capturing mean yields and long term average impacts under a wide range of conditions with data limitations, it may not reproduce well yields obtained under extreme

climatic conditions for some crops and locations. Easterling et al. (1996) testing the EPIC model and Carbone et al. (2003) testing the CROPGRO model in DSSAT similarly observed that over larger areas where a lot of estimations have to be made to run models, they are less reliable under extreme weather especially rainfall. Rotter et al. (2011) in assessing the usefulness of crop models in for climate change impact assessments state that crop models do not properly simulate the effects of extreme heat or drought on crops especially the flowering stages. More in-depth investigation is required under shorter times, preferably with more detailed data to fully assess model usefulness under extreme climates. The ability of crop models to represent yields changes under extreme climates is particularly of interest for dryland systems of southern Africa where farmers regularly operate under sub-optimal conditions and are very prone to the vagaries of climate. More reliable estimations of season to season variation in low input dryland systems are therefore necessary. Some efforts have been made to improve crop modelling (particularly the APSIM model) in the dryland low input systems in southern Africa (Dimes et al., 2003; Ncube et al., 2006; Twomlow et al., 2008). Reliability of crop models can be improved through improvements in data. Detailed soil input parameters related to processes that constrain crop growth under very dry conditions or boost yields under wet conditions e.g. water retention characteristics, organic matter and nitrogen turnover will be required. Gaiser et al., 2010 while validating the EPIC model in the drylands of western Africa, also found this to be true. A more detailed representation of smallholder agronomic practices especially fertiliser application and sowing times, which are known to considerably affect crop yields in extreme climate conditions will also help to improve model performance.

The over estimation of yields shown in Table 3.4 can partly be attributed to events unaccounted for by the model (e.g. hail), differences in actual and simulated environments (soils, climate, crop varieties, management practices, etc.) and errors in recorded district data. Other studies have also shown similar over estimation from crop models e.g. CROPGRO (Jagtap and Jones, 2002) and EPIC (Brown and Rosenberg, 1999) when estimating crop yields over a large area like a district. This also points towards the need to gather more data regarding the variation of climate, soils, crop varieties and agronomic practices in the area under study in order to fairly represent dryland systems. Under dryland conditions in southern Africa, nutrient and water limitations are primary drivers of systems performance (Whitbread et al., 2010). Carrying out experimental trials and surveys to collect data relating to nutrient and water limitations along with variation of physical conditions and agronomic practices of

dryland systems over time and space in the region would be invaluable for capturing these peculiar conditions and for better model initialisation and parameterisation to account for them. This can be supported through collaborations between the modelling community, local farmers and extension and better data preservation and sharing.

The approach used in this study to represent dryland cropping conditions of southern Africa where biophysical data limitations are common i.e. bias corrected district averaged yields, is not without its caveats. However, it proved useful in assessing crop model performance and highlighting areas of further interest in setting up crop models, notably improvement of models for seasonal yield change estimation, particularly under extremes. Overall, barring limitations in simulating extreme climatic conditions and complex factors such as effects of weeds, pest and diseases, all which are important in low input dryland systems, the DSSAT group of models can be considered robust in diverse environments in southern Africa for simulating impacts of climate and agronomic management strategies on various dryland crops in the region. The study showed that the DSSAT group of models would perform better at simulating crop yield responses to climate and agronomy with detailed agricultural trial data than under spatial and temporal data limitations.

3.6 Conclusion

The DSSAT crop model was used as a modelling sample for testing crop model usefulness for simulating crop yields in conditions common in southern Africa; dryland farming systems with data limitations. Three locations were selected for the study, one each in Lesotho, Malawi and Swaziland. Testing was done by way of validation, first using data from experimental trials and secondly, district averaged yields as a proxy for yields obtainable under sub-optimal management conditions common in drylands of southern Africa.

Acknowledging DSSAT model limitations under the varied physical and management conditions in the region, which play a different role depending on alternate objectives, the crop modelling capacity for sub-optimal dryland conditions in southern Africa in response to climate and agronomic management was acceptable. Results suggested that under data limitations, crop models are useful for long term average impact assessments (e.g. climate change), but may require deeper investigation regarding their usefulness for simulating yields

over shorter time scale (climate variability), especially in areas prone to extreme climates. This understanding is critical in dryland systems given their climate dependency. Further investigations into improving parameterisation to capture yields under extreme climates will be helpful for model applications. For better capture of site specific crop responses and yield variation, more effort should be directed towards improved characterisation of soils variation, soil input parameterisation (initial soil water and nitrogen, organic content etc.) and the determination of relevant agronomic practices of farmers (fertilisation and planting). This study demonstrated that despite data limitations in southern Africa, where data requirements for model validation are not easily met, crop models can be satisfactorily tested and are still useful for impact studies, especially long term yield responses.

CHAPTER 4

LOCAL IMPACTS OF CLIMATE CHANGE AND AGRONOMIC PRACTICES ON DRYLAND CROPS IN SOUTHERN AFRICA

Climate change impact assessments on agriculture in southern Africa are mostly carried out at large spatial scales, risking missing out on local impacts and adaptation potential that reflect the range of multiple and unique bio-physical and agronomic conditions under which farmers in the region operate. This study investigated how climate change may affect yields of various major food crops in specific locations in the region; maize and sorghum (Mohale's Hoek – Lesotho and Big Bend – Swaziland), maize and groundnut (Lilongwe – Malawi). Using statistically downscaled climate projections from nine GCMs and the DSSAT crop model and simulating selected agronomic strategies practised in each location, the study confirmed that impacts of climate change on crop yields in southern Africa vary across locations and crops. Despite various uncertainties associated with such assessments, the results showed that crop yields were predominantly projected to decline on average in Big Bend (maize (-20%); sorghum (-16%)) and Lilongwe (maize (-5%); groundnut (-33%)). However, crop yields in Mohale's Hoek, located in a high altitude region historically prone to cold related crop yield losses were on average projected to increase (maize (+8%) and sorghum (+51%)). The geographical variation of yield projections highlights the importance of location specific climate change impact assessments. The exploration of local agronomic management alternatives revealed prospects for identifying locally relevant adaptation strategies, which cannot easily be captured at larger scales.

4.1 Introduction

Agriculture is one of the most climate dependent of human activities (Hansen 2002), particularly in Sub-Saharan Africa (SSA) where close to 70% of the population depends on smallholder agriculture (Cooper et al. 2008). This makes SSA extremely prone to the effects of climate change and variability. The Intergovernmental Panel on Climate Change (IPCC), (2007b) states that by 2050, crop yield losses could reach up to 50% in some countries in SSA. Compounded by increased population and low adaptive capacity, the crop yield losses will severely compromise food security in Africa. In a review study of projected climate change impacts in the 21st century, Zinyengere et al. (2013) show that while there is significant uncertainty about the impact of climate change in the early 21st century (2020s), projected impacts further into the 21st century largely show that climate change will negatively impact crops in southern Africa. Some recent studies in Africa concur and suggest similar negative impacts on crops (Knox et al., 2012; Berg et al., 2013; Liu et al., 2013; Waha et al., 2013; Muller, 2013, Folberth et al., 2014), while others suggest yields may increase, especially for wheat (Estes et al., 2013) . Food security and livelihoods on the continent are at risk.

The majority of studies on climate change impacts on agriculture in SSA are commonly performed at large spatial scales, aggregated over entire countries, the region or the continent as a whole (Zinyengere et al. 2013). This kind of assessment leads to generalised and broad conclusions about the impact of climate change on crop production that are not reflective of impacts at farm or community level. While these types of studies might be useful for national and regional planning, they run the risk of missing out on local peculiarities, where impacts vary considerably in both space and time. At coarse scales, it is difficult to sensibly identify useful on-farm adaptive measures. Large scale studies usually make broad-brush recommendation of adaptation strategies over large areas, which may not speak to local smallholder dryland farmers. These farmers operate under peculiar conditions and practices more often emanating from personal/community experience, culture, financial and physical resources, and varying over short spatial scales. In order to understand how climate change may affect crop production in the systems and conditions that dryland farmers operate and to identify adaptation strategies suited to those conditions, climate change impact studies need

to be performed at high spatial resolutions (Thornton et al., 2011, Lobell et al., 2008). The few studies that have carried out such assessments in southern Africa were limited in the number of crops studied e.g. maize alone (Walker and Schulze, 2008 and Abraha and Savage, 2006) and focused on one location thereby lacking a simultaneous analysis of impacts in the region. Furthermore, studies do not attempt to explicitly assess the impacts of climate change with agronomic scenarios representative of local farming practices.

This study presents a location specific climate change impact assessment for dryland crop production in southern Africa. Three distinct locations in southern Africa (Mohale's Hoek - Lesotho, Big Bend - Swaziland and Lilongwe - Malawi) with unique agro-ecological conditions and cropping practices were selected for the study. Climate projections were downscaled from nine Global Circulation Models (GCMs) for the three locations and used to drive a crop model to simulate impacts on three major southern African crops (maize, sorghum and groundnut). Projected baseline (1961-2000) and future (2046-2065) climate scenarios for two contrasting Special Report on Emission Scenarios (SRES) representing low (B1) and high (A2) future carbon dioxide (CO₂) emissions were used (Nakicenovic et al., 2000). Scenarios representing some agronomic strategies practiced by dryland farmers in each location were also simulated to provide insight into their potential for adaptation.

4.2 Methodology

4.2.1 Study location

Study locations were selected to represent a diversity of agro-ecological and agronomic conditions in southern Africa while crops were selected depending on local and regional importance to food security as follows; maize and sorghum in Big Bend; maize and sorghum in Mohale's Hoek; maize and groundnut in Lilongwe. Big Bend (-26.82°, 31.93°) is found in the low veld of Swaziland, a region considered marginal for maize and more suited to sorghum. Temperatures are high with a monthly average of 30 °C during the cropping season (Manyatsi et al., 2013). Mohale's Hoek (-30.15°, 27.47°) is located in the low veld, the main agricultural region of Lesotho, a high altitude country prone to cold related crop yield losses. Average annual minimum temperatures are below 10 °C (Gwimbi et al., 2013). Lilongwe (-13.98°, 33.78°) is located in a mid-altitude region that is considered one of the most

productive for cereals in Malawi (Saka et al., 2013). Temperatures are moderate. All three locations experience uni-modal summer rainfall between October and April, averaging 507 mm, 602 mm and 810 mm during the cropping season for Big Bend, Mohale's Hoek and Lilongwe respectively. Agriculture in all locations is dominated by dryland smallholder production on old sandy clay loam soils.

4.2.2 Scenario based impact assessment

In this study, the Decision Support System for Agro- technology Transfer (DSSAT) deals with the crop growth (Jones et al., 2003). To assess the impacts of climate change on crops at a fine level scale (farm/community), local climate variables (e.g. maximum temperature, minimum temperature, solar radiation and precipitation), crop and soil parameters, and management practices were crucial inputs.

4.2.3 Climate data and scenarios

The study used nine Comprehensive Model Intercomparison Project 3 (CMIP3) GCMs data (Meehl et al., 2007) as summarized in Table 4.1. The data was downscaled to a climate station to represent climate projections in each location for a baseline (1961 - 2000) and future period (2046 - 2065). The statistical downscaling was done using the self-organising maps (SOMs) approach by Hewitson and Crane (2006). Daily weather records (minimum and maximum temperatures and rainfall) were obtained from national meteorological institutions in each study country. Solar radiation was estimated with a routine based on daily minimum and maximum temperatures, latitude and elevation using the methods of Allen et al. (1998) and Ball et al. (2004) which were shown to be efficient over southern Africa (Hachigonta, 2011). For each of the nine GCMs, contrasting scenarios, namely the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC SRES) carbon dioxide (CO₂) emissions were used, respectively designated for B1 (low emission) and A2 (high emission).

Table 4.1 Comprehensive Model Intercomparison Project 3 (CMIP3) Global Circulation Models (GCMs) from which climate scenarios were obtained.

Name used	Originating group(s)	Country	Model name	full Primary reference
CCMA	Canadian Centre for Climate Modeling & Analysis	Canada	CGCM3.1 (T47)	Flato and Boer, 2001
CNRM	Météo-France / Centre National de Recherches Météorologiques	France	CNRM-CM3	Salas-Mélia et al., 2005
CSIRO	Australia's Commonwealth Scientific and Industrial Research Organisation	Australia	CSIRO_MK3.5	Gordon et al. 2002
GFDL	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.1	Delworth et al., 2006
GISS	NASA / Goddard Institute for Space Studies	USA	GISS-ER	Russell et al., 2000
IPSL	Institute Pierre Simon Laplace	France	IPSL-CM4	Dufresne et al., 2005
MIUB	Meteorological Institute of the University of Bonn, Meteorological Research Institute of Korea KMA, Model and Data group at MPI-M	Germany / Korea	ECHO-G	Legutke and Voss, 1999
MPI	Max Planck Institute for Meteorology	Germany	ECHAM5/MPI-OM	Jungclaus et al., 2006
MRI	Meteorological Research Institute	Japan	MRI-CGCM2.3.2	Yukimoto et al., 2001

4.2.4 Crops, soils and management practices

DSSAT was driven by the above climate scenarios. The crops, soils and management scenarios used were summarised in Table 4.2. Soil texture was sandy clay loam for all locations although with different characteristics representative of each study area as shown by the varying soil bulk density (BD), organic carbon content (OC), clay content percentage (CL) and silt content percentage (SI) of the top soils. Crop cultivars used were selected from those previously used in the past, with enough experimental data for crop model calibration. Similar cultivars in the DSSAT database were tailored to suit those shown in Table 4.2. Management practices included planting density, fertilizer amount and planting date. A planting density representative of those practiced by smallholder dryland farmers in each

location was used. Two fertilizer applications were used in combination with two planting dates to make four agronomic management scenarios. Agronomic management scenarios included “common” (an estimate of what local farmers commonly use) and “expert recommended” (what local experts recommend for farmers) agronomic practices. These were obtained from agricultural reports in respective countries. Explored fertilizer amounts shown in Table 4.2 translate common fertilizer (CF) amounts and those recommended by experts (RF). Two planting dates were considered, an early planting date (EP) corresponding to dates smallholder dryland farmers usually sow in response to the first rains, and a later planting date (LP) as recommended by experts. Combinations of two treatments of two fertilizer amounts and two planting dates were simulated in combinations as follows: EP with RF; EP with CF; LP with RF; LP with CF.

Table 4.2 Showing simulated conditions; agronomic management (planting density, fertiliser application amount and timing and planting dates), soils (Bulk density (BD), Organic Carbon (OC), Clay content (CL), Silt Content (SI)) and mean crop yields per location and crop.

			Big Bend				Mohale's Hoek				Lilongwe					
Soil			Sandy clay loam				Sandy clay loam				Sandy clay loam					
			BD	OC	CL	SI	BD	OC	CL	SI	BD	OC	CL	SI		
			1.6	0.3	30	11	1.4	1.1	21	37	1.5	0.8	28	9		
Management	Crop 1	Name	Maize hybrid: PAN473				Maize hybrid: PAN 473				Maize hybrid: MH 17					
		Mean yield (kg/ha)	1 700				2 200				2 700					
		Plant density (plants/ha)	30 000				33 000				37 000					
		Fertiliser application (kg N/ha)	Common		Recom-mended		Common		Recom-mended		Common		Recom-mended			
		Basal	7		16		10		25		35		23			
		Top	2		8		5		13		0		46			
		Planting dates	Early		Early - mid November				Mid November				Late November			
		Late	Early - mid December				Mid December				Late December					
	Management	Crop 2	Name	Sorghum: DC 75				Sorghum: PAN 845				Groundnut: Malimba				
			Mean yield (kg/ha)	1 800				850				700				
		Plant density (plants/ha)	60 000				60 000				45 000					
		Fertiliser application (kg N/ha)	Common		Recom-mended		Common		Recom-mended		Common		Recom-mended			
		Basal	4		20		8		25		0		0			
		Top	8		35		4		13		0		0			
		Planting dates	Early		Mid - late November				Mid November				Mid November			
		Top	Mid - late December				Mid December				Mid December					

Fertiliser was applied at planting (Basal) and at 4-5 weeks (Top). Two applications of fertiliser were simulated per crop and location i.e. common (as usually applied by farmers) and recommended (as suggested by experts). Planting dates included an early and late planting date per crop and location, simulated based on a date within a given period e.g. early – mid November being an early planting period for maize (PAN473) in Big Bend. Also

shown are simulated mean yields and planting densities per crop and location.

DSSAT was calibrated and validated for simulating crop yields under local conditions in study locations (Zinyengere et al., 2014). The locally calibrated and validated DSSAT model was used to simulate crop yields for the baseline (1961- 2000) and future (2046-2065) periods by changing climate parameters and holding constant all other factors (soils, cultivars, management strategies, CO₂ concentration). The effect of enhanced CO₂ was not investigated because it is still poorly understood and C4 crops, the major crops studied here (except groundnut) are known to have a very small response to the increase of atmospheric CO₂ (Long et al., 2006; Tubiello et al., 2007; Ainsworth and Ort, 2010; Gornall et al., 2010).

4.2.5 Confidence and uncertainty assessment

In this study, uncertainty in the projected impact of climate change on crops was assessed through methods similar to Ruiz-Ramos and Minguéz (2010) as follows:

1) *Sign of mean yield change* (negative or positive): This was done for each crop and location under study for each combination of SRES CO₂ emission, GCM and management scenarios. Coincidence of GCMs and management scenarios with the same sign of change across CO₂ emission scenarios was used to ascertain the degree of confidence in the direction of yield change.

2) *Comparisons of time series means*: Combinations of time series were compared for coincidence in projected yields through testing for significant differences in means. A two tailed t-test with unequal variance was used. For each location, emission scenario and management strategy, each time series was compared two by two with the other eight to represent the influence of GCMs on the overall coincidence of time series. For location, emission scenario and GCM, each time series was also compared two by two with the other seven to represent the influence of management strategies on overall coincidence of time series. The degree of coincidence was measured as the percentage of pairs showing a non-significant difference, at the 0.05 level of significance. A large degree of coincidence is associated with low uncertainty and *vice versa*. This also provided insight into the strength of the source of uncertainty (GCMs, management strategy etc.).

3) *Comparisons of yield variability*: Mean coefficients of variation were compared for CO₂ emission scenarios, GCMs and management scenarios, thereby identifying the sources of large uncertainty through high inter-annual variability.

4.3 Results

4.3.1 Climate change projections

Climate models consistently projected increased temperatures for all study locations. Projected temperature changes showed a mean increase of 1.7 - 2.4 °C, with a range of 1.3 – 2.7 °C (Table 4.3). Mohale's Hoek showed the highest projected increase in temperature, recorded under the A2 scenario while Big Bend had the least temperature increase. In contrast, the projected change in rainfall varied from one location to the other and in some cases depending on the CO₂ emission scenario. Projected mean rainfall changes were small, within a 7% average, although varying considerably across GCMs. Projected mean rainfall changes for Big Bend were a decline of -2.9% for the B1 scenario and an increase of +4.2% for the A2 scenario with a range of projections of -12% to +5% and -7% to +10% respectively (Table 4.3). Projected mean rainfall for Mohale's Hoek increased by +5.5% (B1) and +7% (A2) with a range of -1% to +16% and -1% to +18%. Mean rainfall in Lilongwe decreased only slightly with a range of -15% to +7% (B1) and -9% to +7% (A2) (Table 4.3).

Table 4.3 Mean change in projected climate between baseline (1961- 2000) and future (2046- 2065) for two CO₂ emission scenarios; low (B1) and high (A2) and the range (min-max) of projections across all nine Global Circulation Models (GCMs).

		Temperature (°C)			Rainfall (%)
		Average	Minimum	Maximum	
Big Bend	B1	2.1 (1.6-2.5)	2.2 (1.6-2.6)	2.0 (1.6-2.4)	-2.9 (-12 to 5)
	A2	2.0 (1.6-2.2)	2.1 (1.7-2.4)	1.9 (1.5-2.1)	4.2 (-7 to 10)
Mohale's Hoek	B1	1.8 (1.3-2.3)	1.9 (1.3-2.4)	1.9 (1.3-2.3)	5.5 (-1 to 16)
	A2	2.4 (1.8-2.7)	2.4 (1.8-2.7)	2.4 (1.7-2.6)	7.0 (-1 to 18)
Lilongwe	B1	1.8 (1.4-2.2)	1.7 (1.3-2)	1.8 (1.4-2.3)	-2.4 (-15 to 7)
	A2	2.2 (1.8-2.6)	2.1 (1.7-2.6)	2.3 (1.9-2.7)	-1.1 (-9 to 7)

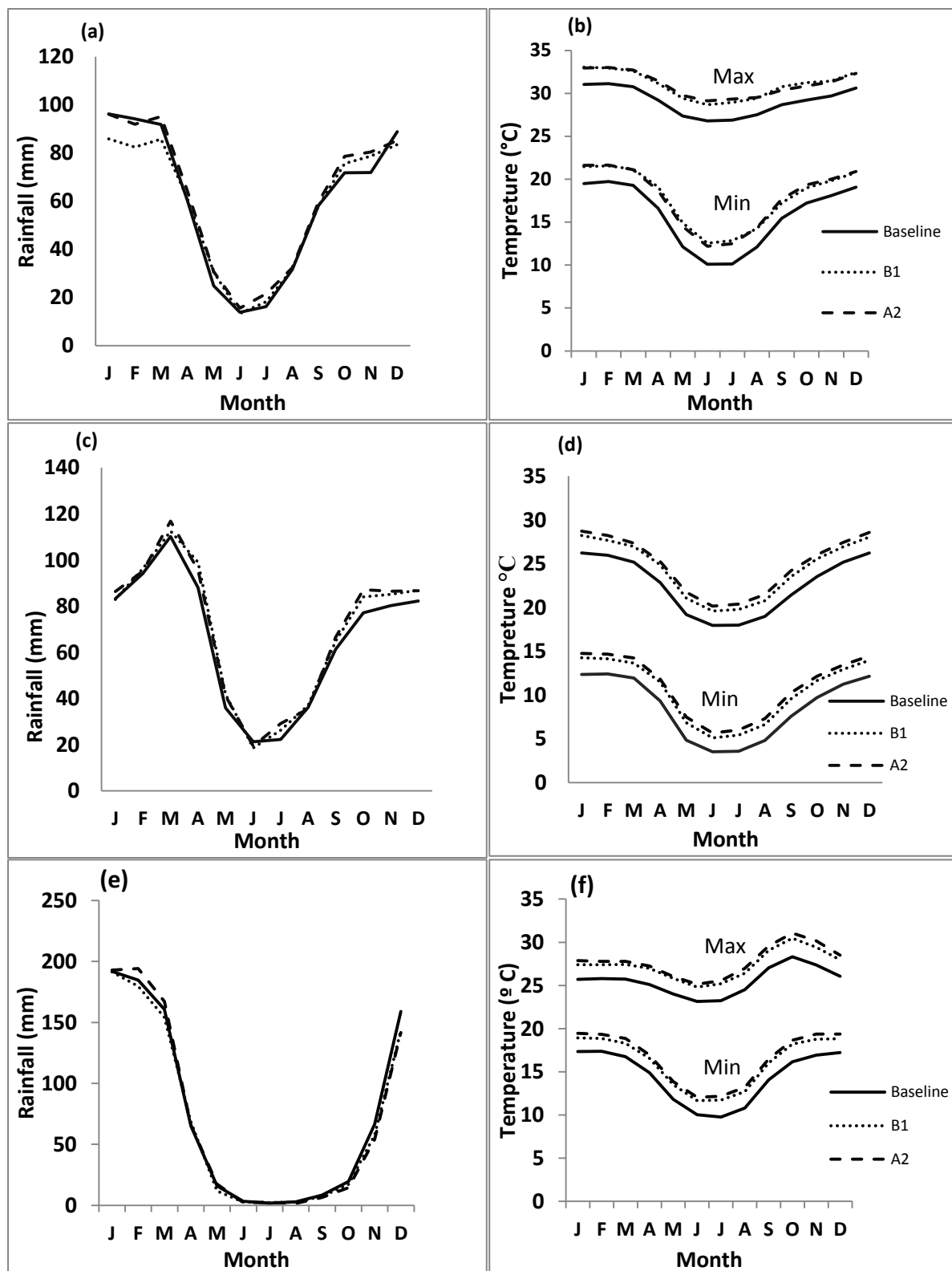


Fig 4.1 Projected ensemble mean monthly rainfall and temperature for Big Bend (a-b), Mohale's Hoek (c-d), and Lilongwe (e-f) for two emission scenarios: low (B1) and high (A2).

Climate projections exhibited the seasonality of temperature in all locations (Figure 4.1). Similarly, seasonality of rainfall was shown in the projections, with wet summers (October – April) and dry winters (May – August). Mean monthly rainfall for Mohale’s Hoek increased slightly during the summer cropping season (October – April), peaking towards the end of the season. Projected rainfall for Big Bend was higher than the baseline during the early months of the cropping season (October and November). Rainfall remained the same (A2) or declined during the perennial peak period of December, January and February (B1). Projected rainfall for Lilongwe peaked during the perennial peak period. Mean changes were negligible. While projected rainfall changes were variable and uncertain, the projected monthly temperature changes, showed strong signals and consistency, towards an increase (Figure 4.1).

4.3.2 Projected impacts on crop yields

Projected mean crop yield changes for Big Bend (Table 4.4) showed a consistent decline for maize and sorghum yields. Average yield decline across all scenarios was 20% and 16% for maize and sorghum respectively, with a range from -43.8 to -6% and -40% to +8.7%. Yield increase was projected for sorghum under the agronomic practice of late planting with common fertilizer (LP with CF). Sorghum yields under a scenario of early planting with common fertilizer (EP with CF) were the most severe, consistently above a decline of 25% across all climate scenarios.

Projected mean maize yield changes for Mohale’s Hoek were large and the most inconsistent across climate scenarios (-60.4% to +120%), albeit with a mean increase of 8% across all scenarios (Table 4.5). However, under scenarios where the management strategy of late planting (LP) was simulated, shown as LP with RF and LP with CF in Table 4.5, mean maize yields largely increased. Projected increase in mean maize yields averaged 18% and 15% for the two management scenarios respectively. The GISS climate model largely contributed to the variation in projected mean maize yield changes (-27% to +120%). Sorghum yields for Mohale’s Hoek were projected to increase from baseline, mostly above 25%, with an average increase of 51% across all scenarios. Under some scenarios, sorghum yields were projected to

increase by up to three times the baseline yields.

Table 4.4 Percentage mean maize and sorghum yield changes between baseline and future periods: Big Bend for nine Global Circulation Models (GCMs), four management treatments: early planting (EP), late planting (LP), common fertilizer (CF) and recommended fertilizer (RF), and two CO₂ emission scenarios: low (B1) and high (A2). GCMs references; see Table 4.1.

	EP with RF		LP with RF		EP with CF		LP with CF	
	B1	A2	B1	A2	B1	A2	B1	A2
MAIZE								
CCMA	-40	-34	-36.4	-28	-15.6	-18	-21.8	-14
CNRM	-17.7	-12	-10.5	-14	-20.6	-15	-12.5	-15
CSIRO	-32.6	-37	-14.3	-28	-30	-26	-13.4	-11
GFDL	-9.3	-4.7	-21.9	-15	-27.1	-22	-15.1	-7.4
GISS	-25.8	-20	-19.2	-16	-29.4	-18	-19	-16
IPSL	-19	-6	-21.3	-17	-11.5	-15	-9.6	-13
MIUB	-24.2	-25	-14.5	-16	-24.9	-25	-16.9	-13
MPI	-43.8	-24	-21.8	-24	-13.6	-23	-7.8	-15
MRI	-19.4	-12	-29.3	-22	-21.8	-20	-23.6	-19
SORGHUM								
CCMA	-39	-26	-40	-34	-28	-26	-13	-5
CNRM	-8	-10	-1.2	-10	-31	-30	8.7	6
CSIRO	-18	-28	-23.7	-27	-28	-28	-5.1	-14
GFDL	-9.9	0	-25	-16	-27	-26	-3.7	-1
GISS	-9	-9	-8.8	-6	-29	-30	2.5	1
IPSL	-19.1	-15	-9.6	0	-30	-32	6.2	6
MIUB	-12	-19	-23	-18	-31	-31	0	8
MPI	-26	-12	-18	3	-30	-26	-11	4
MRI	-21	-12	-28	-19	-30	-32	-10	-6
Legend								
		< -25	-25 to -15	-15 to -5	-5 to +5	+5 to +15	+15 to +25	> +25

Table 4.5 Percentage mean maize and sorghum yield changes between baseline and future periods: Mohale's Hoek for nine Global Circulation Models (GCMs), four management treatments: early planting (EP), late planting (LP), common fertilizer (CF) and recommended fertilizer (RF), and two CO₂ emission scenarios: low (B1) and high (A2). GCMs references; see Table 4.1.

	EP with RF		LP with RF		EP with CF		LP with CF	
	B1	A2	B1	A2	B1	A2	B1	A2
MAIZE								
CCMA	2.2	6.1	6.8	7.7	-18	-60.6	-13.4	-24.1
CNRM	10.4	11.2	25.9	23	-5.3	-1.5	14.7	27
CSIRO	2.8	0.6	10	5.9	-1	1.2	10.8	13.4
GFDL	1.3	-0.5	12.5	13.7	-11.9	2.5	-0.5	5.2
GISS	-5	8.2	61.8	68.2	-27	103	35.3	120
IPSL	7	11.6	10.5	16.2	1.6	-52	10.4	21.5
MIUB	4	1.6	30.6	29.2	-7.9	-8.9	11.5	17.1
MPI	-1.8	11	1.9	7.1	5.6	2.6	7	6.7
MRI	-6.1	-6.3	6	-5.7	4.4	8.6	13.3	-0.5
SORGHUM								
CCMA	149.5	1.3	93.7	21.6	187.9	69.8	58.0	39.1
CNRM	33.1	33.6	29.8	32.2	55.0	68.0	48.5	48.8
CSIRO	18.8	215.9	17.6	79.7	7.0	101.2	64.7	156.3
GFDL	14.9	17.6	8.8	25.8	72.0	82.6	48.5	48.5
GISS	88.1		44.2		77.2		213.8	
IPSL	15.5	28.8	11.3	26.6	47.2	56.1	65.3	64.7
MIUB	37.9	41.3	31.9	32.1	49.7	55.0	84.6	84.6
MPI	-9.4	12.5	-1.7	20.6	37.1	48.5	54.3	51.6
MRI	8.3	1.3	6.7	6.1	51.5	48.5	37.8	37.9
Legend	< -25	-25 to -15	-15 to -5	-5 to +5	+5 to +15	+15 to +25	> +25	

Projected impacts for Lilongwe were of a slight decline in mean maize yields and more pronounced decline in groundnut yields. Projections were consistent across all scenarios with an average decline of 5% for maize and 33% for groundnut, with a range of -11.3% to +2.9% and -51% to -20% respectively. Only one simulation treatment was made for the management practice of fertilizer application for groundnut. Simulations of 0 kg N/ha were made, following common and recommended practice in Lilongwe, hence only two scenarios were shown for groundnut.

Table 4.6 Percentage mean maize and sorghum yield changes between baseline and future periods: Lilongwe for nine Global Circulation Models (GCMs), four management treatments: early planting (EP), late planting (LP), common fertilizer (CF) and recommended fertilizer (RF), and two CO₂ emission scenarios: low (B1) and high (A2). GCMs references; see Table 4.1.

	EP with RF		LP with RF		EP with CF		LP with CF	
	B1	A2	B1	A2	B1	A2	B1	A2
GCMs	MAIZE							
CCMA	-5.3	-0.5	-5.6	-5.5	0	-0.5	-5.8	-4
CNRM	-5.6	0	-5.8	-3.4	-4.5	-5.6	-5.9	-4.6
CSIRO	-1.6		-2.6		-4.2		-4.6	
GFDL	-6	0.6	-9.2	-7.2	-7	-5.6	-11.3	-10
GISS	-2.8	-3.2	-5.3	-5.2	-5.3	-0.2	-5	-9
IPSL	-3.5	-5.9	-7.8	-4.3	-3.8	-6	-6	-3.7
MIUB	-5.1	-5.4	-6.5	-1.1	-4.4	-5.8	-2.6	-1.2
MPI	-2.6	2.9	-8.4	-5.9	-6.2	-3.1	-5.8	-3.7
MRI	0.7	-6.7	-5.5	-9.3	1.1	-1.8	-2.5	-7.6
	GROUNDNUT							
CCMA					-32	-51	-22	-35
CNRM					-29	-47	-30	-41
CSIRO					-35		-25	
GFDL					-40	-47	-20	-21
GISS					-35	-37	-23	-26
IPSL					-31	-32	-22	-22
MIUB					-42	-44	-35	-32
MPI					-26	-35	-26	-26
MRI					-49	-45	-27	-27
Legend	< -25	-25 to -15	-15 to -5	-5 to +5	+5 to +15	+15 to +25	> +25	

4.3.3 Uncertainty and confidence degrees

High agreement on the sign of yield change was found across all locations and crops except for maize in Mohale's Hoek (Table 4.4, 4.5 and 4.6). High coincidence was also found across management strategies (45 – 88%) despite the large disparity of climate projections from GCMs (Table 4.7). The mean degree of coincidence was highest in maize yield projections for all locations. Lowest coincidence of time series was found for EP with RF and LP with RF for sorghum in Big Bend and groundnut in Lilongwe, where less than half the time series had non-significant differences. Treatments of EP with CF for maize and sorghum in Big Bend showed 100% coincidence among time series. Average coincidence was low among GCMs scenarios, ranging from 19 to 52%. Lilongwe had the lowest agreement across time series for both maize and groundnut, averaging 25 and 19% respectively (Table 4.7).

Table 4.7 Degree of coincidence (percentage of time series showing non-significant differences). Represents percentage yield projection uncertainty per location and crops based on differences in time series by management strategy and GCM scenarios. Management and GCMs references: see tables 4.1 and 4.4.

	Big Bend		Mohale's Hoek		Lilongwe	
	Maize	Sorghum	Maize	Sorghum	Maize	Groundnut
Management						
EP with RF	70	42	66	71	81	42
LP with RF	56	45	89	67	97	49
EP with CF	100	100	86	77	91	-
LP with CF	91	68	68	72	83	-
Mean	79	64	77	71	88	45
GCMs						
CCMA	43	71	43	43	43	67
CNRM	29	43	29	29	0	0
CSIRO	43	57	29	43	0	0
GFDL	14	43	29	43	14	0
GISS	14	43	29	14	43	0
IPSL	43	57	43	43	14	0
MIUB	43	43	43	43	29	33
MPI	29	71	43	57	43	0
MRI	43	43	43	43	43	67
Mean	33	52	37	40	25	19

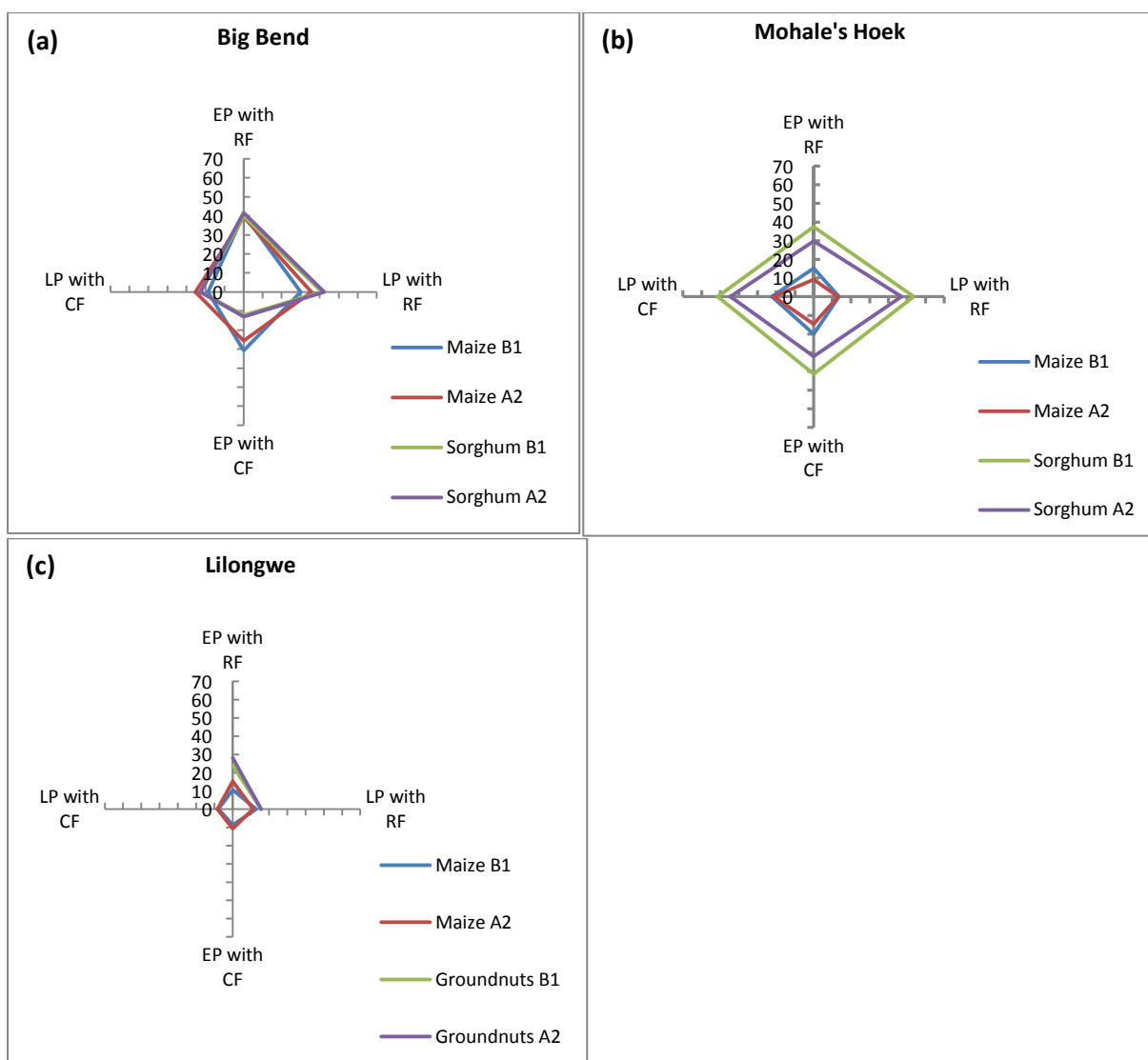


Fig 4.2 Mean percentage values of coefficient of variation. A measure of interannual variability of projected crop yields per locations and CO₂ emission scenarios B1 (low) and A2 (high), clustered by management strategy. Management references: see Table 4.4.

Yield response variation across all management strategies ranged from a mean CV of 7% to 53% (Figure 4.2). CVs for each management treatment were highest for sorghum in Mohale's Hoek, between 30 and 53%. Simulated CVs were also high for Big Bend, reaching up to 40% for maize and sorghum. Among the high CVs in Big Bend, were notably low CVs for sorghum (12 %) under EP with CF (Figure 4.2a). Similarly, yield variation was low for maize in Mohale's Hoek, particularly for the LP with RF and LP with CF treatments (Figure 4.2b). Overall yield variation was lowest in Lilongwe (7 – 28%), with groundnuts having higher CVs than maize. Clustering CVs by GCMs as shown in Figure 4.3 revealed high variation in sorghum yields for Mohale's Hoek, peaking at a CV of 70%. Big Bend had the second

highest CVs for both maize and sorghum of between 13 and 42%. Least variation was found for maize in Lilongwe (7 - 15%).

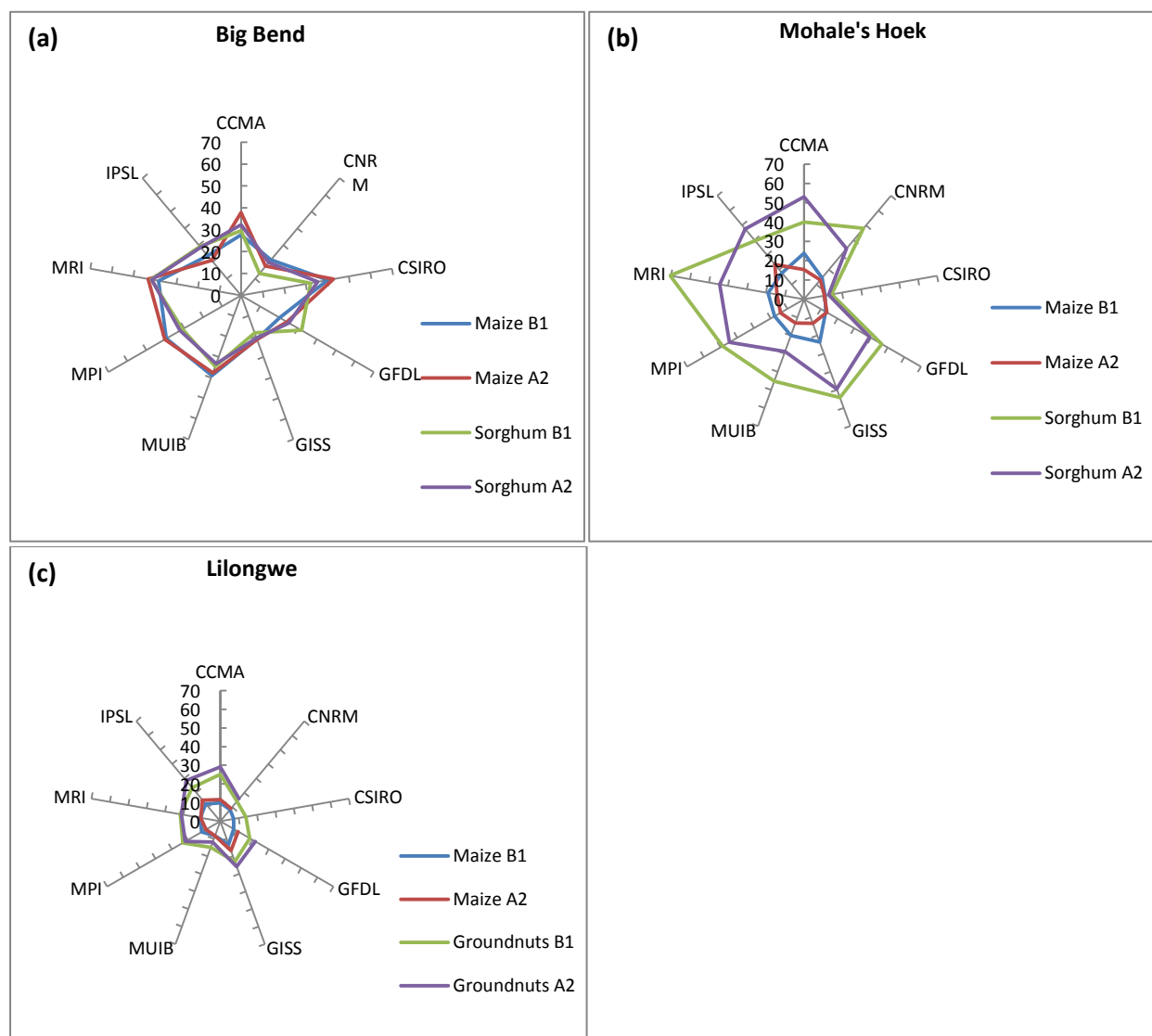


Fig 4.3 Mean percentage values of coefficient of variation. A measure of interannual variability of projected crop yields per locations and CO₂ emission scenarios B1 (low) and A2 (high), clustered by GCMs. GCMs references: see Table 4.1.

4.4 Discussion

4.4.1 Crop yield changes

The apparent effect of climate change on crops in this study was a decline in crop yields due to higher temperatures which potentially reduced the crop growth season and thereby reduced the yield in the arid area at Big Bend. This effect was however compensated in the high altitude and cooler location (Mohale's Hoek), leading to increased mean yields. Maize and sorghum yields in Big Bend were shown to be negatively affected by temperature increase due to climate change. Being a dry area, increase in temperature along with little or no increase in future mean total rainfall, Big Bend becomes even less conducive for rain fed maize and sorghum. Maize and groundnut yield changes in Lilongwe were also projected to be negative. However, maize yield changes were small compared to the other locations. This is due to the moderate Lilongwe climate and the smaller changes projected for rainfall and temperature. Despite the moderate changes in climate, groundnut yields were severely affected, with an average decline in yield of 33%. A lack of fertilizer application (P and K) as is common with smallholder communities in Lilongwe may lead to larger negative impacts for groundnut. Furthermore, studies have shown that increasing temperature can dramatically reduce groundnut yields i.e. 31% in Bulawayo, Zimbabwe (Dimes et al., 2007) and by up to 36% under normal conditions (Kaur and Hundal, 1996) and 10% under optimal growing conditions in India (Hundal and Kaur, 2006). This is despite that CO₂ fertilisation can increase groundnut yields by up to 8% (Dimes et al., 2007). Although average temperatures are moderate in Lilongwe compared to the other study locations, average temperatures during the growing season in Lilongwe (22 °C), are within the optimum range for reproductive growth of groundnut, i.e. between 22 and 24 °C (Ong, 1984). Therefore, temperature increase of 2 °C estimated for Lilongwe would have a significant effect on yields. Simulated impacts for Mohale's Hoek showed a mix of positive and negative impacts for maize and positive impacts for sorghum. Positive impacts were more consistent across GCMs scenarios for some management scenarios. Lesotho being a high altitude country that perennially experiences cold related crop yield losses benefits from favourable crop growth conditions created by warming temperatures. Mean minimum temperatures during crucial growth periods (grain filling) were projected to rise above 10 °C (base temperature for some maize varieties) thereby reducing crop yield losses due to dormancy, slowed grain filling and cold stress. Coupled with the peaking of rainfall during the same period (February, March and April),

conductive conditions for crop growth and increased yields were created. Sorghum being more tolerant to heat and water stress benefited even more from a warmer and wetter climate in Mohale's Hoek (Table 4.5). However, large responses of up to three times the baseline yields could be related to an over-sensitive sorghum model or effects beyond the bio-physical crop model e.g. the varying climate scenarios.

Broadly negative impacts projected for crops in Big Bend and Lilongwe are largely consistent with studies in the region, which are predominantly large scale. Jones and Thornton (2003) and Thornton et al. (2011) projected that maize yields will likely decline in most countries in southern Africa by an average of 10% and 16% respectively by mid-21st century. Parry et al. (2004) projected a decline of 5 – 30% in cereals yields and Schlenkler and Lobell (2010) projected a decline of up to 22%, 17% and 18% for maize, sorghum and groundnuts respectively. In a study involving eight countries in southern Africa, Hachigonta et al. (2013) also broadly projected a decline in crop yields. Similarly, in a local study in South Africa, Walker and Schulze (2008) projected an average decline of maize yields of 30%. Projections of increased crop yields as a result of climate change in Lesotho have largely been unexplored. Recent studies by Malebajoa (2010) and Gwimbi et al. (2013) suggest a decline in maize yields in Mohale's Hoek by 2050 of more than 25% and a decline in sorghum yields of up to 10% and 25% respectively. However, Gwimbi et al. (2013) give indications of possible sorghum yield increase in other parts of Lesotho. In this study, yield gains for maize and sorghum were robustly apparent. While results from this study globally agree with large scale studies in the region, it draws out the location and crop specificity of impacts not necessarily accounted for by large scale studies. In Mohale's Hoek, the study showed that impacts are likely to evolve differently from those presented by common national and regional projections. It was therefore apparent that broad-brushed recommendations for suitable strategies to adapting crop production to climate change in dryland systems were not sufficient. Finer scale investigations will be required.

4.4.2 Agronomic management strategies

Defining adaptation strategies for an uncertain future is a challenge. However, this study showed that valuable information regarding the potential of locally practised agronomic strategies for adaptation to climate change can be obtained through high resolution

simulations. The study showed that for most locations and crops, despite the incoherent climate projections from GCMs (rainfall), there was a considerable coincidence and agreement in simulated yield impacts per agronomic practise (Table 4.7). Furthermore, agronomic strategies that have a strong influence (positive or negative) on the overall yield response to climate change can be identified e.g. the practice of early planting with common fertilizer application (EP with CF) in Big Bend, which had very low yield variation (Figure 4.2a), and the practice of late planting with recommended fertilizer (LP with RF) or common fertilizer (LP with CF) for maize in Mohale's Hoek (Figure 4.2b). These practices corresponded to strong positive impacts on maize yields in Mohale's Hoek (Table 4.5) and strong negative impacts for maize and sorghum in Big Bend (Table 4.4).

The study suggested that in some locations, agronomic strategies practiced by farmers may exacerbate the negative impacts of climate change (Big Bend). The common practise of planting early exposes crops to unfavourable growth conditions. Furthermore, the application of high fertiliser amounts (RF) in Big Bend is unlikely to have a significant positive effect on yields owing to the limitations placed by low available moisture e.g. through nitrogen being stranded on dry surfaces. High fertiliser amounts (RF) under uncertain and unreliable moisture conditions can also cause fertiliser injury thereby affecting yields (Dowling, 1998). Sorghum however, could suffer less due to its water stress resistance especially in the absence of the detrimental high fertilisation i.e. under common fertilisation (CF) as shown in Table 4.1. In other locations, agronomic practices provided yield benefits. Late planting of maize in Mohale's Hoek provided the opportunity to take advantage of the peaking of rainfall towards the end of the season (February, March, April), regardless of the fertilizer amounts applied. Late planting (LP) coincided with high moisture content which in cooler areas increases the chance of losing nitrogen to volatilization. Losses of up to 44% of applied nitrogen have been reported when fertilizer has been applied during moist periods in cool regions (Jones et al., 2013). As such, the effect of high fertiliser amounts (RF) would have been reduced. Where early planting occurred, coinciding with lower rainfall and thus lower moisture levels, the effect of fertilisation was more important, in this case leading to stronger negative yield change under lower fertiliser amounts (CF). It should be noted however that yields of crops differ considerably depending on a number of complex interactions of management, climate, soil properties and other environmental conditions that were not fully explored in this chapter and may warrant further investigation.

Insight about the potential contribution of agronomic strategies of local farmers to climate change adaptation is difficult to obtain with coarse scale studies as indicated by Lobell et al. (2008) and Thornton et al. (2011). Finer scale studies can provide more detailed information. In Lesotho, planting late is not a common practise or considered a beneficial alternative, yet through fine scale simulations, this study showed that late planting could provide yield benefits as the climate changes. This kind of information provides better understanding of areas for further assessments and stakeholder engagement towards identifying agronomic strategies better suited to changing climates in particular farming communities and possibly fostering adoption.

4.4.3 Uncertainties and limitations

Overall, while uncertainty remains a factor in this study, a clear trend was established, decreasing crop yields in Big Bend and Lilongwe and increasing crop yields in Mohale's Hoek. GCM scenarios tended to be the primary influence on total uncertainty in studies that used a single crop model (Challinor et al., 2009b). This was apparent in our study, where yield variation driven by GCM scenarios was high (Figure. 4.3b). However, our study also demonstrated that agronomic management scenarios can contribute significantly to overall uncertainty. In Mohale's Hoek (sorghum) and Big Bend (maize and sorghum), changing the agronomic strategies influenced uncertainty considerably as shown by high CVs of up to 40% (Figure 4.2a and 2b). For Big Bend, this was almost as high as variations introduced by GCM scenarios. Emission scenarios on the other hand weren't as important for most locations and crops as shown by the limited differences in simulated variations (Figure 4.2 and 4.3). Exploring uncertainties from management scenarios in addition to GCMs is vital in impact assessment.

A number of limitations remain and could form areas for further research. This study did not investigate the direct effect of increased CO₂ on crops. Modelling the effect of increased CO₂ on various crops is still a matter of debate (Long et al., 2006; Ewert et al., 2007; Tubiello et al., 2007; Ainsworth and Ort, 2010) and predictions of crop production under elevated CO₂ and climate change conditions require more research (Tubiello and Ewert (2002); Tubiello et al., 2007). However, some studies have suggested that C4 plants (e.g. maize and sorghum studied) do not respond much to higher ambient CO₂ (Sultan et al., 2013), while others state

that elevated CO₂ may significantly reduce the negative impacts of climate change on C3 crops (Tingem et al., 2008). In the case on Malawi where maize yield decline was small, averaging -5 %, a small positive effect of enhanced CO₂ could mean the difference between a decline in yields and no change at all. On the other, while a stronger effect could be expected on groundnut, a C3 under enhanced CO₂ effects, some studies have shown that despite possible positive effects of up to an 8% increase in yields with elevated CO₂, the combined effect of climate change (increased temperature and declining rainfall), can lead to a decline of 30% in groundnut yields (Dimes et al., 2007). Prasad et al. (2003) also confirm that the effect of temperature on groundnut yield will have a significant negative impact regardless of any potential effect of enhanced CO₂. While not addressed in this study, the modelling of crop responses to elevated CO₂ is a major source of uncertainty in climate change impact studies (McGrath and Lobell, 2013), more insight could be provided through further studies.

Although crop modelling contribution to uncertainty was sampled by simulating various agronomic practices, our study used a single crop model thereby limiting the quantification of uncertainty. Future studies may consider the use of multiple process-based crop models. Such a process is currently underway with the Agricultural Model Intercomparison Project (AgMIP) and can improve the quantification of uncertainty in impact studies (Rosenzweig et al., 2013). Other studies suggest the use of different classes of crop models in combination i.e. mechanistic and empirical models so as to better characterize different modelled aspects and different sensitivities for a fuller picture of uncertainties in crop climate responses that single class ensembles as those by AgMIP may not capture (Estes et al., 2013; Holzkämper et al., 2015; Soltani et al., 2016). While an assessment with multiple crop models was difficult to carry out in our study given data and time limitation, future studies that use single crop models and simulate crop response to agronomic management strategies could perform a sensitivity analysis to get a clearer understanding of how the model responds to the different agronomic practices, over and above the calibration of the crop model.

4.5 Conclusion

Through a location specific assessment, this study was able to demonstrate that impacts of climate change on crops in southern Africa will be significant, but vary across locations and crops. Some places will be impacted negatively while other places will benefit depending on

crop species. Benefits are likely in Mohale's Hoek, a high altitude area where temperatures are cooler than most of the region. Through simulating location specific agronomic practices of farmers, the study showed that on farm practices could exacerbate the impacts of climate change or help to take advantage of potential benefits. There exists a high confidence in the direction of crop yield changes due to climate change (positive or negative), except for maize at Mohale's Hoek and that existing uncertainties emanate mostly from climate projections and agronomic management scenarios.

The demonstrated location and crop specificity of the impacts of climate change in the region demand site-specific design of adaptive measures with perspectives that focus on the vulnerable dryland farmers, especially smallholders who are considered the most vulnerable. Separating projections of impacts of climate change by location and crop and simulating locally relevant agronomic practises helps avoid the recommendation of one-size-fits-all adaptation strategies brought about by broad-brush conclusions made over large areas. As such, it is important to investigate the potential of various locally practised agronomic management strategies for the efficient adaptation of dryland farming to climate change. This can be done with explicit consideration of the bio-physical and socio-economic conditions that local dryland farmers in the region operate. Location specific study along with a bottom-up approach can provide finer information to feed into outcomes of larger scale studies and provide an avenue for developing relevant policies that support autonomous responses by local farmers to climate change.

CHAPTER 5

UTILITY OF AGRONOMIC MANAGEMENT STRATEGIES FOR ADAPTING DRYLAND CROP PRODUCTION TO CLIMATE CHANGE IN SOUTHERN AFRICA

Owing to perceived vulnerability of African agriculture to climate change, there is a growing interest in identifying strategies for adaptation. This study investigated the usefulness of on-farm agronomic adjustments for adapting dryland crop production to climate change in southern Africa. Three agronomic strategies (choice of planting date, planting density and fertiliser amount) were tested separately and in combination (a total of 294 combinations) to assess effectiveness for adaptation in contrasting locations in southern Africa. The DSSAT CERES-maize model was used to simulate maize yields in response to climate and agronomic strategies in three locations: Mohale's Hoek in Lesotho; Big Bend in Swaziland; and Lilongwe in Malawi. Downscaled climate projections from four GCMs for the A2 SRES emission scenario were used to drive the crop model for a baseline (1971-2000) and future (2046-2065) period. Results showed that agronomic adjustments can be useful for adaptation in drylands of southern Africa depending on location. In cool and moderate climates (e.g. Mohale's Hoek and Lilongwe), future maize yield benefits of up to 15% can be achieved through modest fertiliser increases and appropriate timing of planting. In heat and water stress prone areas (e.g. Big Bend), there are fewer options to adapt through agronomic adjustments. Future yields declined by up to 34% under some agronomic strategy combinations in Big Bend and no agronomic options alleviated the negative impacts of climate change. Such areas will require more investment e.g. irrigation and livelihood diversification to promote food security and preserve livelihoods. The study demonstrated the need for assessing multiple agronomic options together and factoring location specific conditions of farming communities for better understanding of adaptation potential and targeting of adaptation support.

5.1 Introduction

Adaptation is a key factor that will shape the future severity of climate change impacts on crop production (Lobell et al., 2008; IPCC, 2014), and continues to receive increasing attention. Technology progress in recent times may make it appear that adaptation choices for farming communities are plentiful. This is not necessarily so. It is widely accepted that adaptation options that are likely to be the most effective are either investment or time demanding, as is the case for irrigation and the breeding of improved crop varieties respectively (Rosenzweig and Parry, 1994; Araus et al., 2008). Smallholder dryland farmers in low income regions such as southern Africa cannot easily access (partly due to costs) and adopt some technologies in order to increase and stabilise yields under climate change and variability. In regions such as these, it is important to explore and take advantage of easily accessible strategies for adaptation to climate change.

Farmers in Sub Saharan Africa (SSA) have learnt to cope with climate variability through various locally appropriate strategies (Cooper et al., 2008; Twomlow et al., 2008; Vincent et al., 2013). Their most immediate response is to adjust on-farm agronomic management strategies to suit prevailing or expected climatic conditions (Nhemachena, 2007; Below et al., 2010). Low cost agronomic management changes at the tactical level e.g. adjustments in sowing dates, fertilisation, and in-field water management can offer farming communities cheaper and easily accessible options for adapting to climate change as demonstrated by Lehmann et al. (2013) and Folberth et al. (2014). However, studies that seek to identify agronomic strategies suitable for adapting crop production to climate change in southern Africa are limited. This stems partly from the fact that most studies are performed at large scale owing to the need to inform national or regional policies, the demands of Global Circulation Models (GCMs), and a lack of data and resources for location specific investigations.

Large scale adaptation studies that include southern Africa e.g. Waha et al., 2013 (sequential cropping and optimised sowing dates), Folberth et al., 2014 (fertilisation and fallow/rotation) and Lebel et al., 2015 (In situ rain water harvesting) have shown the adaptation potential of various agronomic strategies. However, these studies were performed without detailed consideration of local conditions. In cases where location specific studies have been carried out in southern Africa, the focus has been on a narrow subset of management options and limited locations. Such studies miss out on possible co-benefits that can arise between different agronomic strategies, and do not provide insight into the varying adaptation potential of agronomic strategies between locations. Abraha and Savage (2006) showed that shifts in planting times can have positive benefits on maize yields under a changing climate.

However, this study was limited to investigating only planting dates in one location i.e. Cedara, South Africa. Walker and Schulze (2006) also performed a study in one location in South Africa (Potshini) to test two management strategies (fertiliser and tillage). Although the study investigated two strategies in combination, simulated maize yields did not show any response to changes in tillage practices due to model limitations. Therefore, the study was unable to investigate or demonstrate potential co-benefits from multiple agronomic strategies. Furthermore, the different effects of management choices between locations were not studied. Model based adaptation studies carried out in southern Africa do not explicitly incorporate socio-economic contexts of the study areas in their assessments. This is a considerable limitation in understanding the usefulness of modelled adaptation practices in drylands, since autonomous adaptation actions occur in the context of capital endowments of the farmers in a given area (i.e. human, social, financial, physical and natural). More recent localised studies e.g. Rurinda et al., (2015) have similar limitations.

Despite the limitations of the climate-crop modelling approach for climate change impact and adaptation studies, it can allow for the exploration of multiple management variables, separately or simultaneously, at one or in multiple locations (Lehman et al., 2013). The approach can therefore provide insight on the effect of not only each management strategy, but also on a combination of strategies. In this study, it was postulated that the usefulness of agronomic management strategies for adapting to climate change in dryland systems of southern Africa, can be better understood if a broad set of management options are investigated separately and simultaneously (in combination), defining and incorporating the local conditions of target farming communities (particularly the varying socio-economic endowments of local farming households) and providing insight into differences in management adaptation possibilities between different locations.

The aim of the study was to demonstrate the value of investigating multiple location specific agronomic options in contrasting locations as a way of identifying/exploring useful adaptation options to climate change in southern Africa. Seven fertiliser applications, seven planting dates and 6 planting densities were each tested separately and in combination (up to a total of 294 agronomic alternatives). The DSSAT CERES-maize model was run to simulate maize yields in response to these agronomic strategies, driven by downscaled climate projections from four GCMs for the SRES A2 CO₂ emission scenario for a baseline (1961-2000) and future period (2046-2065). The study was carried out in three locations; Big Bend, a low lying, hot and dry area where household reliance on crop production is low; Mohale's Hoek, located in a high altitude area, with a cool climate; Lilongwe, a mid-altitude area with moderate temperatures, high rainfall and households that rely heavily on crop production for food security and livelihoods. The locations were selected their distinctly diverse agro-ecological conditions and agronomic practices to represent a wide range of conditions that

5.2 Data and methods

5.2.1 *Climate and socio-economics circumstances of each location*

In-order to better ascertain suitable agronomic management options for crop production under climate change in farming communities, specific conditions under which crop production is being practiced need to be understood. Bennett et al. (2012) state that farmers' choice of cropping systems and tactical decisions are based on biophysical and socio-economic factors e.g. economic market trends, availability of inputs such as seeds, fertilizer and pesticides and current land-use etc. This section provides the local context under which crop production is practised in each of the study locations. Bio-physical and socio-economic data was obtained from household surveys carried out in Maphutseng, in Mohale's Hoek district (2573 households), Mpolonjeni, near Big Bend (3212 households) and in Chitekwere in Lilongwe district (1156 households). All socio-economic data presented in this study refer to these communities in the study locations. Information was obtained from questionnaires carried out as part of a study funded by the International Development Research Centre (IDRC), titled: *Strengthening Evidence-Based Climate Change Adaptation Policies, (SECCAP)* implemented by the Food, Agriculture and Natural Resource Policy Analysis Network (FANRPAN) during the 2012/2013 agricultural season (see Annex 1). Table 5.1 presents a subset of these data extracted via SPSS, considered to be relevant to the understanding of farming and the on-farm tactical choices in study locations.

5.2.1.1 *Climate*

Big Bend (26.85° S, 31.92° E) is located in the south east of the Kingdom of Swaziland. The region is low lying, hot and dry. It lies at an altitude of 138m above sea level (asl.), with average annual temperature of 22 °C and summer temperatures that regularly reach 35 °C. Rainfall is low, averaging 507 mm during the crop growing period (October – April) annually. Mohale's Hoek (30.15° S, 27.47° E) is located in the south western lowlands of the mountainous Kingdom of Lesotho at an altitude of 1620m asl. Lesotho experiences a climate colder than most of southern Africa and cold related crop yield losses are common. Average annual temperature in Mohale's Hoek is 15.6 °C and mean minimum temperature is below 10 °C. Annual rainfall is moderate to low, averaging 602 mm during the perennial crop growing period. Lilongwe (13.78°E, 31.77°S) is located in the mid-altitude region of Malawi, at

1229m asl. Temperatures are moderate, with an annual average of 19°C. Rainfall in Lilongwe is uni-modal, averaging 810 mm during the growing season.

5.2.1.2 Household socio-economics

The importance of crop production to food security and livelihoods varies across the study locations depending on their socio-economic capital endowments. Production is carried out on small pieces of land averaging 2ha in Big Bend and Lilongwe and 3ha in Mohale's Hoek. Maize is the staple crop and the most cultivated crop. Crop production is an important livelihood activity, more so in Lilongwe than in Big Bend and Mohale's Hoek. 96.8%, 62%, and 57% of households in Lilongwe, Big Bend and Mohale's Hoek consider crop production their major livelihood activity respectively. Less than 5% of the households in Big Bend and Mohale's Hoek and up to 25% of households in Lilongwe draw their major income from crop production. Households in Big Bend rarely fully utilise their land for crop production (only 47% of the land was cultivated). Large proportions of households (33%) perform off-farm formal work for incomes but still fully utilise their land. Households in Mohale's Hoek also rely strongly on off-farm work for incomes (37% of households earn incomes from informal work). Households in Lilongwe regularly utilise all their land. 56% of the households in Lilongwe obtain their major incomes from agriculture.

Most of the household heads in Lilongwe are unemployed (87.5%), despite being on average the youngest across the three locations with an average age of 43 years. Although most households in the study locations follow a male headed household model, Lilongwe has about 30% more male headed households (85% of households) compared to the other locations. Household heads in the study locations on average have a primary school education, heading an average household of 6, 4.5 and 5 people for Big Bend, Mohale's Hoek and Lilongwe respectively.

Farming households in Big Bend invest little in crop production. Only 8% of households reinvest major portions of their income into farm inputs (seeds and fertilisers). Instead, most households receive their farming inputs from external sources (government, NGOs, etc.). Furthermore, they have fairly good access to finances and physical assets. 89% of households receive financial remittances from family. 18% of households own a car, 9% own a tractor and about half of the farmers own more than two oxen. While households in Mohale's Hoek also invest very little in farm inputs (only 5% of households), they however, do not have access to external sources of farm inputs. Only 6.6% and 15% of farming households in Mohale's Hoek have access to external financial services and family remittances respectively.

However, 73% of households in Mohale's Hoek have access to more than two cattle and 56% apply at least a bag of fertiliser on their fields.

Table 5.1 A selection of household (HH) endowments and activities in Big Bend, Mohale's Hoek and Lilongwe based on demographics, assets, livelihood activities, access to production inputs, finance, information and coping strategies.

Endowments/activities	Big Bend	M's Hoek	Lilongwe
Demographics			
Average HH size	6	4.5	5
Mean age of HH head	50	52	43
Gender of HH head			
Male	51%	56%	85%
Female	49%	44%	15%
Average education of HH head	Primary	Primary	Primary
Unemployed HH heads	N/A	74%	87.5%
General			
HH median land size	2ha	3ha	2ha
HH that planted all their fields	47%	99%	82.9%
Livelihoods and employment			
HHs' major livelihood is crop production	62%	57%	96.8%
HHs with crops as major income source	2.3%	3%	25%
HHs major source of income	Formal work (33%)	Informal work (37%)	Agriculture (56%)
Access to production Inputs			
HHs apply >50 kg/ha fertiliser	N/A	56%	47%
HHs with external access to seeds	51%	0.08%	0%
HHs' major use of income is farm inputs	8%	5%	21.7%
Access to external support			
HH has access to external financial services	N/A	6.6%	11%
HHs with family support	89%	15%	35%
HHs that receive support for farm inputs	N/A	3.8%	45%
Assets			
HH Owns car	18%	N/A	0.5%
HH Owns tractor	9%	N/A	0%
HH with more than 2 oxen	51%	73%	5%
Coping strategies			
HH practices seasonal migration	56%	3%	21%
HH consumes or sells seed	59%	7.4%	22%
HH consumes or sells large livestock	22%	9.2%	20%
Access to information			
HHs environmental awareness sessions	23%	29%	58%
HHs has access to crop extension services	0%	1.4%	16%

Households in Lilongwe have poor access to external financial services (only 11% have access) but have better access to external sources of farm inputs (44.2% of households). A fair portion of households invest their income into acquiring farm inputs (21.7%) and receive family remittances (35%). Households in Lilongwe are also poorly endowed in physical assets (car, tractor and cattle) but have better access to information through environmental awareness programs and extension services (although access to extension services is still quite low. Only 16% of households received regular extension visits). More households in Big Bend exercise far-reaching coping strategies to unfavourable climate than in Mohale's Hoek and Lilongwe. 56%, 59% and 22% of households regularly migrate temporarily (up to 3 months), consume seed and/or sell cattle respectively. In Mohale's Hoek and Lilongwe, the corresponding household proportions are 3%, 7.4% and 9.2% and 21%, 22% and 20% respectively.

5.2.2 Climate data and scenarios

Observed climate data was obtained from meteorological departments in Lesotho, Malawi and Swaziland, accessed through agreements with the Climate System Analysis Group (CSAG) at the University of Cape Town and under the SECCAP project. Climate data consisted of daily rainfall and daily maximum and minimum temperatures for a 30 year period 1971-2000, collected at the nearest weather stations in each study location. A more detailed description of the physical conditions of these locations is provided by Zinyengere et al. (2015). Gaps in climate records varied according to station, ranging from a few days to months and were filled with a WGEN based weather generator (Richardson and Wright, 1984) in Weatherman v4.5 (a component of the DSSAT CERES-maize model). Daily solar radiation records were estimated based on the approach by Allen et al. (1998), using minimum and maximum temperatures, Julian day, latitude and altitude.

Table 5.2 Projected change in annual maximum (max) and minimum (min) temperatures and annual total rainfall (%) for Big Bend, Mohale's Hoek and Lilongwe between baseline (1961-2000) and future (2046-2065) periods from four GCMs under the SRES A2.

	Big Bend				Mohale's Hoek				Lilongwe			
	CCMA	GFDL	MPI	IPSL	CCMA	GFDL	MPI	IPSL	CCMA	GFDL	MPI	IPSL
Max (°C)	2.2	2.1	2.1	2.0	2.6	2.6	2.6	2.6	2.7	2.3	2.3	2.3
Min (°C)	2.4	2.3	2.1	1.9	2.6	2.5	2.5	2.6	2.6	2.2	2.1	2.2
Rainfall	3.6	10.4	3.6	-7.1	10.1	2.5	0.4	7.6	-2.1	-0.5	-2.3	-4.9

Future climate scenarios were generated from four GCMs i.e. CGCM3.1 (T47) (Flato and Boer, 2001), GFDL-CM2.1 (Delworth et al., 2006), MPI-ECHAM5 (Jungclaus et al., 2006) and IPSL-CM4 (Dufresne et al., 2005) from the World Climate Research Programme's

(WCRP's) Coupled Model Intercomparison project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007). The models are referred to as CCMA, GFDL, MPI and IPSL respectively in this study and selected in order to show a wide range of rainfall projections. GCMs data was downscaled to a climate station in each study location using Hewitson and Crane (2006) self-organising maps (SOMs) approach for a baseline (1961–2000) and future (2046–2065). The SRES A2 emission scenario was used to represent the upper bound of projected future temperature changes. Atmospheric CO₂ concentrations were kept at a constant level of 400ppm. The effect of increasing CO₂ on C4 crop yields is either very small or a matter of continuing debate (Long et al., 2006; Tubiello et al., 2007). Therefore, the effects of enhanced future CO₂ concentrations were not considered.

Projected climate changes from the four GCMs are summarised in Table 5.2. Projections show a consistent mean annual temperature increase (maximum and minimum) across all locations, averaging 1.9 - 2.7 °C with the largest mean increase projected for Mohale's Hoek and the lowest projected for Big Bend. Rainfall projections were inconsistent for Big Bend, with projections of both decrease and increase (-7.1 to 10.4), and largely of increase in Mohale's Hoek (up to 10.1%) and a small decrease in Lilongwe (less than 5%).

5.2.3 DSSAT CERES-Maize

The Crop Estimation through Resource and Environment Synthesis crop model for maize (CERES-Maize), a component of the Decision Support System for Agrotechnology Transfer (DSSAT v4.5) Jones et al. (2003) was used. DSSAT is a family of crop models that simulate daily crop development and complex interactions with the farm-level environment using biophysical processes. Inputs required to run the model include; local weather data (daily rainfall, minimum and maximum temperatures, and solar radiation), a detailed soil profile, genetic coefficients describing the specific maize cultivar, and crop-management practices (e.g. planting dates and fertiliser applications). CERES-maize has been recently applied for climate change impact studies in southern Africa by Jones and Thornton (2003), Chipanshi et al. (2003), Walker and Schulze (2008), Thornton et al. (2011), Zinyengere et al. (2014) among others. Maize cultivars applied in this study were those used by Zinyengere et al. (2014) i.e. PAN473 for Big Bend and Mohale's Hoek and MH17 for Lilongwe, parameterised according to Zinyengere et al., (2015), who calibrated and tested the DSSAT model for simulating crop yields in dryland conditions under data limitations common in southern Africa. Simulated soils consisted of 11% silt and 30% clay at Big Bend and 38% silt and 23% clay at Mohale's Hoek. Corresponding percentages were 9% silt and 28% clay on simulated shallow Lilongwe soils. Soil organic carbon was 0.3%, 1.1% and 0.8% for Big Bend, Mohale's Hoek and Lilongwe respectively (Zinyengere et al., 2015). Farmers in

southern Africa (and locations under study) cultivate a wide variety of soils using varying seeds, and agronomic practices. Furthermore, the model does not take into account pests, diseases and problematic soil conditions (such as salinity and acidity). As such, modelled conditions will not be the exact conditions under which farmers in the study areas operate. However, this study remains directly valuable to farmers in the study areas, granting that responses to the modelled conditions and strategies are aligned to the farmers' conditions and practices.

Over and above the calibrated conditions applied in this study, from Zinyengere et al., 2015, an exercise examining the response of simulated maize cultivars to climate change and agronomic management options was carried out. This was done to provide a simple initial background understanding of crop response to climate change via a simple step change of climate, before the nuanced effect introduced by the multi-model ensemble projections and to confirm the value of investigating agronomic strategies in combination. The effect of climate change on long term yields was investigated using the CERES-maize model by perturbing historical climate data (1971-2000) by a predetermined amount while holding all other parameters constant. Historical daily climate was perturbed by raising daily minimum and maximum temperature by 1 °C from 0 °C to 3 °C and multiplying daily rainfall by a 10% change each from -20% to 20%. This was done using the environmental modification parameter within CERES-maize. Details of simulations for agronomic management strategies are shown in section 2.4.1.

5.2.4 Agronomic management strategies

Three agronomic management strategies were selected for the modelling exercise, namely, fertiliser amount application, choice of planting date, and choice of planting density. These strategies were selected because they are among some of the common practices in smallholder dryland systems in southern Africa and form part of the first level responses by farmers to prevailing or expected climatic conditions (Nhemachena et al., 2007). The strategies were also selected because they are available, accessible, suited for drylands applications in study locations, and within the crop model limitations. Agronomic strategies were informed by literature and expert advice. The number (n) of simulated management variables per strategy were 7 fertiliser applications, 7 planting dates and 6 planting densities, codified for fertiliser (F), planting date (S) and planting density (D) as follows;

- (i) F_i , where $i= 1$ to 7
- (ii) S_j , where $j= 1$ to 7
- (iii) D_k , where $k= 1$ to 6

The simulated variables for each management strategy were selected to encompass and go beyond what is considered as commonly practiced on-farm agronomic strategies and that which is recommended by experts for each study location. Historically common agronomic strategies are summarised in Table 5.3 and are denoted in this study as *F_o*, *S_o* and *D_o* for fertiliser, planting dates and planting density respectively. The range of variables simulated for fertiliser and planting dates were based on Zinyengere et al. (2014) for all sites and Rauniyar and Goode (1996), Bruns (2012), and Heisey and Smale (1995) for planting density in Big Bend, Mohale's Hoek and Lilongwe respectively. Simulated fertiliser amounts ranged from 0 to 60 kg N/ha for all study locations, with a 10kg N/ha variable increment (Table 5.3). Planting dates were set up to include a planting window of two months with 10 day variable increments starting from 20 October, 24 October and 1 November for Big Bend, Mohale's Hoek and Lilongwe respectively (Table 5.3). Planting densities were simulated at 5 000 plants/ha increments from 20 000, 23 000 and 27 000 plants/ha for Big Bend, Mohale's Hoek and Lilongwe respectively (Table 5.3). Fertiliser was simulated as split applications (basal and top), 5 weeks apart using the ratios applied under historical conditions (Table 5.3). Inter row spacing and planting depth were maintained constant at 61cm and 7 cm respectively across all scenarios and sites. The row spacing is narrower than the common row spacing in the region of 75 cm and above. However, it was selected to account for some of the atypically low planting densities simulated.

Table 5.3 Definition of considered management variables; fertiliser amount (F), planting date (S) and planting density (D) and historical agronomic conditions for Big Bend, Mohale's Hoek and Lilongwe.

Management variable	Unit	Simulation code	Range (Min-Max)			Variable increment		
			Big Bend	M's Hoek	Lilongwe	Big Bend	Mohale's Hoek	Lilongwe
Fertiliser amount	Kg N/ha	F_i , where $i=1$ to 7	0-60	0-60	0-60	10	10	10
Planting date	Days	S_j , where $j=1$ to 7	20 Oct-20 Dec	24 Oct - 24 Dec	1 Nov - 31Dec	10	10	10
Planting density	'000 Plants/ha	D_k , where $k=1$ to 7	20-45	23-48	27-52	5	5	5
Mean historical common agronomic conditions								
Planting date			Fertiliser amount (kg N/ha)			Planting density ('000 plants/ha)		
Big Bend	M's Hoek	Lilongwe	Big Bend	M's Hoek	Lilongwe	Big Bend	M's Hoek	Lilongwe
14 Nov	10 Nov	25 Nov	Base	7	8	33	30	37
			Top	2	4	16		

Simulations were set up to investigate the effects of agronomic management strategies on maize yields in the form of three experiments as follows:

- *Experiment 1*: “Business as usual”, where historical common agronomic practices of farmers ($Fo \times So \times Do$) in each location (as shown in Table 5.3) were simulated unchanged.
- *Experiment 2*: Single factor changes for each of the three agronomic practices ($Fi \times So \times Do$ or $Fo \times Sj \times Do$ or $Fo \times So \times Dk$) were made, while holding all other practices constant at historical common levels per location.
- *Experiment 3*: Combinations of agronomic management options ($Fi \times Sj \times Dk$) were simulated simultaneously per location.

5.2.4.1 Response of historical maize yields to agronomic management changes

To explore the effects of agronomic management practices on maize yields and confirm that investigating combinations of agronomic management strategies adds value to the understanding of adaptation potential, the above experiments were carried out under historical climate conditions. Maize yield responses to farm-level information and management options were examined using historical climate (1971-2000). Three variables were selected for investigation from the full set of management variables (n) per agronomic strategy. Variables were selected to represent low, medium and high rates of application i.e. F1, F3 and F6; S1, S2, and S6; and D1, D3, and D5 for fertiliser amount, planting date and planting density respectively (see Table 5.3 for values). All simulations were averaged over the full climate period (1971-2000). Each variable change of *experiment 2* was compared to *experiment 1* to ascertain singular effect of each variable. Similarly, each variable combination of *experiment 3* was compared to *experiment 1* to ascertain the combined effects of agronomic strategies.

5.2.4.2 Agronomic management strategies for adaptation

To assess the responses of maize yields to varying agronomic strategies under climate change conditions and to identify the potential for agronomic strategies for adaptation to climate change, simulations of various agronomic management strategies were performed using baseline and future climates or all four GCMs under the A2 emission scenario. Simulated yields were averaged across the four GCMs climate scenarios for the baseline (1961–2000) and future (2046–2065) periods. The entire set of management variables (n) per agronomic strategy (Fi , Sj and Dk) was simulated. Each variable change i , j , or k of *experiment 2*,

simulated for baseline and future was compared to each other and *experiment 1* to ascertain singular effect per variable. Similarly, each variable combination $i \times j \times k$ of *experiment 3* (249 in total) for baseline and future was compared to each other and to *experiment 1* to ascertain the effects of each variable combination.

To assess the risk associated with each combination of agronomic management strategies, the frequency of occurrence of mean yields were recorded and compared between baseline and future for each combination. This was achieved by counting the number of hits where simulated yields per combination were close to the mean yields (within 400kg) for all the simulated years for baseline and future periods across all four GCMs per combination of strategies. More hits represented a higher occurrence of simulated average yields and therefore low variability (i.e. stable yields) and vice versa. 400kg/ha was reached at through a trial and error process that included running a few trial simulations and ascertaining a cut-off value that allowed useful information to be drawn from the simulations without the noise created by a small cut-off and masking of changes from a large cut-off.

5.3 Results

5.3.1 Maize yield response to climate

Figure 5.1 shows that mean maize yields were most sensitive to climate in Big Bend and least in Lilongwe. Simulated mean maize yields declined in response to increasing temperature across all study sites, reaching up to a decline of -29.5%, -13% and -5.1% for Big Bend, Mohale's Hoek and Lilongwe respectively under no change rainfall (0%) conditions. Mean yield response to simulated rainfall changes was small across all locations, varying from increase to decrease of -1.7% to +1.3% in Big Bend, -3.9% to 3.0% in Mohale's Hoek and -3.1% to 2.5% in Lilongwe under no change (0°C) temperature simulations. Notably, at all simulated temperature levels above 0 °C, simulated mean maize yields were negative for all locations. Simulated mean yield responses to rainfall were lowest in Big Bend and highest in Lilongwe where simulated yield change with rainfall changes was almost equal to simulated yield changes with temperature. Contrary to Big Bend and Mohale's Hoek where yields decreased with decreasing rainfall, maize yields in Lilongwe increased with decreasing rainfall.

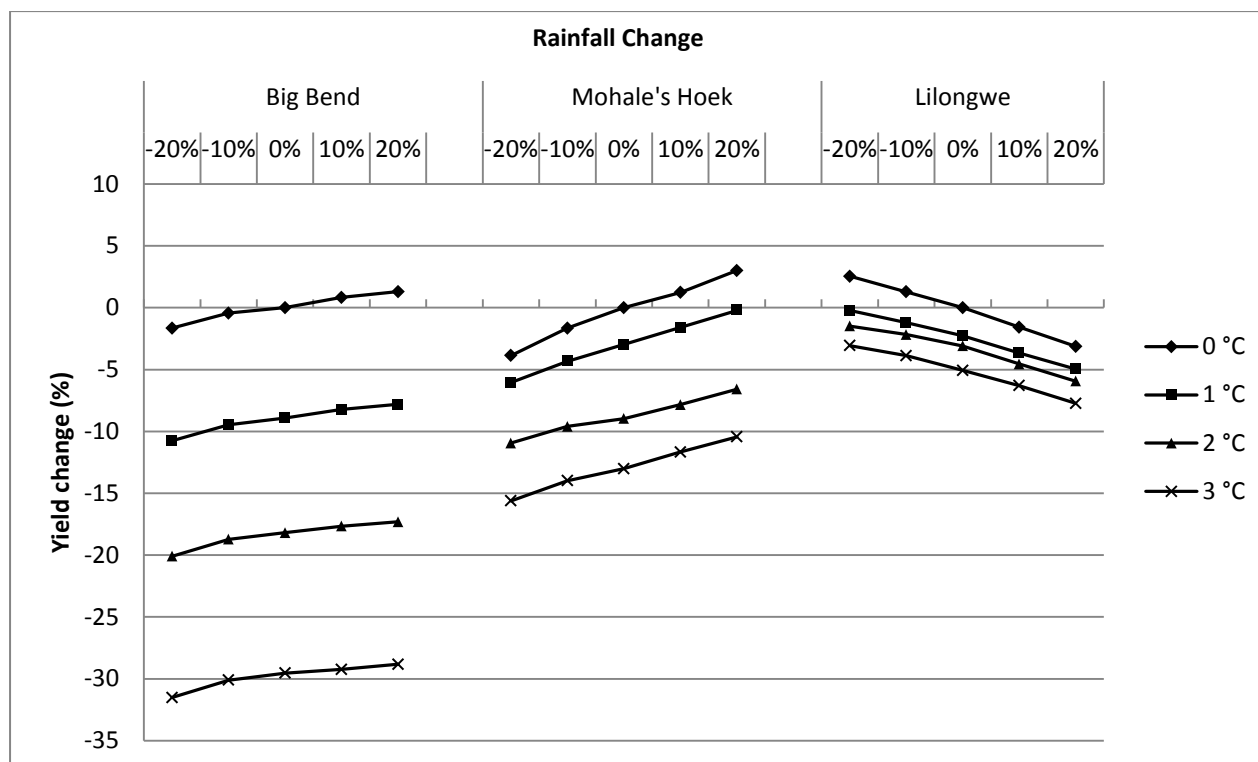


Fig 5.1 Sensitivity of mean maize yields to perturbations of temperature and rainfall from historical climate (1971-2000) in Big Bend, Mohale's Hoek and Lilongwe. Agronomic practices were simulated at average historical common levels.

5.3.2 Maize yield response to agronomic strategies

In Big Bend, maize yields showed a strong positive response to single factor increase in fertiliser amount and shifting of planting to later dates (where only one agronomic strategy was perturbed while holding others constant). Mean maize yield increase was 3% (F1) to 72% (F6) with single factor fertiliser perturbations. Yields increased with later planting from -13.5% (S1) to 63.8% (S6). Mean maize yields declined with single factor increases in planting density, although the changes were much lower than for fertiliser and planting date perturbations i.e. 7.0% (D1) to -6.7% (D5). Mean maize yields under combinations of medium to high fertiliser (F3 and F6), medium to late planting (S3 and S6) and low planting density (D1) were negative, averaging a decline of -10% despite simulated strong positive single effects of each agronomic variable i.e. +41% (F3) and +72% (F6) for fertiliser amount, +13.6% (S3) and +63.8% (S6) for planting date and +7% for planting density (D1). Under medium planting density (D3), where maize yields were shown to decline slightly (-4.1%), mean yields in Big Bend were simulated to increase considerably even where single factor effects of early planting (S1), were demonstrated to result in a decline of -13.5% in mean maize yields.

Table 5.4 Single and combined effects of agronomic strategy perturbations on maize yields; shown as change in percentage mean yields from historical conditions (1971-2000) per perturbation.

			Big Bend						Mohale's Hoek						Lilongwe									
						D1	D3	D5						D1	D3	D5						D1	D3	D5
						7.0	-4.1	-6.7						25.7	-12.8	-22.9						2.5	-1.8	-3.0
			F	S							F	S							F	S				
F1	S1	3	-13.5		9.8	34.7	-7.6			-7.8	-9.1		30.4	-16.4	120.3			-40.6	3.3		0.5	12.7	-1.9	
	S3			13.6		7.6	33.6	-8.3			71.0		28.1	-33.1	37.5				13.5		0.2	-0.4	-0.6	
	S6			63.8		8.6	-11.3	-24.7			141.0		-2.2	-0.9	-28.5				36.7		1.5	-0.9	3.4	
F3	S1		41.0	-13.5	9.0	66.8	-13.6			162.4	-9.1		-20.4	0.2	60.3			22.3	3.3		4.3	-3.0	-6.0	
	S3			13.6		2.2	47.1	-10.3			71.0		-23.1	12.9	34.3				13.5		5.8	-4.4	-9.8	
	S6			63.8		-8.0	-2.0	-12.5			141.0		-21.1	12.2	21.9				36.7		10.9	-3.3	-4.4	
F6	S1		72.0	-13.5	-9.9	54.5	0.7			174.0	-9.1		-24.5	20.3	107.2			171.	3.3		20.0	-16.9	-38.7	
	S3			13.6		-11.1	34.8	13.2			71.0		-26.2	20.9	171.6				13.5		20.5	-16.5	-40.4	
	S6			63.8		-12.2	2.1	11.0			141.0		-29.2	24.5	62.8				36.7		23.5	-18.2	-42.3	
			-160	-140	-120	-100	-80	-60		-40	-20	0	20	40	60	80	100		120	140		160	180	
Legend																								

In Lilongwe, responses of maize yields to single factor changes in fertiliser amount, planting dates and planting density were similar to Big Bend and Mohale's Hoek albeit with varying magnitudes. Although mean maize yields declined with increasing planting density, the change was small i.e. +2.5% (D1) to -3.0% (D5). Mean yields increased with later planting from 3% (S1) to 37.5% (S6), a modest increase compared to Big Bend and Mohale's Hoek. Mean maize yield increased from -40.7% (F1) to 171.7% (F6) with single factor fertiliser increase. Simulated combined effects were consistent with single factor changes in planting densities, especially at higher fertiliser amounts and later planting. Mean maize yields increased at low planting densities (D1) and declined at higher planting densities (D3 and D5). However, yield changes (positive or negative) were magnified with increasing fertiliser. At medium fertiliser amounts (F3), mean maize yield increase ranged from 4.3% to 10.9% while at high fertiliser amounts (F6) mean yield change ranged from 20% to 23.5%, with negligible effect from planting date changes. At higher planting densities, maize yield declined by -2.9% to -9.8% for medium fertiliser amount (F3) and -16.5% to -42.3% for high fertiliser amount (F6). Strongest negative effects were simulated under the highest planting density (D5).

5.3.3 Effect of single factor agronomic strategy changes under climate change

5.3.3.1 Fertiliser amount

Mean yields in Big Bend increased sharply with fertiliser increase for both baseline and future conditions by up to three times, hitting an asymptote at higher fertiliser applications (Figure 5.2a). Future yields were much lower than baseline at high fertiliser applications, highlighting the negative impacts of climate change. Similarly, increasing fertiliser amounts in Mohale's Hoek led to an increase in mean maize yields for baseline and future by up to 3 times (Figure 5.2b), hitting an asymptote at higher fertiliser applications. Simulated mean yield differences between baseline and future conditions were small for low fertiliser applications (F1, F2). Notably, future mean yields were higher than baseline for F3, but declined to below baseline yields and continued declining with increasing fertiliser levels (F4-F7), showing a negative effect of climate change on maize yields at high fertiliser levels. Simulated maize yields for Lilongwe increased with increasing fertiliser amounts applied, showing higher future mean yields and thus compensating for the effect of climate change at high fertiliser amounts (F4-F7). Yield variation increased with increasing fertiliser application across all locations. Future yield variation was lower than under baseline for all fertiliser treatments in Mohale's Hoek, particularly at high fertiliser applications (F4-F6).

Future yields in Lilongwe on the other hand were higher than under baseline at high fertiliser application (F4-F7).

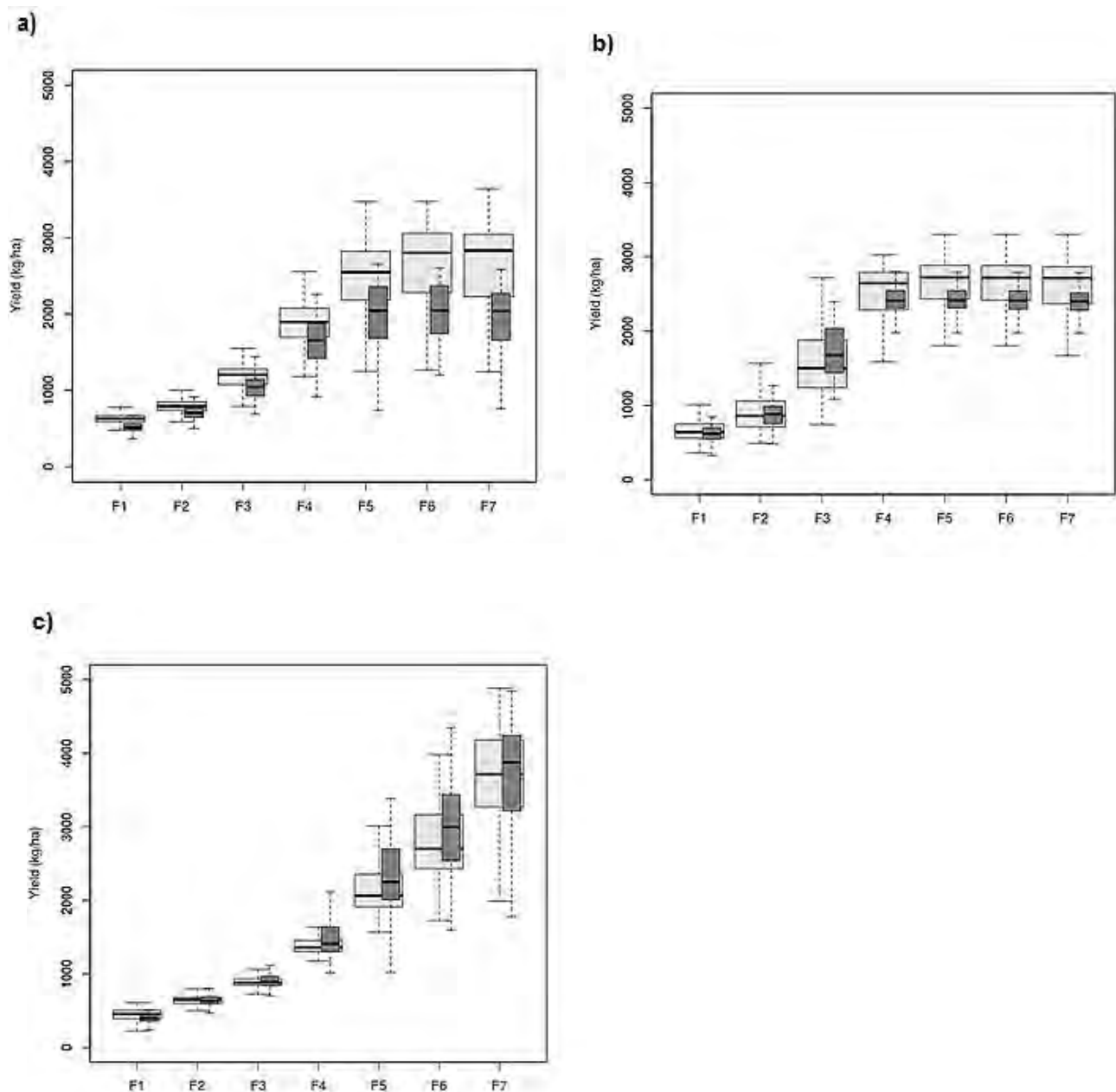


Fig 5.2 Boxplots showing simulated maize yields for baseline (1961-2000) (light grey) and future (2046-2065) (dark grey) for Big Bend (a), Mohale's Hoek (b) and Lilongwe (c) from four GCMs with changing fertiliser amounts (F1 – F7). In each box plot, outer horizontal lines represent from top to bottom, the 10th percentile, 25th percentile, median, 75th percentile and 90th percentile of all simulations per treatment. The maize yields are indicative and should not be read as absolute yields but as an indicative of yield change and variability.

5.3.3.2 Planting date

Figure 5.3 shows crop yields increased with later planting for both the baseline and future periods across all sites. Yield variation also increased with later planting for both periods. In Big Bend (Figure 5.3a) and Lilongwe (Figure 5.3c), changes in planting dates did not compensate for the negative effect of climate change. Future mean yields were lower than baseline for all planting dates. Simulated yield variation was lower for the future than baseline for Lilongwe across all simulated planting dates. Figure 5.3b shows that the negative effect of climate change on maize in Mohale's Hoek was reversed with later planting. Future mean maize yields were lower than baseline for earlier planting dates (S1-S3) and higher than baseline yields for later planting dates (S4-S7), reaching up to a mean increase of 32.1% for the latest simulated date. Yield variation was lower under future conditions across all simulated dates in Mohale's Hoek.

5.3.3.3 Planting density

Figure 5.4 shows that simulated single factor changes in planting density did not compensate for or reduce the effects of climate change across all study location. In fact, negative impacts of climate change increased with increasing planting density across all sites. Under baseline conditions for Big Bend (Figure 5.4a), mean maize yields were modelled to increase slightly with increasing planting density while mean yields under future conditions remained mostly unchanged. Mean maize yields in Mohale's Hoek remained mostly unchanged under baseline conditions albeit with noticeably higher yield variation as planting density increased (Figure 5.4b). Mean yields for future conditions declined with increasing density, thereby leading to an increase in negative impacts on yields with increasing planting densities. In Lilongwe, both baseline and future yields declined with increasing planting densities (Figure 5.4c).

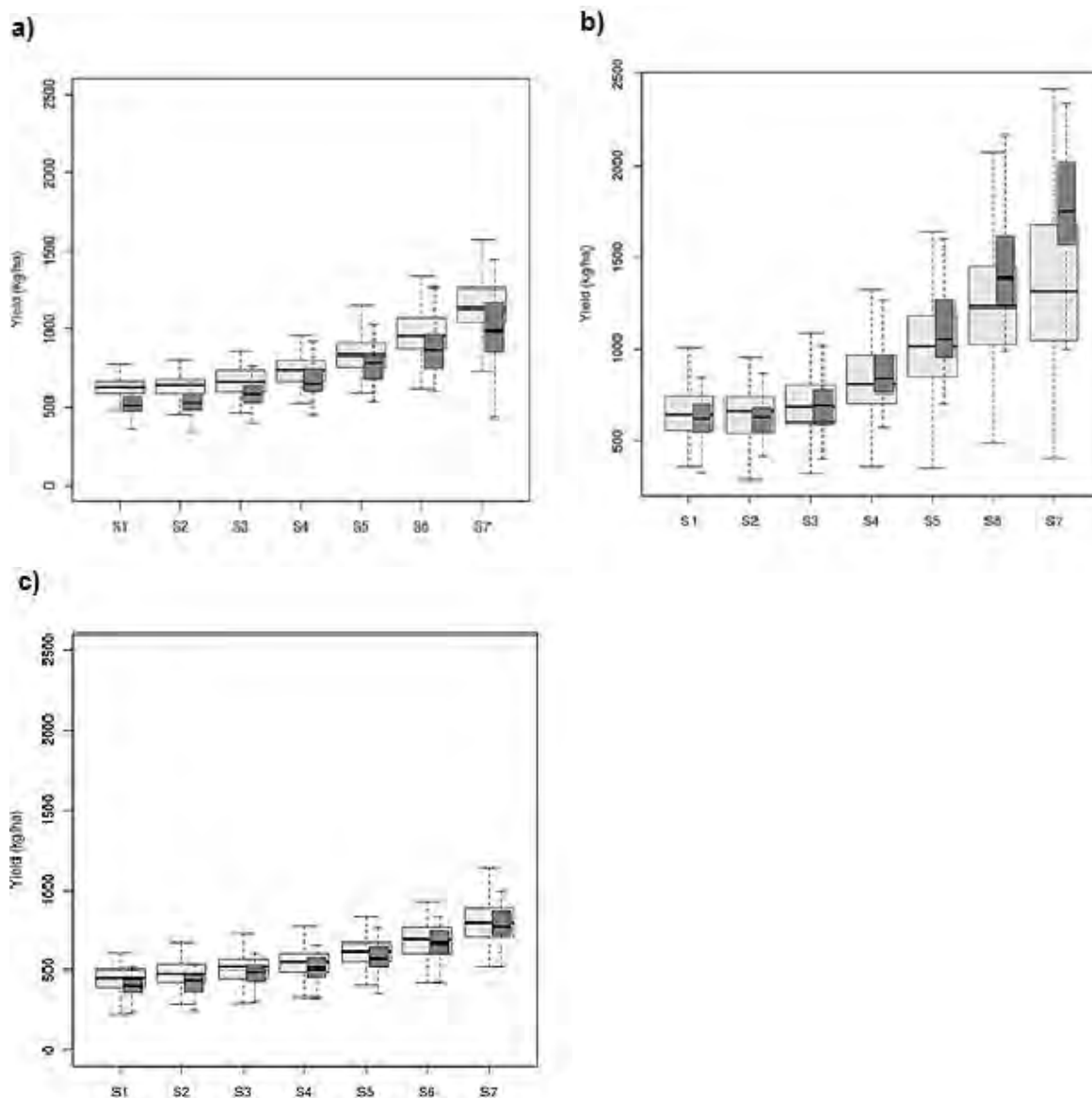


Fig 5.3 Boxplots showing simulated mean maize yield for baseline (1961-2000) (light grey) and future (2046-2065) (dark grey) for Big Bend (a), Mohale’s Hoek (b) and Lilongwe (c) from four GCMs with changing planting dates (S1 – S7). In each box plot, outer horizontal lines represent from top to bottom, the 10th percentile, 25th percentile, median, 75th percentile and 90th percentile of all simulations per treatment. The maize yields are indicative and should not be read as absolute yields but as an indicative of yield change and variability.

5.3.4 Effects of combined changes in management strategy under climate change

Maize yields declined on average between baseline and future by -12.9% for Big Bend, - 5.8% for Mohale’s Hoek and -5.1% for Lilongwe, across all climate scenarios under the “business as usual scenario” *experiment 1*. Table 5.5 summarises the simulated combinations of alternative management options and their effects on mean maize yields under climate change.

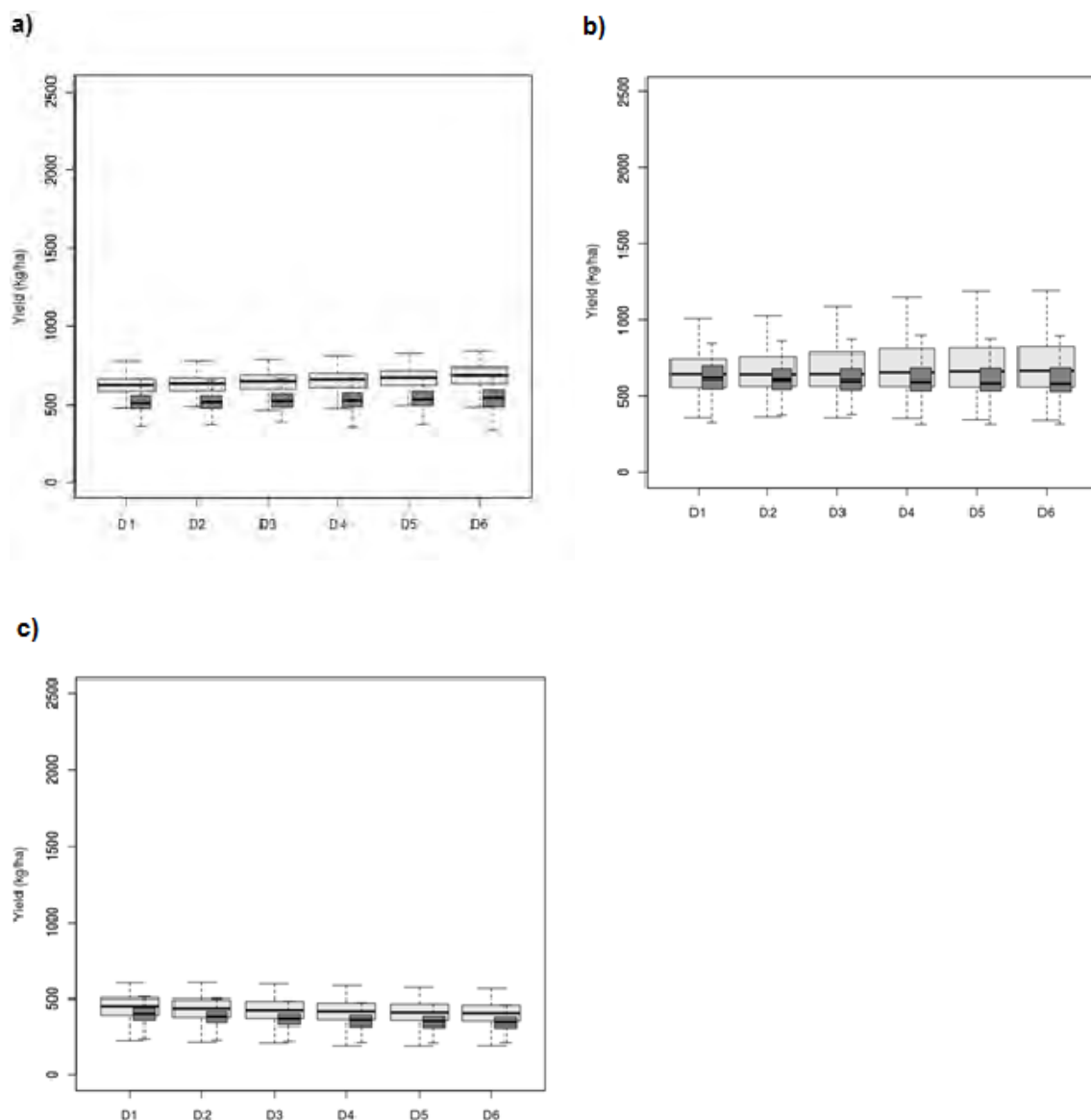


Fig 5.4 Boxplots showing simulated mean maize yield for baseline (1961-2000) (light grey) and future (2046-2065) (dark grey) for Big Bend (a), Mohale's Hoek (b) and Lilongwe (c) from four GCMs with changing planting density (D1 – D7). In each box plot, outer horizontal lines represent from top to bottom, the 10th percentile, 25th percentile, median, 75th percentile and 90th percentile of all simulations per treatment. The maize yields are indicative and should not be read as absolute yields but as an indicative of yield change and variability.

5.3.4.1 Big Bend

None of the simulated combinations of agronomic practices in Big Bend overturned the negative impacts of climate change. Meagre yield change advantage of no more than 3% from the “business as usual” scenario was obtainable at low fertiliser applications, low planting densities and early to medium planting dates (Table 5.5). Most combinations of agronomic management strategies in Big Bend exacerbated the negative impacts of climate change, particularly when higher amounts of fertiliser application (S4 -S7) and later planting (S5-S7) were simulated. Under these simulations, mean yields declined by more than 25% (more than 10% worse than under “business as usual” conditions) (Table 5.5).

Low yield variation in Big Bend coincided with the lowest simulated mean yields i.e. below 1500kg/ha (Figure 5.5). The lowest yield variations were simulated under early to medium late planting (S1-S5) and low fertiliser application (F1-F3) for both baseline and future scenarios. The highest yield variations were simulated under high fertiliser amounts (F5-F7) and late planting dates (S5-S7). These same combinations of agronomic practices yielded the strongest simulated negative impacts of climate change (Table 5.5).

5.3.4.2 Mohale's Hoek

As shown in Table 5.5, altering agronomic practices in Mohale's Hoek was shown to have a considerable effect on the impact of climate change. Agronomic practices either exacerbated the negative impacts of climate change on maize yields or moderated and reversed them. Mean maize yield decline of up to -11.9% was simulated. Strong mean yield decline was simulated under combinations of early planting (S1-S3), medium to high planting density (D3-D6) and low fertiliser applications (F1 and F2). At higher fertiliser applications (F5-F7) however, negative impacts were simulated at early to medium planting dates (S1-S4) and low planting densities, the reverse of simulations with low fertiliser applications. Positive yield changes were most common under low to medium high fertiliser applications (F2-F4), where most combinations resulted in future yield gain. Notably, positive future yields were consistent with late planting (S6 and S7) regardless of fertiliser amount or planting densities, more so for the latest planting date (S7), where yield gains were consistently above 20% (i.e. more than 25% higher than under the "business as usual scenario").

Simulated yield variation was lowest for early to medium planting (S1-S4) and low fertiliser amounts (F1-F3) for both the baseline and future in Mohale's Hoek (Figure 5.6). With an increase in planting densities, yield variation was low for later planting and medium to low fertiliser applications (up to F5). At high fertiliser amounts (F5-F7), variation in mean yields increased with medium to high planting densities in Mohale's Hoek. High yield variation coincided with the strongest mean yield benefits as shown in Table 5.5.

Table 5.5 Mean yield changes between baseline (1961-2000) and future (2046-2065) per combination of agronomic management strategies i.e. fertiliser amount (Fi), planting date (Sj) and planting density (Dk). Yields were averaged across four GCMs. Mean yield change under “Business as usual scenarios” is shown next to site name.

		-12.9 Big Bend						-5.8 Mohale's Hoek						-5.1 Lilongwe					
		D1	D2	D3	D4	D5	D6	D1	D2	D3	D4	D5	D6	D1	D2	D3	D4	D5	D6
F1	S1	-17.5	-17.7	-18.2	-18.7	-19.3	-20.1	-5	-6.9	-8.3	-9.7	-10.9	-11.9	-11.4	-13.1	-14.1	-14.5	-15.1	-15.5
	S2	-16.3	-17.7	-18.6	-19.1	-19.7	-20.5	-4.4	-6.7	-8.4	-9.5	-10.6	-11.3	-11.4	-12.9	-14.1	-14.5	-14.6	-14.6
	S3	-12.7	-14.1	-15.6	-16.4	-16.9	-17.4	-0.1	-4.1	-6.5	-8.2	-9.3	-10.3	-5.9	-7.5	-9.2	-10.9	-11.6	-11.9
	S4	-10.1	-12.4	-14	-15.3	-16.2	-16.5	4.4	0.5	-2.5	-4.8	-6.4	-8.3	-7.2	-8.6	-9.8	-11.4	-13.1	-13.9
	S5	-10.3	-12.5	-12.6	-16	-13.8	-15.1	8.6	6.1	2.6	-0.6	-3.1	-5	-5.7	-6.7	-7.7	-8.8	-10.1	-11.6
	S6	-12.3	-15.7	-14.4	-15.6	-16	-15.2	18.5	16.6	12.6	9.7	7.7	6.3	-3.5	-4.4	-5.3	-6.2	-7.3	-8.9
	S7	-15.7	-14.7	-16	-17.2	-18.1	-19.2	32.1	32	30	27.8	26	24.2	-3.3	-4.4	-5.1	-5.8	-6.5	-7.7
F2	S1	-11	-12.2	-13.2	-14.3	-15.3	-15.8	0.9	-4.2	-7	-8.4	-9.4	-10.6	-0.3	-2.1	-3.1	-3.4	-2.5	-2
	S2	-8.5	-10.4	-11.7	-12.8	-13.4	-13.8	7.6	2	-1	-2.8	-4.3	-5.4	-2.2	-3.6	-5	-6.2	-6.4	-5.8
	S3	-13.4	-13.6	-13.3	-13.2	-13	-12.9	11.6	7.7	4.8	1.6	-0.8	-2.5	-0.1	-1.2	-2.4	-3.7	-4.7	-4.7
	S4	-14.1	-14.1	-14.8	-15	-16.8	-17.1	11.2	10.1	8.4	5.3	3.2	1.1	-0.9	-1.5	-2.6	-3.8	-4.7	-5.3
	S5	-13.3	-14.3	-15	-16	-16.5	-13.6	10.9	11.1	10.6	8.8	6.4	4	0	-0.9	-1.6	-2.7	-3.2	-4.1
	S6	-15.6	-16.9	-16.8	-15.4	-14.1	-14.1	17.4	16.9	15.9	15.4	14.2	12.2	0.9	-0.3	-1.2	-2.1	-2.7	-3.3
	S7	-21.7	-22	-22.1	-21.7	-21.5	-21.5	34	32.8	30.1	28.8	27.9	26.5	1.1	-0.1	-1.5	-2.9	-3.8	-4.6
F3	S1	-11.6	-11.6	-12.1	-12.8	-13.7	-14.5	11.9	6.3	1.3	-2.3	-4.7	-6.4	3.5	2.8	1.8	0.9	-0.1	-0.7
	S2	-13	-13.6	-14.1	-14.9	-14.5	-14.7	10.2	10.2	5.7	2.1	-0.2	-2.1	-0.2	-0.4	-0.6	-1.4	-2.2	-3.2
	S3	-17.9	-15.3	-15.1	-14.6	-14.9	-16.2	5.8	11	8.8	7.1	4.4	2.1	1.5	1.7	1.4	0.9	0.1	-0.4
	S4	-15.4	-14.5	-14.7	-16.5	-17.2	-17.6	4.8	10.2	9.1	9.3	7.7	5.5	1.7	1.5	1.1	0.5	-0.1	-1.1
	S5	-17	-17.3	-17.3	-18.1	-19.2	-18.4	6.1	9.7	9.6	9.1	8.8	7.6	1.8	1.4	0.6	-0.2	-0.9	-1.8
	S6	-19	-19.8	-19.2	-19.1	-17.8	-17.5	14.1	17.1	16.6	14.8	13.4	13.3	1.1	0.2	-0.5	-1.5	-2.3	-3
	S7	-23.4	-25.6	-25	-23.7	-22.9	-22.5	32.2	33.4	31.5	29.7	27.3	26.3	1.4	0.1	-1	-2.1	-3	-4.2
F4	S1	-14.2	-13.6	-12.6	-11.9	-11.7	-11.8	-1.8	8.7	11.8	8.6	5.2	1.6	5.9	6.3	6.5	6.4	6.4	6.4
	S2	-14.1	-14.2	-14.2	-14.7	-14.8	-14.6	-5.2	2.6	10.2	8.6	6	3.3	4.1	4.1	4	4.1	3.6	3.5
	S3	-20.1	-18.9	-18.6	-17.5	-17.9	-17.3	-3.9	-0.2	5.7	6	4.9	4.5	7.5	7.1	6.5	6.2	6.3	6.6
	S4	-19.1	-17.1	-16.5	-15.9	-16	-16.8	-1.1	1.5	6.4	6.5	4.5	5	6.1	5.8	4.9	4.3	3.8	3.1
	S5	-24.4	-22.2	-22.6	-22.5	-23	-23.3	1.4	3.9	6.7	6.4	5.7	5.4	2.6	2.2	1.1	0.2	-0.5	-0.9
	S6	-24.9	-23	-22	-22.1	-19.7	-19.6	10.7	12.4	14.9	15.5	13.2	11.4	1.3	0.4	-0.6	-1.5	-2.4	-3.1
	S7	-28	-25.9	-26.3	-25.6	-25.4	-24.9	31.1	30.8	30.9	29.9	27.7	26.9	1.8	0.4	-0.6	-1.6	-2.7	-3.3
F5	S1	-19.4	-15.6	-14.2	-13.8	-13	-12.4	-4.9	-3.7	2.6	8.9	10.6	8.6	8.6	10	10.3	10.6	10.9	10.6
	S2	-21.5	-17.8	-16.3	-15.6	-15.5	-15.3	-6.5	-6.7	-3.7	2.3	4.7	3.8	8.5	8.4	8.2	8.3	8.4	8.2
	S3	-24.7	-19	-18.7	-17.4	-16.9	-15.9	-6.2	-6.5	-4.8	-2.1	1.3	1	9	9.3	9.3	9.2	9.1	8.7
	S4	-26.1	-19.7	-18.6	-17.9	-18.1	-18	-3.6	-3.1	-2	0.3	2.7	2.5	8.2	8.1	7.2	6.5	5.6	5
	S5	-29.2	-26.9	-26.3	-26.5	-26.7	-26.6	0.2	-0.7	0.5	1.9	3.1	2.5	2.4	1.7	1	0.4	-0.4	-0.8
	S6	-29.9	-26.4	-24.6	-24.3	-22.2	-22.3	10	9.5	9.5	10.2	11	10.1	1	0.2	-0.5	-1.2	-1.9	-2.7
	S7	-31.1	-28.8	-27.4	-26.7	-26.9	-26.8	31.1	29.3	27.9	27	26.1	25.4	1.6	0.9	-0.1	-0.9	-1.8	-2.7
F6	S1	-23	-20.7	-17.4	-15.9	-14.8	-14.1	-5.4	-5.8	-4.4	1.1	5.8	9.4	6.3	8.7	10.6	10.8	10.9	11.5
	S2	-25.5	-21.8	-18.9	-17.5	-16.7	-16.2	-7	-7.9	-8	-5.5	-2.1	0.2	7.9	8.3	8.6	9.2	9.5	10.1
	S3	-27.9	-22.3	-19.4	-18	-18.1	-17.7	-6.9	-8.4	-8.6	-7.4	-5.1	-2.7	6.3	7.3	7.8	7.6	8	7.6
	S4	-28	-24.7	-22.1	-20.2	-19.5	-19.7	-4	-4.9	-5	-4.3	-2.6	-0.7	6.7	7.5	7	6.7	6.3	5.9
	S5	-30.2	-29.9	-27.7	-27.9	-27.8	-28.1	0.1	-1.7	-2.7	-2.2	-0.9	0.1	1.2	1.2	0.6	0	-0.5	-1.1
	S6	-30.7	-29.9	-27.8	-26.6	-24.2	-24	10	8.8	7.5	6.9	6.6	7.1	-0.1	-0.2	-0.7	-1.2	-1.7	-2.2
	S7	-32.1	-30.8	-29.1	-28.1	-27.6	-27.4	31.1	29.1	27	25.7	24.3	23.2	0.4	0.7	-0.1	-0.7	-1.5	-2.4
F7	S1	-26.1	-26.5	-25	-22.2	-19.9	-18	-5.7	-6.3	-6.6	-6.2	-3.9	-0.2	-1.9	0.8	2.5	4.1	5.1	6.1
	S2	-29.3	-28.4	-25.1	-22.1	-20.9	-19.1	-7.4	-8.7	-9.4	-10.6	-10.3	-8.2	0.8	3.1	4.3	5.4	6	6.8
	S3	-29.2	-26.9	-24	-21	-20	-19.2	-7.1	-9.4	-11.1	-11.6	-11.7	-10.2	1.5	2.9	3.8	4.4	4.5	4.8
	S4	-29	-28.7	-26.2	-24.2	-22.9	-22.2	-4.1	-5.8	-6.9	-7.7	-7.4	-6.7	2.3	3.8	4.8	5.2	5.2	5
	S5	-31	-31.9	-30.9	-29.7	-29.4	-29	0	-2.1	-4.2	-5.6	-5.6	-4.7	-1	-0.8	-0.5	-0.8	-1.1	-1.4
	S6	-31.3	-31.8	-30.8	-30.2	-27.3	-26.6	10	8.6	6.7	4.7	3.4	3	-1.4	-1.6	-1.6	-1.9	-2.1	-2.5
	S7	-33.1	-33.3	-31.3	-30.7	-29.5	-29.3	31.1	29.1	26.8	24.8	22.6	21.5	-0.8	-0.7	-0.6	-0.5	-1.1	-1.7
Legend																			

5.3.4.3 Lilongwe

Altering agronomic practices was also shown to have a strong effect on the impact of climate change on maize yields in Lilongwe. Negative yields were compensated and overturned under some combinations and exacerbated under others. Mean yield decrease of up to -15.5% was simulated (more than 10% worse than under “business as usual” scenarios (Table 5.5)). The strongest negative mean yields were simulated under low fertiliser (F1 and F2) application, particularly under high planting density (D4-D6). However, with increasing fertiliser amounts (F3-F7), the negative effects of climate change were largely reduced and overturned. The strongest yield benefits were simulated under medium to high fertiliser applications (F3-F7) and early to medium planting dates (S1-S4), up to an increase of 11.5% from baseline (about 15% better than under “business as usual”).

In general, simulated yield variation was low for most of the simulated combinations of agronomic practices for baseline and future conditions in Lilongwe (Figure 5.7). Under future conditions, yield variation was high for high fertiliser applications (F5-F7), more so with early planting (S1-S4). Yield variation was low and coincided with higher yields (up to 3000kg/ha) with increasing planting density and later planting for high fertiliser applications. However, as shown by Table 5.5, the yield gains between baseline and future under these combinations were small (no more than 3% increase), although these were up to 8% higher than when commonly applied agronomy was simulated (“business as usual”). The lowest future yield variation occurred under simulations of medium to low fertiliser application (F1-F4) under future conditions, regardless of planting times and planting density. These also yielded the lowest yields, largely below 2000kg/ha.

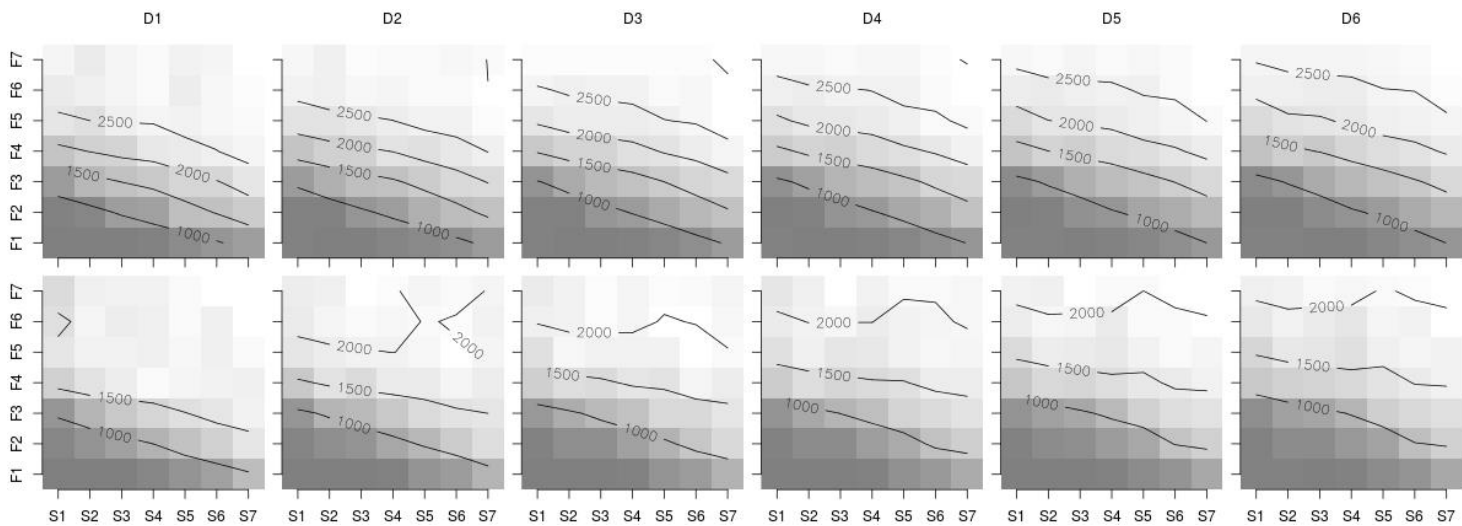


Fig 5.5 Frequency of occurrence of mean yields (contours) in Big Bend per combination of management strategies i.e. fertiliser amount (F), planting date (S), and planting density (D) under baseline (1961-2000) (upper panel) and future (2046-2065) (lower panel) conditions, averaged across all four GCMs. High frequencies of occurrence of mean yields are indicated by darker shades of grey and represent lower yield variability and therefore more stable yields across simulated scenarios

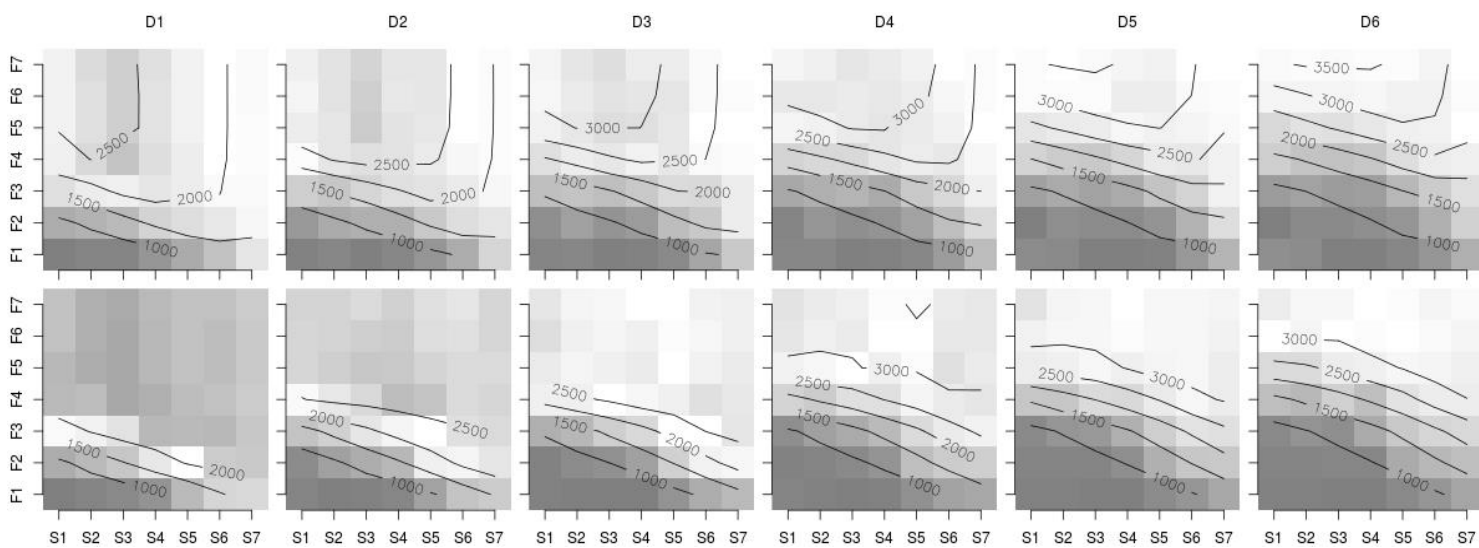


Fig 5.6 Frequency of occurrence of mean yields (contours) in Mohale's Hoek per combination of management strategies i.e. fertiliser amount (F), planting date (S), and planting density (D) under baseline (1961-2000) (upper panel) and future (2046-2065) (lower panel) conditions, averaged across all four GCMs. High frequencies of occurrence of mean yields are indicated by darker shades of grey and represent lower yield variability and therefore more stable yields across simulated scenarios.

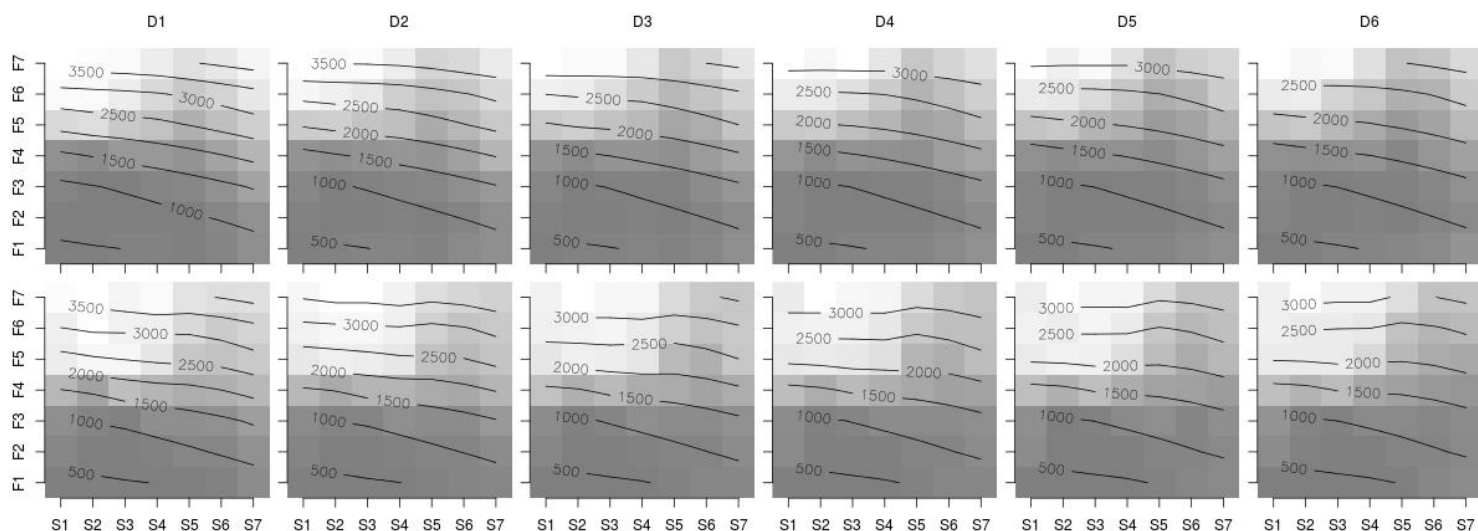


Fig 5.7 frequency of occurrence of mean yields (contours) in Lilongwe per combination of management strategies i.e. fertiliser amount (F), planting date (S), and planting density (D) under baseline (1961-2000) (upper panel) and future (2046-2065) (lower panel) conditions, averaged across all four GCMs. High frequencies of occurrence of mean yields are indicated by darker shades of grey and represent lower yield variability and therefore more stable yields across simulated scenarios.

5.4 Discussion

5.4.1 Maize response to climate change

The simulated decline in mean maize yields with changing climate across all locations is expected, partly owing to increasing evapotranspiration and shortening of growing periods (Alexandrov and Hoogenboom, 2000; Waha et al., 2013). Yield response to climate change in Big Bend was the largest. Yields declined dramatically with an increase in temperature (approximately -10% per 1°C increase in temperature). Owing to the already high temperatures in Big Bend, it would be expected that rising temperatures result in significantly increased heat stress related yield losses in the future and pose considerable challenges for adaptation. High temperatures have significant effects on growth and development of the maize crop (Cairns et al., 2012). Maize is extremely sensitive to temperature stress during the seedling, vegetative and reproductive stages (Schoper et al., 1987; Jones et al., 1984). Optimal growth in tropical areas peaks at a little over 30 °C, with some potential levelling off thereafter (Badu-Apraku et al., 1983; O’Keefe, 2009). Given that average maximum temperatures during the crop growing period in Big bend are above 30 °C (Table 3.1), and temperatures regularly rise above 35°C, climate change will likely present the maize crop with extreme high temperatures outside its optimal growth conditions and negatively affect yields. In Mohale’s Hoek and Lilongwe, while maize yields were sensitive to changes in climate, the negative effect of climate change was lower and rainfall importance as a driver of yield change was higher compared to Big Bend. The negative response of mean maize yields to increasing rainfall in Lilongwe could be a result of the effect of waterlogging in the shallow soils with fairly high clay content as those sampled for Lilongwe in this study. Cairns et al., 2012 showed that the central region of Malawi where Lilongwe is located is a waterlogging prone area. Farmers are known to plant their maize crops on raised row beds to improve drainage and reduce erosion from high rainfall. Given the different conditions under which farmers operate in each location and the varying constraints climatic changes place on maize yields, it would be expected that the adaptation challenges and opportunities for farmers in the region would differ considerably.

5.4.2 Maize response to agronomic strategies

The response of maize yields to on-farm agronomic management strategies was shown to differ from one location to the other and depending on simulated combinations of agronomic strategies. Notably, the interaction between agronomic strategies (as under combined simulations), although not explicitly explored resulted in significantly different yield outcomes from those under single factor changes of one agronomic strategy. In some instances, the combination of practices reversed the single factor effects (Table 5.4).

Strong yield increases with rising fertiliser application rates shown in this study are common in drylands and have been recorded in other studies (Folberth et al., 2013; Ruane et al., 2013), with mean yield increases of over 60% and diminishing returns in response to rising fertiliser applications as shown in Big Bend and Mohale's Hoek. In Lilongwe however, the simulated mean maize yields continued to increase even at high fertiliser application partly owing to the losses of nitrogen through leaching in shallow soils. The strong positive effects of increased fertiliser were largely moderated or reversed when other agronomic strategies were simulated simultaneously. Given the low and highly variable rainfall in Big Bend and Mohale's Hoek, fertiliser application can have a considerable effect (positive or negative) on yields. As shown in Table 5.4, at low planting densities, low plant population is likely to result in low fertiliser use efficiency and therefore crop yield losses from fertiliser damage. On the other hand, higher plant densities lead to increased fertiliser use efficiencies and therefore yield increase. The opposite effect was simulated in Lilongwe, where at low planting density, maize yields increased with increasing fertiliser amount, albeit in moderation i.e. with an increase of no more than 24%. At higher planting densities, strong negative effects were simulated with increasing fertiliser amounts and later planting in Lilongwe, despite strong positive single effects of high fertiliser amounts and later planting. This is likely attributable to a combination of factors that include nutrient leaching, which is common under wet conditions in shallow soils (Fixen et al., 2015), increasing nutrient competition and the possible onset of moisture stress later in the season owing to soil water depletion and faster exhaustion by the densely planted maize crop.

Abraha and Savage (2006), Tingem et al., 2008, Laux et al. (2010), Crespo et al. (2011), Waha et al. (2013) showed that the alteration of sowing dates has considerable effect on crop yields as shown across all locations in this study. Simulated yields in this study showed poor to no yield benefits for early planting and benefits with later planting especially in Mohale's

Hoek and Big Bend (Table 5.4). This is consistent with trends of erratic and/or delayed onset of the rainy season in southern Africa (Tadross et al., 2005; Tadross et al., 2009; Tongwane and Moeletsi (2014); Fiwa et al., 2014) and shows that the practise of planting with the first rains practised widely in the region is risky. However, medium to short season maize varieties were simulated in this study and are therefore more suited to later planting because they can mature within the growing season despite later planting, thereby avoiding water stress early on in the season and at other critical growth periods like grain filling. Results could differ significantly if longer season varieties were simulated.

Similar to fertiliser application, when planting dates were altered with other agronomic practices, the strong positive effects of later planting were moderated or overturned across all locations. The decline of yields with single factor increase in planting densities was consistent with the effect of increasing nutrient competition across all locations. The negative effects were reversed at high fertilisation in Big Bend and amplified in Lilongwe. These benefits or losses resulting from the interactions of different agronomic strategies are not accounted for when only single agronomic strategies are tested. Farmers have many on-farm agronomic practices at their disposal and usually apply multiple practices at once by making choices about e.g. planting dates, fertiliser amounts to apply, planting density, tillage type and time etc. This study suggests that estimating the combined effect of agronomic practices based on simulated single effects can be misleading in some locations and conditions. Hence, it is necessary to explore multiple combinations of practices (at least as a precaution) to obtain a more complete representation of the effects of agronomic practises and their adaptation potential under climate change.

5.4.3 Effects of management strategies under climate change

Adaptation benefits of changing on-farm agronomic management practices for dryland farmers in Big Bend are very limited. None of the simulated single factor (Figure 5.2a, Figure 5.3a, Figure 5.4a) and combinations of management options overturned the negative effects of climate change. Management practices close to what farmers exercise presently (low fertiliser, early planting, low planting densities) appeared to provide the best options under climate change, suggesting that investment in tactical on-farm adjustments will not suffice in helping dryland farmers adapt to climate change. In fact, owing to the limits placed on maize

yields by low and erratic rainfall and high temperatures (Figure 5.1), on-farm changes that would in some cases provide potential benefits e.g. high fertilisers and later planting will actually exacerbate the negative impacts of climate change in Big Bend. This is in agreement with Lobell et al. (2008) who stated that in drier parts of the continent where dryland agriculture is practiced, larger investments may be required for adaptation e.g. breeding and irrigation.

Dryland farmers in Mohale's Hoek have a wider range of opportunities for reducing the negative impacts of climate change through on-farm agronomic management adjustments. A large proportion of the simulated combinations of agronomic management strategies showed the potential for improved future mean yields under climate change. Farmers in Mohale's Hoek can benefit most from changing planting times. Negative yields were overturned and increased by above 15 % through late planting. Studies in various locations and conditions have shown the benefit of shifting planting dates under climate change e.g. in Bulgaria (Alexandrov and Hoogenboom, 2000), and Romania (Cuculeanu et al., 2002). The benefits of late planting in a moderate-low rainfall, high altitude area was also shown by Kassie et al. (2015) for locations in Ethiopia. Future climate projections from Zinyengere et al., 2014 showed an increase and peaking of rainfall and rising of temperatures above base temperatures of maize towards the end of the growing season in Mohale's Hoek, creating conducive climatic conditions for later planted maize. At high fertiliser application rates (F5-F7) however, the negative impacts of climate change with some combinations of on-farm practices increased and later planting was shown to be risky due to high yield variation in Mohale's Hoek (Figure 5.6). Farmers in Mohale's Hoek have lower risk options for on-farm adaptation that include delayed planting and the application of moderate fertiliser amounts (20-40kg N/ha). Folberth et al., (2013) showed that in SSA moderate to low fertiliser applications (less than 50 kg N/ha) can still ensure sufficient future maize production levels. Medium planting dates (S3-S5) and moderate to high planting densities (D3-D6) can also offer farmers lower risk adaptation options in combination with moderate fertiliser amounts, while still ensuring yield benefits of 5 to 15%.

Farmers in Lilongwe can receive the best benefits to mean maize yields by applying medium to high fertiliser amounts (30-60 kg N/ha) and early to medium planting dates (S1-S4). These practices however come with the highest risk as they coincide with high future yield variation (Figure 5.7). Although in general future conditions presented higher risk to maize production in Lilongwe compared to baseline, risk can be reduced through lower fertiliser application

(no more than 30kg N/ha). This is in agreement with the assertion that modest fertiliser application in SSA can yield sufficient maize production benefits (Folbert et al., 2013). Yields of up to 15% higher than those attainable under current practises (“business as usual”) can be obtained in the future with such modest fertiliser application especially with earlier planting (S1-S4) in Lilongwe. Another low risk option consists of applying high fertiliser amounts (F5-F7) and planting later (S5-S7), although this coincides with lower mean yield gains of no more than 8% from current practise. The application of low fertiliser amounts while planting crops at high densities was shown to be a mal-adaptive practice in Lilongwe with the potential to exacerbate the negative impacts of climate change.

5.4.4 Adaptation options for households

Although crop production is a major livelihood activity, households in Big Bend do not earn much from crop production, rather depending on formal employment for income. Households are therefore not greatly invested in crop production. It appears that there is an understanding in Big Bend that the climate in the area may not suit maize production, hence the limited investment in crop production. However, households in Big Bend still engage in crop production (62%), planting maize every season as a staple crop although the area is known to be unsuitable (Manyatsi et al. 2013). This could largely be due to cultural preferences. As such, farmers put in as little as they can in food crop production in the hope of gaining from the occasional “good seasons” and thus reducing strain on their off-farm incomes. Given that the impacts of climate change in the coming decades will render the more marginal crop production areas such as Big Bend increasingly risky for maize cropping, and given that options for adaptation through small on-farm tactical changes are low, the limited investments in crop production (little expenditure on inputs, poor utilisation of available cropland, consumption of input seeds etc.) by households in Big Bend (Table 5.4) is likely to continue. The practise could be useful if resources saved by so doing can be re-directed to other livelihood activities and income earners more suited to increasingly difficult cropping conditions under climate change e.g. livestock rearing. Given the cultural value of maize for food, efforts may still be required to promote adaptation of maize crop production to climate change. Other investment demanding adaptation options such as irrigation and the breeding and use of drought resistant crop varieties can be used. While farmers in Big Bend appear to have good access to income and credit thereby being in a better position to invest in irrigation

(small scale), broader stakeholder (government, NGOs and private sector) involvement will be required to support efforts for adaptation in the area.

Similar to Big Bend, most households in Mohale's Hoek do not earn much income from crop production yet crop production is a major livelihood activity. Maize is the staple crop and therefore most farmers grow crops to subsist while earning income informally. On-farm adjustments such as later planting and application of appropriate fertiliser amounts could have beneficial effects on household food security and income levels in Mohale's Hoek. The majority of farmers in this area may not be able to afford to take substantial risk since most do not have a steady income flow (37% earn income from informal work), have poor access to external financial resources (6.6% of households) and family support (15% of households only). Low risk management adaptation options will suit the promotion of maize production under climate change in Mohale's Hoek. Farmers can apply moderate fertiliser applications (20-40 kg N/ha), medium planting dates and medium to high planting densities. Although these options do not offer the highest yield benefits (as under late planting), they offer good risk averse options with good benefits for maize production (up to 15% increase). Households in Mohale's Hoek have fairly good access to fertiliser and draught power, and can thus apply fair amounts of fertilisers on fields and afford to plant timely. However, improvement in access to agricultural extension services will be vital. Nhemachena et al. 2014 identified extension service access a major determinant of adaptation in southern Africa. Similarly, support programmes for timely access to seed input will benefit farmers immensely.

Adaptation in Lilongwe is imperative, owing to the considerable dependency of households on crop production compared to the other locations. However, based on the climatic conditions in Lilongwe, there exist reasonable opportunities to adapt using on-farm management adjustments. Proper timing of planting times and the application of appropriate fertiliser amounts will benefit livelihoods in Lilongwe. Medium to high fertiliser application and early planting have the potential to increase maize yields by up to 15% higher than under current practise in Lilongwe, albeit with considerable risk (Figure 5.7), which can be reduced by later planting, albeit with lower future yield gains. While farmers in Lilongwe make efforts to invest in agriculture, they are poorly endowed in terms of assets (draught power, tractors, etc.) and access to financial resources. Although access to agricultural extension is better than the other locations (16% households), it is still quite low. Applying medium fertiliser amounts (no more than 30kg N/kg) will still also help farmers to reap yield benefits under more stable yield regimes. Since this is a modest increase from current application

rates, this presents households in Lilongwe with an opportunity to reduce the negative effects of climate change and promote food and livelihood security. Support will be required through improved access to extension services (physical support or through radios that are common in Lilongwe), fertiliser and timely access to tractors for preparing land. Successes have already been demonstrated in Malawi through input and extension support programmes carried out between 2005 and 2010 (Juma et al., 2011) and will be of even more benefit in the future under climate change.

5.4.5 Uncertainties and limitations

The estimated impacts of climate change and the contributions of agronomic management options for adaptation can depend on the processes and mechanisms of a particular model used. The modelling approach and model performance in simulating the physiological impacts of extreme weather events such as droughts and high-temperature stress is vital. Useful adaptation strategies identified should be considered bearing in mind that climate change includes not only long-term changes in mean conditions, but also a change in the frequency and magnitude of extreme weather events (Hulme et al. 1999; Moriondo et al. 2010). The set-up of the CERES-Maize model in this study followed that by Zinyengere et al. (2015), which was done with limited data and showed high uncertainty in the simulation of seasonal yield variation, especially under extreme weather conditions. This may limit the capture of risk associated with different agronomic practices.

Only four GCMs and the A2 emission scenario were used in the study to sample climate model uncertainty. However, more models could have been applied to sample the variability in climate projections between different GCMs. More uncertainty in this study comes via the downscaling of GCM data to the appropriate spatial and temporal resolution to be used in the crop model. Furthermore, historical empirical relationships from which future projections are made may change in the future. More could have been done to explicitly quantify and hierarchize the main sources of uncertainty; this was however considered outside the scope of this study.

The role of on-farm autonomous adaptation has been missing in the climate change component of large-scale projection studies in southern Africa, let alone assessments of agronomic strategies in combination. Despite advances of this study, the number of

agronomic practices modelled remains limited. Dryland farmers in southern Africa have access to more on-farm management choices that include choice of tillage practice, the use of organic manure as fertiliser, water conservation techniques, different cultivars etc. These were not modelled because of crop model limitations and analytical complexities that would be introduced by a larger set of agronomic strategies. As such, any potential benefits from these strategies were not included. No account was made for the effects of weeds, diseases and pests since these are not explicitly included in the crop model. However, given the sub optimal conditions common in smallholder dryland systems of southern Africa (Cooper et al, 2008; Twomlow et al., 2008), these factors are likely to affect crop growth and final yield. The potential of future technology innovations and CO₂ fertilisation were also not explicitly included in this study. This was because the progress of technology is hard to anticipate and there are many uncertainties associated with CO₂ fertilisation, and effects of rising CO₂ on crop growth are still contestable (Long et al., 2006; Tubiello et al., 2007; Ainsworth et al., 2008; Kimball, 2010) and may be small especially for C4 crops (Tubiello, 2007). However, it should be understood that despite the fact that the positive effects of CO₂ fertilisation are known to be small for maize, in some of the study locations, especially Lilongwe, where small negative impacts of climate change are projected, results could be considerably different, if the positive effect of agronomic changes were bolstered by the positive effects of CO₂ fertilisation, albeit small.

Big Bend, Mohale's Hoek and Lilongwe are broadly representative of the bio-physical conditions of agricultural systems in other parts of southern Africa. Noting the differences in climatic conditions, soils, and agricultural practices from place to place within the region, the modelling results presented in this study, when interpreted with caution, could be used to anticipate the nature of adaptation demands placed on dryland farming by climate change in similar locations.

5.5 Conclusion

Farmers in southern Africa apply a wide range of on-farm agronomic strategies and adjust them in several ways in response to unfavourable climates. This study showed that multiple agronomic strategies need to be investigated in combination. Such investigations performed within the context in which farming communities in the region operate furthers the

understanding of farmers' adaptation options to climate change. It was shown that adjusting on-farm agronomic management strategies can help to reduce the expected negative impacts of climate change. Areas with cool or moderate temperatures and adequate rainfall (e.g. Mohale's Hoek and Lilongwe) will benefit from on-farm agronomic strategy adjustments such as appropriate timing of planting and fertiliser applications. Areas that already present harsh marginal climatic conditions for cropping i.e. high temperatures and low and erratic rainfall such as Big Bend will unlikely benefit. More investment demanding adaptations e.g. irrigation, plant breeding and livelihoods diversification will be required to improve household food security and livelihoods in marginal areas.

Support towards the adaptation needs of farming communities in southern Africa will need to be targeted based on the bio-physical challenges and opportunities presented by climate change in each locality, and the socio-economic capital endowments of communities thereof. Strong extension services and timely access to inputs (seeds and fertiliser) and farming implements (e.g. tractors in Malawi) will be required for farmers to be able to take advantage of the potential of on-farm agronomic adjustments for adaptation. On-farm agronomic adjustments should however not be considered a panacea to climate change adaptation in resource poor dryland systems in southern Africa but should be considered as a building block or "1st level defence" against climate change. Other factors such as access to improved infrastructure (roads, electricity, water supply etc.), access to information, markets and political processes, etc. are important and should be strengthened. Furthermore, dryland farmers have access to many other agronomic practices which were not investigated in this study. Given the demonstrated value of investigating multiple options for farmers simultaneously, more on-farm options will need to be considered in future adaptation studies. More research efforts are also required to better characterise local adaptation and inform policies through seamless bridging of biophysical adaptation approaches, vulnerability assessments and small scale participatory approaches.

CHAPTER 6

SYNTHESIS, CONCLUSIONS & RECOMMENDATIONS

6.1 Introduction

This study sought to understand the impacts of climate change on crop production in southern Africa and ascertain how useful on-farm agronomic practices used by farmers in the region could be for adaptation. The thesis sought to highlight that such an understanding demands a refined study that explicitly considers the heterogeneity inherent in the region via location specific studies. A climate-crop modelling approach was implemented at the local scale. The DSSAT crop model was used, driven by multiple downscaled climate projections from up to 9 GCMs in three distinct locations in southern Africa (Big Bend in Swaziland, Mohale's Hoek in Lesotho and Lilongwe in Malawi) for up to three crops (maize, sorghum and groundnut). Specific bio-physical conditions (soils, climate, etc.) and agronomic management practices (crop management, timing of activities, etc.) for each location were used. Survey data was applied to provide a socio-economic context to adaptation modelling processes and results. The thesis answers objectives set out in **Chapter 1** to specifically understand the following:

1. How future crop production in southern Africa will be affected by climate change.
 - A quantitative review of crop modelling studies in southern Africa was carried out (**Chapter 2**). Following the review, a simulation study was performed to project the local impacts of climate change on maize, sorghum and groundnut in study locations (**Chapter 4**).
2. How well crop models set-up under data limitations can simulate local effects of climate and agronomic practices on crop yields in southern Africa.
 - The DSSAT crop model was set-up using limited data (crop cultivars, soils, climate, and agronomy) common in southern Africa through “loose” parameterisation and tested for the capture of crop yields (maize, sorghum and groundnut) at field scale and using district-wide crop yields in study locations (**Chapter 3**).

3. How useful on-farm agronomic management strategies used by local farmers are in adapting dryland crop production to climate change in southern Africa.

- Agronomic management strategies in study locations were selected and tested for usefulness under climate change. Two strategies (commonly practiced and recommended by experts) of planting dates and fertiliser applications were tested for maize, sorghum and groundnuts (**Chapter 4**). At least six alternatives each for planting dates, fertiliser amount and planting density were also tested (**Chapter 5**).
4. The value of simulating combinations of agronomic strategies for a better understanding adaptation potential of agronomic practices of farmers in southern Africa.
- Multiple combinations of agronomic strategies of planting date, fertiliser application and planting density were simulated. A total of 294 combinations of agronomic strategies were tested for usefulness under climate change. Survey data was used to provide a socio-economic context for ascertaining the suitability of bio-physically determined adaptation strategies (**Chapter 5**).

6.2 Key findings

6.2.1 Summary

Dryland crops in southern Africa are projected to be strongly impacted by climate change. The projected impacts depend largely on the scale, location and crop of study, and can be altered by the agronomic management strategies of farmers in the region. Simulating multiple agronomic strategies simultaneously and understanding the local conditions farmers operate under helps to better understand adaptation potential of agronomic practices. Key findings are found in Chapters 2, 3, 4 and 5 as follows:

1. Aggregated crop yields in southern Africa were projected to decline by 18% in mid-21st century (2050s) and 30% in the late 21st century (2080s) with a range from -5% to -32% and -5% to -50% respectively. Maize yields were particularly shown to be negatively impacted. However, impacts varied depending on the methodologies used (crop models, GCM scenarios, CO₂ emission scenarios, scale etc.).

2. Most studies in southern Africa have been performed at large scales, leading to potentially erroneous broad-brush recommendations for adaptation that do not account for important differences in local conditions (i.e. crops, soil, climatic, conditions, agronomic practices, socio-economic aspects etc.).
3. Despite widespread data challenges that limit location specific climate change impacts and adaptation studies, crop models can be set-up satisfactorily and used to simulate crop response to climate and agronomy in southern Africa. The DSSAT family of crop models can capture mean crop yields over long periods with limited parameterisation, but may require more detailed parameterisation to capture crop yield variation under low occurrence events/conditions such as extreme climates.
4. Location specific study helps to show disparities between locations and to identify potential benefits of climate change that large scale studies may not capture. Some locations and crops may benefit from climate change, especially those in regions where cold related crop losses are a perennial challenge, e.g. high altitude areas of Lesotho.
5. The local impacts of climate change in southern Africa were shown to vary considerably by location and crop. Yields were projected to mostly decline in Big Bend (a hot and dry area), ranging from -43.8% to -6% and -40% to +8.7% for maize and sorghum respectively. In Lilongwe, an area with a moderate climate, mean yields declined with a range from -11.3% to +2.9% and -51% to -20% for maize and groundnut respectively. In Mohale's Hoek, a cool mountainous region, mean yields increased albeit with the largest uncertainties, ranging from -60.4% to +120% and -9.4% to 216% for maize and sorghum.
6. Dryland farmers can potentially reduce the negative effects of climate change on crops or take advantage of benefits through small on-farm agronomic adjustments. Applying modest fertiliser amounts of no more than 40kg N/ha is less risky than high fertiliser applications yet also provides considerable yield benefits in Lilongwe and Mohale's Hoek. Late planting can be particularly beneficial in Mohale's Hoek.
7. Hot and dry locations (e.g. Big Bend) will have less on-farm agronomic adaptation options than the moderate and cooler locations (e.g. Lilongwe and Mohale's Hoek respectively). On-farm agronomic adjustments did not reduce the negative impacts of climate change in Big Bend. However, future yield benefits of over 15% in Mohale's Hoek (up to 40% under some

agronomic combinations) and up to 20% in Lilongwe can be obtained with on-farm adjustments.

8. Identifying useful agronomic adaptation strategies for farmers can be obtained best by analysing the effects of agronomic strategies separately and in combination to account for non-linear interactions. Yield benefits observed through simulating agronomic strategies independently were moderated or reversed when simulated in combination with others, while in some cases they were enhanced. The process of identifying suitable adaptation strategies can be supported by insight into local socio-economic conditions.

6.2.2. Aggregate impacts and modelling challenges

Climate change will result in largely negative future aggregate crop yields. It was shown in review *Chapter 2* that despite the uncertainty introduced by the different research methods and tools applied by various studies carried out in the region, the projected impacts of climate change were robustly negative in the mid (2050s) and late (2080s) 21st century i.e. -18% and -30% respectively. There were indications that although adaptation strategies could be useful in compensating the negative impacts of climate change in the early 21st century (2030s), they are likely to be less effective in the later part of the century. Aggregate impact projections were based mostly on studies done over large scales (national, regional etc.). This was seen to have potential shortcomings given the differing conditions that local dryland farmers in southern Africa operate (climate, soils, agronomic etc.), which such studies do not explicitly address. Further studies to ascertain the localised impacts of climate change on crops and to explore the identification of suitable adaptation strategies were recommend. Such work is presented in *Chapter 4 and Chapter 5*. However, to start with, a calibration and validation the DSSAT family of crop models for use in climate change impact and adaptation assessments was performed.

Chapter 3 of the thesis sought to determine if crop models can be used with limited parameterisation commensurate with data limitations in the region for impact studies. Despite the model being parametrised with limited data, it was found that the DSSAT family of crop models was able to simulate observed crop yields (maize, sorghum and groundnut) well (with an R^2 of at least 0.70) for all study sites (Big Bend – Swaziland, Mohale’s Hoek – Lesotho,

Lilongwe – Malawi) when reported experimental trial data was used. When the model was tested using district wide crop yields from 6-14 years with bias correction as a proxy for yields attainable under smallholder dryland conditions, the model predicted yields ranged from -12.2% to 2.9% from observations. It was concluded that crop models can be used with limited parameterisation to provide useful estimates of the impacts of climate and agronomic management practices on crop yields in the region. However, the capture of crop yield responses to climate during extreme weather, especially for rainfall was found to be highly uncertain. Data improvements in soil input parameters related to processes that constrain crop growth under very dry conditions or boost yields under wet conditions e.g. water retention characteristics, organic matter and nitrogen turnover were found to be necessary to help improve model performance and reliability especially under extreme climate conditions.

6.2.3 Location specific climate change impacts

In *Chapter 4*, the DSSAT family of crop models driven by downscaled climate scenarios were used to simulate the impacts of climate change on crops from a baseline (1961-2000) to the 2050s in three distinct locations in southern Africa; Big Bend-Swaziland (hot and dry), Mohale's Hoek-Lesotho (cool, wet and dry) and Lilongwe-Malawi (moderate and wet). It was shown through this location specific assessment that the impacts of climate change on crops in southern Africa will be significant (in support of *Chapter 2*), and will vary across locations and crops. Most places and crops will be impacted negatively while other places will benefit. Maize and sorghum yields in Big bend declined across all nine GCM and four agronomic scenarios by an average -20% and -16% respectively, with a range from -43.8 to -6% and -40% to +8.7%. Maize and groundnut yields in Lilongwe declined by an average of -5% and -33% respectively, with a range of -11.3% to +2.9% and -51% to -20%. In Mohale's Hoek, maize yields were projected to increase by up to +8% (with a range of -60.4% to +120%) with even larger benefits averaging +51% projected for sorghum yields. Average temperature increases of 1.7-2.4 °C across all sites had a significant effect on crop yields. In Big Bend where the climate is already marginal for crop production, increasing future temperatures along with little or no change in future rainfall create even less conducive conditions for maize and sorghum. In Mohale's Hoek on the other hand, climate change may create conditions more conducive for crop growth. Where high altitudes have perennially led to cold related crop yield losses, warming can lead to a reduction in crop losses or an increase

in cereal crop yields. Indications of the potential of agronomic management practices to provide adaptation options for dryland farmers were also found. Prevalent benefits of climate change on crops in Mohale's Hoek were largely attributable to the practice of planting late. Such a practice can lead to the early-medium maturing maize cultivar growing into a warmer late season (March and April) where temperatures are perennially known to decline below the crop's base level (below which the crop is dormant and no grain accumulation occurs). On the other hand, simulations also indicated that crop yields could be negatively affected by mal-adaptation. In Big Bend, planting early with the first rains, a practice common with dryland farmer in the region and other parts of Africa (Kassie et al., 2015) and applying very low fertiliser will likely exacerbate the negative impacts of climate change. Sorghum yields in Big Bend averaged a decline of -29% under such practices. These results motivated further investigation into the potential of local agronomic management practises for adapting to climate change, presented in *Chapter 5*.

6.2.4 Adaptation to climate change

Chapter 5 focused largely on investigating the potential of agronomic strategy adjustments for adaptation to climate change. By simulating agronomic strategies (planting dates, fertiliser amounts, and planting densities) singly and in combination under historical climate conditions (Table 5.4), it was shown that simulating combinations of agronomic strategies can help account for non-linear interactions of agronomic practices. Simply adding together the effect of singular agronomic practices to ascertain overall impact on yields and the effects of climate change in a linear fashion could over or underestimate the effects of on-farm agronomic strategy adjustments on yields. As such climate change adaptation investigations could be better informed by simulations that include various combinations of agronomic strategies, especially given that dryland farmers in southern Africa apply multiple agronomic practices at once by making choices about e.g. planting dates, fertiliser amounts to apply, planting density, tillage type and time etc.

Chapter 5 shows that adjustments of on-farm agronomic strategies have considerable effects on crop yields and can provide dryland farmers with easily accessible adaptation options. Results showed that adaptation benefits of on-farm agronomic adjustments vary from one location to the other. In Big Bend, where the climate is already harsh for maize production

and yields are strongly sensitive to temperature changes (Figure 5.1), the options for adapting through on-farm agronomic adjustments are limited compared to milder (Lilongwe) and cooler (Mohale's Hoek) locations. Most on-farm strategies simulated for Big Bend exacerbated the negative impacts of climate change. Yields declined by more than 30% with the practise of planting late and applying high fertiliser amounts. This suggests that dryland farmers in Big Bend are already "farming on the edge". Most households in the area are more engaged in off-farm activities for income generation (Table 5.1), but still grow maize for food due cultural preferences, thereby suggesting investment demanding adaptation strategies will be required to promote future yields e.g. irrigation. Farmers in Mohale's Hoek can obtain more that 25% higher future maize yields than under historically common agronomic practises by making appropriate on-farm agronomic adjustments. Farmers in Lilongwe can obtain up to 15% higher future maize yields (Table 5.5). It was found that the most beneficial adjustments e.g. late planting, with high fertiliser application in Mohale's Hoek were the most risky. However, lower risk options that include the application of modest fertiliser amounts of no more than 40 kg N/ha could still be beneficial. This is in agreement with findings of Folberth et al., 2013 who suggested that modest fertiliser applications of below 50 kg N/ha in SSA can yield sufficient future maize production levels. Farmers' socio-economic endowments or lack thereof can limit their ability to take advantage of some agronomic practises, and would need to be considered in recommending suitable adaptation practices. On-farm agronomic adjustments should however not be considered a cure-all for climate change adaptation in resource poor drylands, since more severe climatic change in the late 21st century can limit their usefulness (Folberth et al., 2014).

6.3 Implication of findings

Climate change impacts and adaptation research such as performed in this study can support already existing autonomous efforts of dryland farmers through providing insights into useful and accessible on-farm adaptation options. Such research can also help governments, policy makers and development organisations to better target adaptation investments to the needs of local farmers and to avoid unnecessary exhaustion of already meagre resources. Building on existing coping strategies in efforts to support adaptation, may contribute to overcoming prevailing food security challenges in resource constrained farming communities and

countries, while supporting sustainable future crop production. This thesis showed that there is potential to make use of already available low cost agronomic management strategies for climate change adaptation given additional efforts to identify these strategies. It was shown that it is vital despite stated challenges to quantify the potential impacts attributable to climate change at local levels and to investigate potential local adaptation solutions as opposed to large scale national and regional quantifications alone if research is to better inform local and regional decision making, interventions and policy. While improved projections will help to produce better assessments of future risk to future food crop production and potential solutions, uncertainties should not prevent adaptation, especially given that low cost and low risk adaptation options do exist as demonstrated in *Chapter 5* of this thesis. Low income countries in southern Africa have also shown that despite meagre internal resources, institutional and organisational constraints can be overcome to boost farm productivity of resource poor dryland farmers through encouraging and facilitating access to improved seeds and inorganic fertilizers e.g. the agricultural input support programme instituted between 2005 and 2010 in Malawi (Juma, 2011). Results from this thesis can be helpful in encouraging such efforts by demonstrating their long term benefits and potential for crop production under climate change.

6.4 Uncertainties and limitations of the study

The simulation results and conclusions of this thesis should be considered within the context of uncertainties inherent in the design of the study and the measures taken to mitigate them where possible. Uncertainties in a simulation study of this nature cascade through from selection of CO₂ emission pathways and GCMs, downscaling techniques used to provide location specific climate change projections, choice of crop models, parameterisation and structural uncertainty of crop models, choice of modelled agronomic conditions etc.

- Only one crop model was used, thereby limiting the simulation study to the structural bias of the DSSAT family of crop models. Parameterisation and validation was performed to try to reduce the uncertainties owing from the crop models. The effect of weeds, pests and diseases which are not accounted for by the model were also add another level of uncertainty especially given that farmers in dryland systems of the region operate under suboptimal conditions where such factors grow in importance.

The study was limited by the number of CO₂ emission scenarios (A2 and B1) and GCM scenarios (a total of 9) used. Although this allowed for sampling a wide range of plausible future climatic changes, access to more scenarios could have led to better uncertainty sampling. Statistical downscaling of GCM data applied in this study adds to overall uncertainty through the propagation of uncertainty inherent in the GCMs, possible failure to capture the degree to which topography, and land cover changes can feedback to impact local climate. Statistical downscaling is limited to the stationarity assumption, which may not hold under a changing climate. The effects of CO₂ fertilisation were not explicitly considered in the study. This is a major limitation. Although debates continue around the effects of enhanced atmospheric CO₂ on the growth and yield of crops, it is known that the effect is stronger in C3 crops (up to 10% increase in yields) than in C4 crops (below 5%) (Long et al., 2006; Tubiello et al., 2007; Ainsworth and Ort, 2010; Cairns et al., 2013; Kassie et al., 2015). Some of the results presented in this thesis could be different if enhanced CO₂ effects were investigated e.g. the small negative effect of climate change on maize yields in Lilongwe, particularly given the positive benefits of some on-farm agronomic strategy adjustments. Future changes in technology were also not considered in this study. Simulated agronomy was found to be a major source of uncertainty in climate change impact and adaptation studies. As such, it is important to sample as many agronomic management practices as possible to get a fuller picture of impacts and adaptation potential. In this study, three major agronomic practices in the region were sampled and an analysis of how yields respond to agronomic adjustments was performed. However, yields in dryland systems of southern Africa are likely influenced by many more agronomic choices that this study could not sample due to time and computational constraints and limitations of the crop models applied.

6.5 Recommendations for further study

Climate change impact studies of this nature could be made better and improved through further investigations and research around issues to do with improving data, crop modelling. Climate modelling, the investigation of agronomic strategies and integration of socio-economic data as summarised in this section;

Crop modelling: The crop modelling process in southern Africa could be improved through research that seeks to support

- Improved data sources through preparation and formatting of available trial data into a single data set, made available through a data portal.
- The inclusion of dryland farmers in experimental trials through farmer field schools (Stigter et al., 2013).
- Agricultural trials that target the collection of data relating to nutrient and water limitations along with variation of physical conditions and agronomic practices peculiar to dryland systems conditions.
- Proper documentation of how trials have been conducted to ensure that data is useful to crop modellers e.g. whether yields are expressed as fresh or dry matter, whether crop water use includes evapotranspiration or evaporation only etc.
- Improvements in crop modelling standards for climate change impact assessments such as the developing standards espoused by ongoing efforts under the AgMIP project (Rosenzweig et al., 2013) which is in its 2nd stage.
- Improvement of crop model parameterisation for input factors related to processes that affect crop growth under extreme weather conditions.
- Simulation of the effect of enhanced atmospheric CO₂ on crop growth and yields.

Climate modelling: The climate modelling process for impact and adaptation assessments in southern Africa could be improved through;

- Using downscaled data sets for more localised assessments. Downscaled projections are available for many locations in southern Africa through the Climate System Analysis Group (CSAG) at the University of Cape Town.
- Using more recent GCM projections from Comprehensive Model Intercomparison Project 5 (CMIP5) dataset. Although, IPCC (2013) and Grosse et al., 2014 suggest that there is overall consistency of large-scale climate patterns and the magnitudes of climate change of projections from CMIP3 and CMIP5, insights from impact modelling should constantly be re-engaged and evaluated as new climate model data becomes available as suggested by Wilby et al. (2004).
- Efforts to make GCM and downscaled climate projection datasets easily available to agricultural impact researchers through collaboration of climate data repositories in

the region, particularly national meteorological departments of countries in the region.

Agronomic strategies and socio-economics: Limitations to the location specific assessments include the limited agronomic strategies investigated and socio-economic data not being fully integrated with bio-physical simulations. Future research could;

- Include and test more agronomic strategies used in the region e.g. different crop varieties, crop residue incorporation and zero tillage (Nhemachena et al., 2014), staggered planting (Mhizha et al., 2014), crop rotation and intercropping (Kumwenda et al., 1996; Snapp et al., 1998), use of organic manure etc.
- Explicitly investigate the exact nature of interactions, co-benefits and the relative contributions of agronomic practices to overall benefits for autonomous adaptation
- Use of optimisation modelling to provide better information on best use of farmer resources in selecting agronomic management practices to prioritise (Crespo et al., 2010; Bergez et al., 2010). Development or adaption of methodologies to integrate socio-economic data to better identify suitable agronomic adaptation strategies for farmers.
- Exploration of various survey supported assessment methodologies e.g. cost benefit analyses and household vulnerability indices based on survey data.

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ANNEX

I. CO₂ fertilisation

Carbon dioxide (CO₂) fertilization refers to plant growth enhancement resulting from increased atmospheric CO₂ concentrations (Maunder, 1992). CO₂ has a direct effect on plants through increase in photosynthesis and reduction in transpiration. Ordinarily, plants adjust stomatal openings to balance CO₂ assimilation and transpiration. At enhanced concentration of CO₂, plants assimilate required CO₂ at a faster rate through reduced stomatal openings, at the same time reducing transpiration, this leads to increased crop yields (Blanc, 2011). This effect differs across crops depending on their CO₂ dependency. C₄ plants, such as maize, sorghum and millet, are more efficient at assimilating CO₂ than C₃ crops such as cassava, groundnut, soybean, and wheat (Kimball et al., 2002) and are therefore less CO₂ dependent.

Given that atmospheric CO₂ has been rising over the past couple of centuries and is predicted to continue into the 21st century, its effect on crops is of interest to crop impact modellers. Crop models have been used to simulate the impact of elevated CO₂ using parameters obtained from chamber experiments or Free-air CO₂ enrichment (FACE) experiments (Ainsworth et al. 2008). Some studies suggest that modelling studies using CO₂ fertilization factors derived from enclosure experiments may overestimate the field responses of crops to enhanced CO₂ fertilisation (Long et al. 2006; Ainsworth (2008); Ainsworth et al., 2008). Others argue that crop models are suitable for simulating enhanced CO₂ effects. Tubiello et al. (2007) report that even though some key models used in impact modelling studies have not been validated against FACE experiments (considered to provide a more realistic measure of the effect of elevated CO₂ on crop yield (Ainsworth et al., 2008)), those that have been tested against FACE data performed well and therefore crop models can be used for assessing enhanced CO₂ effects on crops. Nevertheless, several uncertainties remain about the strength of enhanced CO₂ effect on crop growth and yields on farmer's fields and therefore more research is required to better understand interactions of elevated CO₂ with increasing temperatures, changes in moisture and nutrient availability and altered incidence of pests, diseases and weeds (Tubiello et al., 2007; Vanuytrecht et al., 2012; Bassu et al. 2014).

Generally, research suggests that based on their CO₂ fixation pathways, C₄ plants are less affected by rising atmospheric CO₂ levels compared to C₃ crops that respond considerably. Yield gains with doubling CO₂ can be well above 15% for C₃ plants (Ewert et al., 2002; Ainsworth and Long 2005; Challinor and Wheeler, 2008; Vanuytrecht et al., 2012) while between 0 to 10% for C₄ plants (Long et al., 2006; Leakey, 2009; Bassu et al., 2014).

In this thesis, a methodological choice to perform climate change impact and adaptation assessment without accounting for the direct effect of enhanced CO₂ on crop development was made. This was done so as to obtain an understanding of the effect of temperature and rainfall changes on crop yields and particularly to understand the potential of agronomic effects on yields under climate change, without the added complexities emanating from uncertainties of enhanced CO₂ effects as highlighted above. This however is a limitation of the study. The study provides in discussion some insight into how this limitation could affect some of the results obtained. It should however be noted that although some figures and results of climate change impacts and adaptation potential could look different for some location, crops, and agronomic strategies with enhanced CO₂ effect simulations, the fundamental messages of this thesis remains unchanged.

A notable example of the limitation of the study regarding enhanced CO₂ effects is the case of maize and groundnut yields in Lilongwe – Malawi. Lilongwe presents a case where it can be fairly anticipated that simulated crop yield changes could have been considerably different had enhanced CO₂ effects been simulated. Simulated maize yield decline between the baseline (2000s) and future period (2050s) was small, averaging -5 %. Despite C4 crops being known to respond less to enhanced CO₂, a small positive effect of enhanced CO₂ (0-10%) could have meant the difference between a decline, no change or an increase in yields in Lilongwe. Coupled with the positive benefits of appropriate agronomic practices, simulated negative maize yields in Lilongwe could have easily been different. The simulation of CO₂ effects could have also altered the results of groundnut yield responses to climate change in Lilongwe. Although yields declined by up to 30%, enhanced CO₂ effects could have significantly moderated the negative impacts. However, given that the interaction of temperature, moisture and nutrient availability is likely to play an important role in determining the overall effect of enhanced CO₂ on crop yields, it can't be stated for sure how increasing CO₂ could have affected the results of this study for crops in Lilongwe and other investigated crops in Mohale's Hoek – Lesotho and Big Bend – Swaziland. Therefore, the results of this study should be interpreted in conjunction with an understanding of this limitation. Further studies in the region could seek to explicitly take into account the direct effect of increasing CO₂ fertilisation on yields with an understanding of the interaction with temperature, moisture and nutrients availability.

II. Sample farmer survey questionnaire

○ Hello. My name is _____.

○ I am working with the development programmes team of XXXX in this area. In order to get more information about development issues and quality of life in XXXX, we are conducting a census of households in the area. I would like to ask you some questions related to your household.

○ The information you provide will be useful to find out the status of quality of life in your household, and will be used to plan future development programs in this area and also in the country. XXXX is conducting this census on household vulnerabilities in all XXXX households.

○ Participation in the survey is voluntary, and you can choose not to take part. However; the information collected by this effort will be used for planning and guiding interventions for several years; and it is in yours households' interest to be part of this census. All the information you give will be confidential. The information will be used to prepare general reports, but will not include any specific names.

○ If you have any questions about the survey, you can ask me, my field supervisor who is here with the census team, or one of the development workers at XXXX in XXXX. At this time do you have any questions about the survey?

General Information

Name of Respondent:	Date:/...../.....	Start Time:	Stop Time:
Respondent agreed to be interviewed: 0 = No 1 = Yes			
Homestead Number (assign):			
Region ¹ :	Inkhundla ² :	Household Number (assign):	
		ADP Name ³ :	
Chiefdom:		Village:	

¹ 1 = Hhohho 2 = Manzini 3 = Shiselweni 4 = Lubombo

² 1 = Lomahasha 2 = Ngwenpisi 3 = Lugongolweni 4 = Shiselweni 5 = Mhlosheni 6 = Mpolonjeni 7 = Maphalaleni 8 = Bulunga 9 = Sithobela 10 = Gilgal 11 = Matsanjeni 12 = Ngudzeni 13 = Lubulini 14 = Nkilonko 15 = Ekukhanyeni 16 = Maseyisini 17 = Hlane 18 = Mbangweni 19 = Tikhuba 20 = Nhlabeni 21 = Mkhweni 22 = Madlangamphisi 23 = Gege

³ 1 = Lubombo 2 = Nkalashane 3 = Plateau 4 = Shiselweni 5 = Mhlosheni 6 = Mpolonjeni 7 = Maphalaleni 8 = Bulunga 9 = Sithobela 10 = Gilgal 11 = Matsanjeni 12 = Ngudzeni 13 = Lubulini 14 = Nkilonko 15 = Ekukhanyeni 16 = Maseyisini 17 = Shewula 18 = Mahlali 19 = Macuduvulwini 20 = Velezizweni 21 = Mkhweni 22 = Madlangamphisi 23 = Gege

Occupants (For 1-1 I include members who have stayed for three months and above)

I18, Record household members who have died in the last three months

B: GENERAL HOUSEHOLD DETAILS

Housing Structures

B1.1. Observe and state the material the house(s) is(are)made of (tick appropriately)	Bricks and Mortar	Concrete Blocks	Corrugated Iron	Pre-fabricated	Wood	Stick and Mud	Traditional hut	Grass	Stone
B1.2 Observe and state the material the roof is made of (tick appropriately)	Tiles/Slate /Concrete	Asbestos	Corrugated iron			Thatch grass	Other (specify)		Traditional hut

Services

B1.3 Paid Utility Services Is there any paid utility service? I=Yes 0=No	B1.4 If yes, what is the service type (tick appropriately)		B1.5 Is it currently active I=Yes/ 0=No , 99=n/a		If yes, what is the service type (tick)		Is it currently active I=Yes/ 0=No, 99=n/a	
	a	Water			d	Cellphone Network Access		
	b	Electricity			e	Other, Specify		
	c	Telephone line			f			

Assets and Utilities

Item	B1.6 No. functional	B1.7 No. not functional	Item	No. functional	No. not functional	Item	No. functional	No. not functional
a Car/van/bakkie/truck			g Radio			j Tractor drawn farm implements e.g. plough, cultivator, ridger, trailer, etc		
b Tractor			h Stove: (coal stove, electricity stove, hot plate, handigas stove, paraffin stove)			k Generator		
c TV			i Ox-drawn farm implements plough, cultivator, ridger, cart, etc			l Bicycle		
d Fridge/Freezer			j Bed			m Sewing machine		
e Cellphone			k Blankets			n Hand tools: Hoe, bush knife, Spear, Spade, Plough		
f Telephone			l Wheelbarrow			o Other (Specify):		

O	Milk and milk products					
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Food Availability	
DI.6a. Does this family receive food aid? (1=Yes/ 0=No)	DI.6b. If yes, when did household last receive? (1= last month, 2= last 3 months, 3= last 3 months, 4= more than 3 months ago)
DI.6c. If yes, from where? 1= WV 2=Government 3=other NGO 4= other (specify)	
DI.6d. If no, why? 1=not included in the list 2=conflicts 3= other (specify) 4 = no food distribution in area	

E. HOUSEHOLD ACCESS TO SERVICES					
Access to services	EI.1 Location (write name of location)	EI.2 Means of transport (1=Bus; 2=Car; 3=bicycle 4=motor bike 5=horse 6=Train, 7=On foot 8=other (specify))		Location (write name of location)	Means of transport (1=Bus; 2=Car; 3=bicycle 4=motor bike 5=horse 6=Train, 7=On foot 8=other (specify))
a Where is the nearest primary-school?			H Where is the nearest Bank?		
b Where is the nearest secondary-school?			I Where is the nearest agricultural inputs outlet?		
c Where is the nearest high-school?			J Where is the nearest NCPs?		
d Where is the nearest grocery/ supermarket?			K Where is the nearest VCT centre?		
e Where is the nearest grazing land?			L Where is the nearest bus station?		
f Where is the nearest police station?			M Where is nearest RDA's office?		
g Where is the nearest health centre?					

F. WATER, SANITATION AND HEALTH

		Water				FI.4 Time spend waiting at the water source (minutes)	
(i)	Water Source	FI.1 Use water source for drinking? I = Yes, 0 = No	FI.2 What source of water is used for the following?			FI.2.3 Both	
			FI.2.1 Domestic uses	FI.2.2 Agricultural (crop and livestock)			
a	Indoor tap						
b	Tap in yard						
c	Water tank – pumped						
d	Water tank – harvested rain						
e	Well in yard						
f	Bottled Water						
g	Communal tap/borehole						
h	Earth Dam						
i	River						
j	Spring						
k	Communal Well						
l	Canal						
m	Dam / Lake						
n	Other (Specify)						

Sanitation									
FI.5. Which type of toilet is mainly used by the household? (Tick appropriately)									
			Bush		Flush toilet		VIP toilet	Pit latrine	Other
FI.6. Current Status / condition of toilet (limit to pit latrine and VIP)				Poor		Fair		Good	
FI.7. How far is toilet / bush from homestead? (in metres)									
FI.8 How do you dispose of household waste? (Tick only one)				Pit		Burning		Municipal Waste	Recycle
Anywhere									
Health									
FI.9. Which type of Health Facility do household members mainly use?(Tick mostly used)									
Clinic/Hospital					Traditional Healers		Herbalist	Spiritual Preachers	None

G: EXTERNAL SUPPORT NETWORKS						
	List of support	G1.1 Get support 1= Yes, 0=No	G1.2 Source of support 1=Government 2=NGOs/CBOs/FBOs 3=Relatives 4=neighbours 5=churches 6=any other external support, 99=n/a	G1.3 Please rank adequacy of support offered on a scale of 1-3 (1= satisfied, 2= fair, 3= not satisfied, 99=n/a)		
a	Food					
b	Non-food basic					
c	Health					
d	Savings/Financial Services					
e	Transport to work					
f	Transport to clinic					
g	Burial expenses					
h	Farming inputs					
i	Recreation (sports equipment)					
j	School fees, uniforms, stationary					
k	Income Generating Activity					
l	Other (specify)					
G1.4 If household receives external financial support, how much do you receive per month?		1 =<E200, 2= E200 – E500, 3= >E500				
G1.5 Does household receive external social spiritual or counselling support?		Social (1= yes 0= No)	Spiritual (1= yes 0= No)	Counselling (1= yes 0= No)		
G1.6a. Do your household go to church? (1= yes 0= No)		G1.6b. If yes what denomination? 1= Zionist, 2=Pentacostal, 3=Catholic, 4=Anglican, 5=Jericó, 6= Other (specify)				
Sponsor Feasibility						
G1.7 Which are the most critical times in your children's lives do you feel you need external support		1=under five 2=school going age 3=teenagers 4= other (specify)				
G1.8 What form of assistance do the children usually need the most? List In order of priority		0=none 1= educational 2=food 3= clothes 4=medical 5=psychosocial 6= other (specify)				

G1.9 How often do the children usually leave or stay away from the community?	0=none 1= daily 2=weekly 3= monthly 4=at the end of term 5=one year 6=more than a year
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H: HOUSEHOLD INCOME				
H1.1. What are the household's two main sources of income? 1 = salary 2=informal work 3=livestock sales 4=crop sales 5=remittances 6=trading 7=donations from NGOs 8=government allowances 9=other (specify)				
	H1.2 1= Yes 0= No	H1.3 Amount /Type (for goods) Number of bank accounts:	H1.4 Has the balance increased or decreased within the last year (1= Yes 0= No)	H1.5 Reasons for increase or decrease
a Do you have bank accounts?				
b Have you received any remittances?				
c Have you joined any community or formal savings credit scheme?				
d Do you have any Unpaid debt?				
e Have you received any family/neighbour support?				
H1.6 Is the household participating in any Income Generating Activities (IGA) (1= Yes 0= No)				
H1.7 List livelihood activity available in households: (Circle all that apply)				
		1= crop production (maize, cotton, beans, sugar beans, soyabeans, sweet potatoes, jugo beans, cassava etc)	4= vegetable production (onions, cabbages, beetroot, spinach, tomatoes, green pepper etc)	
		2=handicraft	5=savings and credit	
		3= livestock production (poultry, cattle, goats, rabbits, piggery)	6=other (specify)	
NB- For the QH1.8 - QH1.10 use the following codes: 1=food 2= non-food basic goods 3=health 4=savings 5=transport to work 6=transport to clinics 7=burial expenses 8=farming inputs 9=beer and recreation 10=school fees 11 income generating projects 12=other (specify)				
H1.8 Where does the household spend most of its financial resources? Give 2 of the most common				
H1.9 Where would you spend any additional financial resources if they were availed to you? Give 2 of the most common				
H1.10 For what purpose did the household use financial resources from sale of crops/livestock from the last season? Give 2 of the most important				

OBSERVATIONAL (CONFIRM WHERE NEED BE)				
HI.11 Does household have a garden (1 = Yes, 0 = No)		HI.12 Does household have planted fruit trees? (1 = Yes, 0 = No)		HI.13 If yes, what type of fruit 1=oranges 2=mangoes 3=bananas 4=peaches 5=plums 6=other (specify), 99=n/a
HI.14 Is garden planted? (1 = Yes, 0 = No)		HI.15 If yes, what type of vegetables specify (specify)		HI.16 Is there a solid waste pit / trench? (1 = Yes, 0 = No)
HI.17 How would you rank the cleanliness of the yard?	Good (> 3 of 5)		Satisfactory (=3)	Poor* (< 3 of 5)

I: HIV/AIDS KNOWLEDGE	
II.1 Do you know what is HIV/AIDS (1=yes, 0=no)	
II.2 How is it transmitted? (1=Blood transfusion, 2=contact with infected blood, 3=sex with an infected person, 4=organ transplant of an infected person, 5=other, 99=n/a)	
II.3 How often are AIDS related issues discussed with parents (1=Rare, 2=Regular, 3=never)	
II.4 Information sources for HIV/AIDS (1=radio, 2=TV, 3=newspaper, 4=peer educators, 5=Health centre, 6=other)	

J: AGRICULTURAL PRODUCTIVITY				
	J1.1 Size of land	J1.2 Status of the land 0=poor/need improvement 1=satisfactory quality 2=good 88=don't know 99=n/a	J1.3 Asset Increase/reduced within the last year 0=did not change 1=increased 2= decreased 88=don't know 99=n/a	J1.4 Reasons for Increase or decrease of assets
a Land Size (acres/ha)				
b Land area forcibly taken from household (barred by relatives, the chief or other community member acres/ha)				
J1.5 Did you plant the previous year (2007/2008)? (1=Yes, 0=No) <i>If no please proceed to I.27</i>				
	J1.6 Size/ Amount	J1.7 Status of the land 0=poor/need improvement 1=satisfactory quality 2=good 88=don't know 99=n/a	J1.8 Asset Increase/reduced within the last year 0=did not change 1=increased 2= decreased 88=don't know 99=n/a	J1.9 Reasons for Increase or decrease of assets
a Land area under staple crop in the last season (acres/ha)				
b Total land area under crop cultivation in the last season (acres/ha)				
c Land fertilised by manure in the last season (acres/ha)				

d	Land available but not used due to illness or death in the last season (ha)											
e	Top dressing fertilizer used for staple crop (kg) in the last season?											
f	Basal fertilizer use for staple crop (kg) in the last season?											
g	Manure use for staple crop in the last season(bags/wheelbarrows/carts)											
J1.10	What proportion of land was cultivated last season?	(i) Whole area		(ii) > half		(iii) half		(iv) < half		(v) None		
J1.11	If not all land is cultivated, state reason (Tick all that apply)	(i) No farming inputs		(ii) No land		(iii) Child headed		(iv) Other				

Crops, Vegetables and Fruits											
J1.12 Crop Grown in 2007-2008 Season		J1.13 Area planted (ha)	J1.14 Variety I = hybrid, 2=indigenous, 3 =Both	J1.15 Seed Source I=purchased, 2=given, 3=raised	J1.16 Yield (units)		J1.17 Usage duration I = last for 3 months, 2= last for 6-8 months, 3= more than 8 months				
					Sold	Consumed					
a											
b											
c											
J1.18	Vegetables Grown	J1.19 Area planted (ha)		J1.20 Seed Source I=purchased, 2=given, 3=raised	J1.21 Yield (units)						
					Sold	Consumed					
J1.22	Fruit Tree	J1.23 No of Trees		J1.24 Seedling Source I=purchased, 2=given, 3=raised	J1.25 Fruit bearing period		J1.26 Yield (units)				
						Sold	Consumed				
J1.27	Do you have food storage facility? (I= Yes, 0= No)										

Livestock								
	J1.28 Total No	J1.29 Males	J1.30 Female	J1.32a Increased in the past year I = Yes, 0 = No	J1.32b Decreased in the past year I = Yes, 0 = No	J1.33 Reason for increase or decrease	J1.34 Uses I = draught, 2= commercial, 3= subsistence, 4=Other	J1.35 Owner I =Head, 2= Spouse, 3=Relative, 4=Son, 5=Daughter, 6=Grandparents, 7=Other (specify)
Livestock								

a	Cattle								
b	Donkeys								
c	Goats								
d	Sheep								
e	Pigs								
f	Poultry								
g	Other (specify)								

Agricultural Extension Services		Jl.36 I = Yes, 0 = No	Jl.37 If yes indicate No. of visits/month	Jl.38 If yes indicate time spent/ visit
a	Do you have access to agriculture extension services for livestock?			
b	Do you have access to agriculture extension services for crops			

K: HOUSEHOLD ENVIRONMENT

KI.1.1.	Measure taken on nature conservation during crop production? I= contour ploughing 2=organic fertilizers 3=strip farming 4=other (specify)	
KI.1.2.	Measures on nature conservation on livestock rearing? I=rotational grazing 2=reduce the number of livestock	
KI.1.3.	Do you burn grass around household? (I = Yes, 0= No)	
KI.1.4.	If yes when (I = dry season, 2= wet season)	
KI.1.5 Reasons for burning grass	a	
	b	
KI.1.6.	Do you do crop rotation? (I = Yes, 0= No)	If yes How?
Use and management of the environment within the last year		I = Yes, 0= No
KI.1.7	Have you ever resorted to cutting down trees and selling wood as a means of survival?	
KI.1.8	Have you ever resorted to collecting wild fruits because you do not have enough food to eat?	
KI.1.9	Do you practice environment management activities in your area? e.g tree planting, gully filling, manure collection	
KI.1.10	Have you had any awareness sessions on preventing environmental degradation?	
KI.1.11	Has sickness or death of a family member prevented you from managing your environment? e.g. tree planting, gully filling, manure collection, etc	
KI.1.12	Has sickness or death affected the amount or quality of water used by your household? E.g. resorting to collecting water from nearer but unsafe sources or failing to pay for piped water or failing to pay for repairs to safe water sources?	
KI.1.13	Has sickness or death prevented your household from ever developing or participating in planned water or environmental management projects? E.g. borehole drilling, tree planting, participation in community initiatives?	

L: HOUSEHOLD COPING STRATEGIES		I= Yes 0= No
L1.1.	Did household reduce size or number of meals a day, in the last 3 months?	
L1.2.	Did household have any days without eating all day, in the last 3 months?	
L1.3.	Did household change family diet to cheaper or less preferred foods, in the last 3 months?	
L1.4.	Did household resort to longer seasonal migration to find animal pasture, in the last 3 months?	
L1.5.	Did one or more household members work overtime or take another job, in order to have enough food to eat, in the last 3 months?	
L1.6.	Did one or more children discontinue school or had to work to bring income, in order to have enough food to eat, in the last 3 months?	
L1.7.	Did household sell or consume more of small livestock than usual, in order to have enough food to eat, in the last 3 months?	
L1.8.	Did household use money intended for investing in small business, in order to have enough food to eat, in the last 3 months?	
L1.9.	Did household sell some household possessions, in order to have enough food to eat, in the last 3 months?	
L1.10	Did household borrow food or money for food, in order to have enough food to eat, in the last 3 months?	
L1.11.	Did household sell agricultural tools or implements including other productive tools, in order to have enough food to eat, in the last 3 months?	
L1.12.	Did household sell or consume seed meant for planting next season, in order to have enough food to eat, in the last 3 months?	
L1.13.	Did household sell or consume more of large livestock than usual, in order to have enough food to eat, in the last 3 months?	
L1.14.	Did household sell or pledge any property / assets (e.g. land or house) in order to have enough food to eat, in the last 3 months?	

COMMENTS	
Question Number	Comments

III. Publications and conferences

Peer reviewed journal publications

Zinyengere N., Crespo O., Tadross M., Hewitson B., 2015. *Utility of agronomic management strategies for adapting dryland crop production to climate change in southern Africa*. Agricultural Systems. Submitted.

Zinyengere N., Crespo O., Tadross M., Hachigonta S., 2015. *Crop model performance in simulating crop yields in dryland systems of southern Africa*. South African Journal of Plant and Soil. 32(2): 94-105.

Zinyengere N., France M., Thabane K., Makatise P., Crespo O., 2015. *Effects of climate change on maize production in Maseru, Lesotho: simulation results using the PRECIS RCM*. Earth Science Research Journal. Submitted.

Zinyengere N., Crespo O., Tadross M., Hachigonta S., 2014. *Local impacts of climate change on dryland crops in southern Africa*. Agriculture Ecosystems and Environment. 197: 1-10.

Zinyengere N., Crespo O., Hachigonta S., 2013. *Crop response to climate change in southern Africa: A comprehensive review*. Global and Planetary Change. 111: 118-126.

Research briefs

Zinyengere N., Crespo O., Hachigonta S., Sibanda L.M., 2013. *Climate Change Adaptation in Southern Africa: Linking science studies and policy decisions to drive evidence-based action*. FANRPAN policy brief. Issue No. 1, Vol XIII.

Project reports

Zinyengere N., Crespo O., Tadross M., Hewitson B., March 2014. *Strengthening Evidence-based Climate Change Adaptation Policy (SECCAP)*. Report to FANRPAN/IDRC.

Zinyengere N., Kamanga M., Crespo O., March 2014. *Household Vulnerability to Disasters in South Africa: Vulnerability of rural farming systems to climate change in Limpopo and Eastern Cape provinces of South Africa*. Report to Financial Fiscal Commission of South Africa (FFC)/IDRC.

Zinyengere N., Crespo O., Hachigonta S., 2013. *Assessing the impacts of climate change on crop production and farming strategies in southern Africa*. Report to ACCFP/ START.

Conference/presentations and posters

Zinyengere N., Crespo O., Tadross M., Hewitson B., 2015. *Exploring on-farm adaptation options under climate change in southern Africa*. 9th International Conference on Community-Based Adaptation, 23-30 April, Nairobi, Kenya. (poster)

Zinyengere N., 2015. *Adaptation to climate change in African Agriculture: Opportunities for crop production under resource constraints?* International Conference on Research Evidence and Research-Policy Linkages for Adaptation to Climate Change in Africa 10-12 March 2015, Nairobi, Kenya. (oral)

Zinyengere N., Crespo O., Tadross M., Hachigonta S., 2014. *Projecting the local impact of climate change on food crops in southern Africa*. Combined Crops, Soils, Horticulture and Weeds Congress, 20-23 January 2014, Grahamstown, South Africa. ***Awarded best student presentation in crop science***. (oral)

Zinyengere N., Crespo O., Tadross M., Hachigonta S., 2013. *Impact of climate change on dryland food production in southern Africa*. 11th Conference of the African Crop Science Society, 14-17 October. Entebbe, Uganda. (oral)

Zinyengere N., Crespo O., Hachigonta S., 2013. *Projected Impacts of 21st Century Climate on Crops in southern Africa*. Combined Crops, Soils, Horticulture and Weeds Congress , 21-24 January 2013, UKZN, Durban, South Africa. (oral)

Zinyengere N., Crespo O., Hachigonta S., 2012. *How will 21st century climate affect crops in southern Africa?* Pan African Chemistry Network (PACN) Congress on Agricultural Productivity, Water and Waste. 26-28 November, Addis Ababa, Ethiopia. (oral)

Zinyengere N., Crespo O., Hachigonta S., 2012. *Adapting smallholder crop production to an uncertain future climate in Southern Africa*. Annual Conference of South African Society of Atmospheric Scientists. 26-27 September. Cape Town, South Africa. (oral)

Zinyengere N., Crespo O., Hachigonta S., 2012. *Improving crop management strategies under a changing climate in Southern Africa: A preliminary assessment*. International Conference on Climate Change, Population and Development in Africa, 1- 4 July. University of Ghana, Ghana. (oral)