IMPACT OF CLIMATE CHANGE ON SMALLHOLDER FARMING IN ZIMBABWE, USING A MODELLING APPROACH

By

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is the result of own work except for contribution in facilitation of farmer group discussions and interviews by team members from the IDRC/CCAA project number 104144, which has been fully acknowledged. I also declare that this thesis has not been submitted to another university.

Signature:...

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Abstract

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Agriculture is pivotal to the development of most countries in southern Africa, including Zimbabwe, with the sector contributing significantly to the Gross Domestic Product of these countries. The sector also provides labour to the majority of people and most rural populations in these countries derive their livelihoods from agriculture. The relative contribution of agriculture to national economies and to food security is, however, being reduced by climate variability and change. Smallholder farmers in semi-arid areas of Africa are particularly vulnerable to climate variability and change. The overall objective of this study was to establish the extent to which maize yield in the smallholder farming sector of semi-arid Zimbabwe could be affected by climate change, by 2050. The study also sought to establish trends in extreme temperature and rainfall indices, current farmer cropping practices and their current coping/adaptation strategies to climate variability and to assess the likelihood that farmers would adopt selected strategies of adapting to climate change. The study areas, Lower Gweru and Lupane communal areas are located in agricultural regions with low potential, being in Natural Regions III and IV, and lie in the central and western parts of the Zimbabwe, respectively.

Extreme temperature and rainfall indices for Bulawayo Airport meteorological station which is in western Zimbabwe and equidistant from the two study areas, Lower Gweru and Lupane, were computed and their linear trends were calculated for the period 1978-2007 using the Statistical and Regional dynamic Downscaling of Extremes for European regions (STARDEX) software. Significance of the trends was tested using the Kendall-Tau's test. It was found that for the period 1978 to 2007, cold extremes represented by frequency of cold days, coldest day-time and night-time temperatures did not show evidence ($p>0.05$) of warming or cooling for Bulawayo. Warm extremes, however showed significant warming ($p<0.05$), particularly during winter and spring as well as for the year. The greatest signal for warming was shown by trends in hottest day-time temperature and frequency of hot days. Trends in mean diurnal temperature range were positive, but only significant ($p=0.05$) during the winter season, while trends in extreme low (10th percentile) and extreme high (90th percentile) diurnal temperature range were also positive but insignificant ($p>0.05$) across all

seasons. Increasing trends in diurnal temperature are not consistent with climate change, suggesting that warming evidenced by warm extremes are probably not due to climate change per se. Only three indices, two of which are less commonly used indices, namely mean dry spell length during the dry season (April, May and June), the longest dry spell during the first half of the rainfall season and the correlation for spell lengths during the second half of the rainfall season (January, February and March) season, show significant trends ($p<0.05$).

Both quantitative and qualitative methods were used to establish agronomic practices of farmers, constraints they faced and their coping strategies to climate variability. Methods used to collect data included structured interviews with farmers, semi-structured interviews with key informants, focus group discussions and a desktop study. Farmers commonly have coping strategies to address some of the general constraints they encounter in agricultural production as well as strategies to cope and adapt to current climate variability. The study has identified a number of research and extension interventions which may enhance crop productivity in the smallholder farming sector in semi-arid western central Zimbabwe.

Effects of climate change on days to physiological maturity, maize yield and soil water balance components were simulated using the Agricultural Production Systems sIMulator (APSIM) model version 7.3, for maize grown in Lower Gweru, on a sandy soil. Simulated yields and water balance components were compared across three climate scenarios, the current climate (representing no change in temperature and rainfall, and a CO_2 concentration of 370 ppm); Future climate 1 (representing a temperature increase of 3°C, rainfall decrease of 10% and CO_2 concentration of 532 ppm) and Future climate 2 representing a temperature increase of 3°C and a rainfall decrease of 15% and CO_2 concentration of 532 ppm. The reference period for future climate is the year 2050 under the A2 Intergovernmental Panel on Climate Change (IPCC) CO_2 emission scenario. The climate change scenarios were created by perturbing the observed climate data for Gweru Thornhill meteorological station near Lower Gweru. A sensitivity test was done using a range of temperature changes (+0.5 to 3.5°C) and rainfall changes (+5 to -20%) as well as under a range of CO_2 concentration (420 to 700 ppm) and all under nitrogen non-limiting conditions. Results of this test showed that CO_2 offsets the negative effects of both high temperature increases and rainfall reductions with temperature increases in the low range of 0.5 to 1.5 °C, increasing maize grain yield at higher CO_2 concentrations of 580 and 700 ppm. Thus the greatest yield reductions due to either increased temperature or reduced rainfall amounts occurs at lower rather than higher atmospheric CO_2 concentrations. The results of this test also show that maize grain yield increased with increased CO_2 concentration and suggest that temperature and rainfall changes contribute relatively equally to the overall effect of climate change on maize yield in central Zimbabwe.

Significant differences among treatment (different climate scenarios) means were tested using non-parametric tests, namely the Kruskal-Wallis and Mann-Whitney tests for independent samples, for simulated data that were not normally distributed, while for normally distributed data, t-test for independent samples was used. Climate change significantly ($p<0.05$) reduced the number of days taken by both early and late maturing maize varieties to reach physiological maturity, with the late and early maturing varieties taking 29 and 23 days less, respectively, to mature under climate change compared to under the current climate. Under climate change days to maturity of the SC709 late maturing maize variety are reduced to a duration similar to that of the current early maturing variety SC403, grown under current climate. Therefore maize yields could be maintained by shifting from early maturing to late maturing varieties, in the face of climate change. Climate change reduced maize yield, with slightly greater reductions obtained under the drier climate change scenario of 15% reduction in rainfall. Grain, biomass and stover yields were reduced by 13% for the early maturing variety SC403 while for the late maturing variety SC709, these yields were reduced by 16, 18 and 20% respectively. However, the only significant ($p<0.05$) yield reduction was that for stover of the late maturing variety. Climate change reduced the amount of water available at sowing by 8-10%, seasonal soil evaporation by about 10% and transpiration by 5-8%. It also reduced the amount of runoff and drainage by about 26-38%, with greater reductions occurring under the drier future climate. However, the reductions were not significant ($p>0.05$) for any of the components except for runoff. Significant reductions in seasonal runoff due to climate change results in reduced water availability from surface water resources and this calls for efficient use of water.

Lower Gweru farmers' opinions on climate change effects on agricultural productivity and their possibility of adopting selected adaptation strategies against climate change were established during focus group discussions with a total of 36 farmers. Pre-requisite exercises for capturing farmers' reactions to climate change included presentation of the outcome of a survey on farmer perceptions on climate variability and change that had been conducted during 2008 and presentation of the projected climate for Zimbabwe, by 2050. To facilitate discussions on farmers' likelihood of adopting long season maize varieties, use of mulch and planting basins, in the face of climate change, simulated maize grain yield and soil water balance under different climate and agronomic scenarios were presented to the farmers in simple graphical form. Annual simulated yields and water balance were presented for the latest 10 seasons, 1998/99 to 2007/08 seasons. Farmers provided their responses in three groups that were formed based on wealth ranking. All farmers irrespective of wealth category, envisaged negative impacts of climate change on agricultural productivity. They also expressed concern on the likelihood of reduced water availability; reduced food and nutrition security, increased number of school drop-outs and a decline in their general well-being. Farmers did not provide alternative strategies (to deal with climate change effects) to those they use to cope with current climate variability. Also most of their responses were biased towards crops and these ranged from crop choice, reduced input levels and use of water conservation techniques. Farmers also recommended an expansion in irrigation development by the government. The resource rich farmers suggested supplementary pen feeding of livestock as an adaptation strategy against climate change. Smallholder livestock producers can employ other adaptation strategies, which include shifting towards small livestock and browsers rather than the current cattle and grazers. Although use of mulch and planting basins clearly improved soil water balance in terms of reducing the amount of soil evaporation and runoff, this did not translate into an overall increase in maize yield. However, in relatively poor rainfall years both mulch and planting basins gave higher yields than conventional ploughing without mulch. Thus, use of reliable seasonal rainfall forecasts can help farmers to decide on when to use mulch and/or basins. Farmers showed that it was relatively easy to shift from growing early maturing maize varieties to late maturing varieties, but indicated that the cost of hybrid seed and its availability have always been prohibiting factors. They are unlikely to adopt the use of mulch and planting basins due to high labour requirements and limited access to "extra" fertilizer required when mulch is used. Mulch availability is also limited as its main source, stover, has other uses that compete with use as mulch. It appears planting basins are a more important alternative for land preparation and crop establishment for farmers who do not have draft power than for those with draft animals.

It can be concluded that warming is taking place for the station (Bulawayo Airport) considered in this study and this is particularly evident from warm extremes. There is, however, limited evidence of changes in rainfall extremes. Similar analyses as those done for Bulawayo Airport station should be done for more stations and for longer periods. Climate change was found to significantly reduce the number of days taken by maize to reach maturity, with the long-season variety taking about the same number of days to mature under climate change as the short season variety, under current climate. Maize yields are also negatively affected by climate change. Results from the study also indicate that there is a significant reduction in runoff due to climate change. These effects have implications on food and water availability, hence the need to put appropriate adaptation strategies and policies in place. It was encouraging to note that, generally, smallholder farmers in the study area had a sound inference of the likely impact of climate change on agriculture and their well-being. They were also able to suggest possible strategies to deal with climate change, given the expected rainfall and temperature projections for Zimbabwe by 2050.

Smallholder farmers in the study area use several strategies to cope and / or adapt to the numerous constraints they face in crop production. Strengthening farmers' capacity to employ these strategies will improve crop productivity. Based on the current farmer practices in the study areas, the study has identified both research and extension interventions that could be used to increase productivity in the study area and in similar biophysical and economic environments.

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List of Abbreviations used

ACT	African Conservation Tillage Network
AGRITEX	Agricultural Technical and Extension Services, Zimbabwe
AIDS	Acquired Immune Deficiency Syndrome
APSIM	Agricultural Production Systems sIMulator
BD	Bulk Density
CCAA	Climate Change Adaptation in Africa
CCC	Canadian Climate Centre
CEEPA	The Centre for Environmental Economics and Policy in Africa
CGIAR	Consultative Group on International Agricultural Research
CIMMYT	International Centre for Maize and Wheat Improvement
CNR	Carbon-Nitrogen Ratio
CPR	Carbon-Phosphorus Ratio
CSAG	Climate Systems Analysis Group, Univeristy of Cape Town
CSIRO	Commonwealth Science and Industry Research Organization, Australia
DEEDI	Queensland Department of Employment, Economic Development and Innovation, Australia
DFID	Department for International Development, United Kingdom
DOY	Day of Year
DUL	Drained Upper Limit of soil profile
FAO	Food and Agriculture Organization of the United Nations
GCM	Global Climate Model
GMB	Grain Marketing Board, Zimbabwe
HIV	Human Immune Deficiency Syndrome
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IDRC	International Development Research Centre, Canada
IPCC	Inter-governmental Panel on Climate Change
IIRR	International Institute of Rural Reconstruction, Kenya
LL15	Lower Limit of water extraction by a plant from a soil profile
NASA	National Aeronautics and Space Administration, USA
NCDC	National Climatic Data Centre, USA
NGOs	Non-Governmental Organizations
NOAA	National Oceanic and Atmospheric Administration, USA
OPV	Open Pollinated Variety
RadEst	Radiation Estimation
RMP_ICRISAT	Risk Management Project_ICRISAT
SADC	Southern African Development Community
SIPEAA	Strumenti Informatic: per la Pianificazione Eco-compatible delle Aziende Agararie (The Integrated Procedures for Evaluating Technical, Environmental and Economical Aspects in Farms), Italy
SPSS	Statistical Package for Social Scientists
SRES	Special Report on Emission Scenarios
UFS	University of the Free State

CHAPTER 1

GENERAL INTRODUCTION

Climate change is a topical subject of global importance as it is one of the major environmental changes affecting ecosystems and human lives. Its effects are being felt across various sectors of economic development including water resources, forestry, agriculture, fisheries, and health (Intergovernmental Panel for Climate Change [IPCC], 2007a). In this study the effect of climate change on rain-fed maize yield, of smallholder farmers in semi-arid Zimbabwe was assessed. The assessment was carried out using a crop systems model and was part of the International Development Research Centre (IDRC) / Climate Change Adaptation for Africa (CCAA) project (number 104144) entitled "Building Adaptive Capacity to Cope with Increasing Vulnerability Due to Climate Change and Variability" (Twomlow *et al.,* 2008a; Mugabe *et al*., 2010). The overall objective of the project was to "develop education, research and extension competencies to facilitate rural communities to increase their adaptive capacity to cope with risks and opportunities associated with climate change" (Mugabe *et al*., 2010). This research work fell under the fourth specific objective of the project which was to "apply crop modelling, seasonal climate forecasting and participatory action research to improve smallholder crop productivity and climate risk management in drought-prone regions of Zimbabwe and Zambia".

1.1. Background to study

There is consensus that climate is changing (IPCC, 2007b) mainly as a result of global warming, caused by both natural causes and human activity. The most notable aspects of climate change are temperature and precipitation changes and whilst there is much agreement among climate models that temperatures are increasing, there is less agreement among these models on how precipitation is changing across the globe (IPCC, 2007b; Ziervogel *et al*., 2008; Tadross, 2011). The limited agreement among climate models in the prediction of precipitation can be explained by the high variability associated with both the spatial and temporal variability of rainfall (Tadross, 2011). Ziervogel *et al*. (2008) pointed out that predictability of changes in climatic variables differs among regions, with changes in these variables being more predictable in some regions than in others, where different climate models would agree on the predicted change. Some models are also known to have better predictive skills for particular regions, although it is not advisable to rely on projections of a single or of only a few models (Ziervogel *et al*., 2008). According to Ziervogel *et al*. (2008), there is inconsistency in predictions for the December-January precipitation, for the southern Africa region, from an ensemble of 23 Global Climate Models (GCMs), while for the June-August precipitation, a large decrease is projected for 2090-2099 under SRES A1B emissions. The IPCC (2007b) also points out that there have been decreases in northern hemisphere snow cover; increases in the duration of heat waves during the latter half of the 20th century; widespread shrinking of glaciers, especially mountain glaciers in the tropics and increases in sea level, due to climate change (IPCC, 2007b). It has also been observed that climate variability is increasing while climate extremes such as floods, dry spells and droughts are likely to intensify in both magnitude and frequency, under climate change (IPCC, 2007b). Climate change is expected to take place at an unprecedented rate in future and the current coping strategies for climate variability and change may not be able to deal with future change (Barrios *et al*., 2008; Adger *et al*., 2003).

1.1.1 Climate change definition and future climate scenarios

The IPCC (2007b) defines climate change as *"*a change in the state of the climate that can be identified (e.g. by statistical tests) by changes in the mean and / or the variability of its properties, and that persist for an extended period, typically decades, or longer". Climate change may be due to natural internal processes or external forcings or persistent anthropogenic changes in the composition of the atmosphere or in land use. Climate variability on the other hand refers to "variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes etc.) of the climate on all spatial and temporal scales beyond that of individual weather events" (IPCC, 2007b). The main driver of climate change is global warming and the IPCC in its fourth assessment report states that "Warming of the climate system is unequivocal as evidenced by observed increases in average air and ocean temperatures, widespread melting of snow and ice as well as rising global average sea level". Evidence of climate change also includes changes in terrestrial biological systems for example the shift towards earlier timing of spring events such as leaf unfolding and bird migration (Parry *et al*., 2008) and changes in types and abundance of plankton and fish (Parry *et al*., 2008; Rijnsdorp *et al.*, 2009; MCCIP [Marine Climate Change Impacts Partnership], 2012) that have been observed at high latitudes. Global warming is mainly due to the presence of naturally occurring atmospheric greenhouse gases such as water vapour, carbon-dioxide (CO_2) and methane (CH_4), ozone (O_3) and nitrous oxide (N_2O) which impede the escape of out-going long-wave radiation into space, thereby causing warming of the earth. The warming is enhanced by human activities such as burning of carbon-based fossil fuel and deforestation which emit greenhouse gases into the atmosphere and Parry *et al*. (2008) conclude that temperature increases are very likely to be due to anthropogenic emissions of greenhouse gases. Changes in land use also contribute to global warming and together with deforestation, changes in land use contribute about 20% of the CO_2 emitted in a year (World Bank, 2009) while 80% is accounted for by the burning of carbon-based fossil fuels such as coal, oil and natural gas. The highest emission scenario projects an increase of 2.4-6.4^{o}C in global average surface temperature, relative to the 1980-1999 base period, by the year 2100, while the rate of increase of temperature during the two decades, 2010-2030 is estimated at about 0.20^{o}C per decade across all IPCC emission scenarios (IPCC, 2007c). According to Wheeler (2007), however, the IPCC assessments (IPCC, 2007b) of global warming could be conservative as recent studies indicate accelerating change. The IPCC (2001; 2007b) projects high risk of extreme temperature events in future climates. In addition, warming is expected to cause a rise in sea level in the range 0.18-0.59 m during the period 2090-2099, relative to the 1980-1999 period, across all IPCC emission scenarios. For precipitation, there is less agreement among climate models on future projections than for temperature (IPCC, 2007b; Ziervogel *et al*., 2008) with projections over tropical regions being more uncertain than those at higher latitudes (IPCC, 2007b). However, at high latitudes there is a high probability (95%) that precipitation will increase while in the sub-tropics, precipitation is likely to decrease by as much as 20% by 2100. The likely ranges and best estimates (given as the difference in magnitude between the lower and upper limit values of the likely range) for global average surface air warming, differ for the different Special Report on Emission Scenarios (SRES) of the

IPCC (IPCC, 2007b) (Table 1.1). Projected sea level rise also differs, with the lowest CO_2 emission scenario (B2 scenario) having the least rise of 1.80-3.81 m and the highest emission scenario (A1F1) having the greatest rise of 2.59-5.89 m over the period 2090-2099, relative to the 1980-1999 period (Table 1.1). The IPCC SRES scenarios are based on projected future greenhouse gas emissions, particularly CO_2, which is in turn driven by factors such as social, economic and technological changes (Appendix I). Thus, social, economic and technological changes determine the level of vulnerability to climate change (IPCC, 2007c).

Table 1.1. Projected globally averaged surface warming and sea-level rise at the end of the 21st century (IPCC, 2007b)

	Temperature Change (°C at 2090-2099 relative to 1980-1999)		**Sea-Level Rise (cm at 2090-2099 relative to 1980-1999)**
Case	Best Estimate	Likely Range	Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations	0.6	0.3 - 0.9	NA
B1 scenario	1.8	1.1 - 2.9	18.0 - 38.1
A1T scenario	2.4	1.4 - 3.8	20.1 - 45.0
B2 scenario	2.4	1.4 - 3.8	20.1 - 42.9
A1B scenario	2.8	1.7 - 4.4	21.1 - 48.0
A2 scenario	3.4	2.0 - 5.4	23.1 - 51.1
A1Fl scenario	4.0	2.4 - 6.4	25.9 - 58.9

For the whole of Africa and in all seasons, warming is expected to be greater than the global mean values (IPCC, 2007b) and by end of the 21^{st} century, the median temperature increase will be between 3°C and 4°C, roughly 1.5 times the global mean response (Eriksen *et al.,* 2008). In addition, future warming is likely to be greatest over the interior of semi-arid margins of the Sahara and central southern Africa (Eriksen *et al.,* 2008). Drying is expected throughout southern Africa (particularly in the winter rainfall regions) while increases in rainfall over parts of eastern Africa are expected (IPCC, 2007b). According to Eriksen *et al.* (2008) and Kandji *et al.* (2006) evidence exists that the intensity of rainfall events and frequency of droughts are increasing in southern Africa.

1.1.2. Climate change effects

Climate affects various sectors of economic development including hydrology and water resources, agriculture and food security, forestry, tourism, manufacturing and health (IPCC, 2007a; Meadows, 2006). Any change in climatic variables is, thus, likely to affect these sectors. The largest known impact of climate change is on agriculture because of the size and sensitivity of the sector (Kurukulasuriya and Mendelsohn, 2008a; Mendelsohn, 2009). The magnitude of damage by climate change to African agriculture will depend on future climatic scenarios (Mendelsohn, 2009) and the type and level of inputs used for agricultural production (Dimes *et al.,* 2008). Kurukulasuriya *et al.* (2006) concluded that Africa is the continent that will be most affected by climate change with increased temperature and reduced rainfall, although impacts of climate change are unlikely to be uniform across Africa (Kurukulasuriya and Mendelsohn, 2008a) as hotter and drier areas such as western, central and southern Africa are likely to be affected most. In their study to test the sensitivity of farm revenues to future climate scenarios, Kurukulasuriya and Mendelsohn (2008a), also established that African farms were sensitive to climate especially temperature. The sensitivity was greater for dryland farms than irrigation farms with sensitivity elasticities for temperature and precipitation being 1.6 and 0.5 respectively, for the dry-land farms. Therefore, it is worrying to note that, according to FAO (2003), You *et al*. (2010) and Alexandratos and Bruinsma (2012), rainfed agriculture accounts for more than 95% of the cropland in sub-Saharan Africa.

1.1.2.1. Impacts on water resources

Water resources are already limited in Africa and most ecological and economic processes are dependent on water availability (Meadows, 2006). Schulze (2000) estimates marked reductions in runoff by 2050, using the UKMO global climate model under the IS92a emission scenario. The IS92a climate scenario represents a somewhat intermediate greenhouse gas (GHG) emission scenario of the six IS92 emission scenarios developed during 1990 and 1992 (IPCC, 2000; 2001) and compared to the IS92 scenarios, SRES scenarios mentioned/described in section 1.1.1. are based on an improved knowledge base of the driving forces for GHG emissions and other factors such as the difference in per capita income between developing and developed countries as well as the efficiency of resource use among the different regions (IPCC, 2000; 2001). The recommendation to develop "new" scenarios was also driven by the fact that the IS92 scenarios were developed with reference to the 1990 data (baseline), which were estimated data rather than actual measurements, as the observation data were not available at time of developing the scenarios (IPCC, 2000; 2001). Whereas the highest emission scenario for the IS92 series of scenarios is 35.8 Gt of carbon / year (IPCC, 2000), while that for the SRES is 29.0 Gt of carbon / year, by 2100. The lowest emission scenarios are 4.6 and 5.5 Gt of carbon / year, for the IS92, and SRES scenarios, respectively (IPCC, 2000; 2001). So the more recent SRES have a higher minimum value and a much lower maximum value with a smaller range. The significant reduction in runoff estimated for Africa predicted by Schulze (2006) is consistent with Arnell's (1999) estimated runoff reductions of 40%, 30% and 5% for the Zambezi, Limpopo and Orange River basins, respectively. Schulze (2000) however, highlights the high temporal and spatial variability of the hydrological systems in southern Africa, which makes it difficult to detect the impacts of climate change on hydrological trends. For Zimbabwe, rainfall-runoff simulation for a doubling of CO_2 scenario showed that a 15-19% decrease in rainfall and a 7.5-13% increase in potential evapotranspiration will result in a 50% decrease in runoff and a decrease of 30-40% in dam yields, by 2075 across the country (Climate Change Office in Zimbabwe, 1998). Reduced water levels may result in scaling down of irrigation operations, thereby reducing pasture and crop productivity. Zhu and Ringler (2010) also estimated a decrease in runoff of 20-30% by 2030 for the Zimbabwe part of the Limpopo basin. Reduced runoff will impact negatively on quality and quantity of domestic and industrial water sources as well as on production of hydropower (Erikisen *et al*., 2008). DEAT (2000) predicted increased intensity of rainfall events in eastern southern Africa while longer dry spells are expected (Meadows, 2006). The effect of higher intensity rainfall events is increased incidence of flooding (Eriksen *et al*., 2008). Increased temperatures due to global warming, are also likely to have negative effects in water quality (Meadows, 2006). Annual average river runoff and water availability are projected to increase by 10-40% at high latitudes and in some wet tropical areas, by mid-21st century (IPCC, 2007c).

1.1.2.2. Impacts on crop yields

There are potential yield benefits from increased atmospheric CO_2 concentrations as CO_2 increases photosynthesis for both C3 and C4 crop species. Growth response to enhanced CO_2 concentration is generally known to be greater for C3 than for C4 species (Lawlor, 2005; IPCC, 2007a). Crop and pasture yields may also potentially increase due to higher water use efficiency caused by reduced stomatal conductance under elevated CO_2 concentrations (Lawlor, 2005, Tubiello *et al.*, 2007). However, plant response to enhanced CO_2 concentrations may be limited by increased temperature and changes in precipitation (Tubiello *et al.*, 2007). Low soil nitrogen and phosphorus, which is largely the case in many parts of Africa, may also limit plant response to increased CO_2 concentrations (Lawlor, 2005; Tubiello *et al.*, 2007; Cheng *et al.*, 2010). According to Cheng *et al.* (2010) elevated CO_2 concentration may stimulate cation release from soil and enhance plant growth, over the short term, but over the long-term, CO_2-induced cation release may facilitate cation losses and soil acidification. For the southern Africa region, decrease in potential yields is likely to occur as a result of hastened growth and development due to increased temperatures (Rosenzweig and Liverman, 1992; Gordo and Sanz, 2010, Wang *et al*, 2011) and reduced rainfall amounts resulting in water stress. Thus, the actual effect of climate change on crop yields will depend on the interactions between all these various factors. Changes in temperature, CO_2 concentrations and rainfall will have effects on population dynamics, life cycle durations, development, survival, distribution and reproduction of insect pests and pathogens (Gornall *et al.*, 2010; Petzoldt and Seaman, 2010; Fand *et al.*, 2012). Changed patterns of crop production, due to climate change, will also influence the type of pests and pathogens affecting crops. Thus the pest status of these organisms is influenced by climate change, bringing with it changes in the pest and disease management strategies (Petzoldt and Seaman, 2010; Fand *et al.*, 2012). Just like with crop plants, growth and development of weed species is directly and indirectly affected by increased temperatures, changes in rainfall patterns and an enhanced CO_2 atmosphere (Ghannoum *et al.*, 2000; Tang *et al.*, 2006; Ziska, 2010). Thus, the differences in response to these environmental changes by different plant species (crops or weeds) will determine the level of crop-weed interactions in a given cropping system. In most tropical regions, the major food crops are C4 cereals namely maize, sorghum and millets. In such cropping systems, C3 weed species are likely to exert greater competition for resources compared to C4 weed species (other factors remaining equal), as C3 plant species generally show greater and positive response to elevated CO_2, than C4 plants (Lawlor, 2005; IPCC, 2007a).

Several studies have been carried out which show that crop yields in the African region are likely to decrease under future climate (DEAT, 2000; Turpie *et al*., 2002; Jones and Thornton, 2003; Meadows, 2006; IPCC 2007b; Schlenker and Lobell, 2010). Therefore, African communities, in particular those in the sub-Saharan region, are thought to be the most vulnerable (Adger *et al*., 2003; Barrios *et al*, 2008; Challinor *et al.,* 2007; IPCC 2007b; Mertz *et al*., 2009) because of multiple stressors and limited adaptive capacity. In addition, Kurukulasuriya *et al*. (2006) attribute vulnerability of the sub-Saharan African region to the fact that the region already experiences high temperatures; low and highly variable rainfall; countries' economies are highly dependent on agriculture as well as being due to low adoption of modern technology. Tubiello and Rosenzweig (2008) in their review and synthesis of agricultural impacts of climate change, concluded that moderate warming (up to 2^{o}C) in the first part of the 21st century may benefit crop and pasture yields in the temperate regions, but have an opposite effect of reducing crop yields in the semi-arid and tropical regions. However, further warming that is expected during the second half of the century will likely reduce crop yields in all regions (Hertel *et al.,* 2010). Schlenker and Lobell (2010) in their analysis of effects of climate change on African yields, using historical climate and crop production data estimated a reduction in production of 22, 17, 17, 18 and 8% for maize, sorghum, millet, groundnuts and cassava, respectively. Makadho (1996) found varied simulated maize yield responses to climate change across four sites in four different Natural Regions (also called Agro-ecological Regions) of Zimbabwe, under rain-fed maize production. Half the stations consistently gave lower yields under climate change compared to current (1951-1991) climate while the other two stations had higher yields under climate change, particularly for early planted maize. The simulation outputs also showed that late planting would give lower yields under future climate, as it does currently. It was also established that the crop growing season could be shortened by as much as 17% compared to the current (1951-1991) season length. Tadross *et al*. (2009) projected a later start to the onset of the crop growing season compared to the current onset, due to climate change, for southeast Africa, including Zimbabwe. This change has implications on the growing season length and on crop yields, as delayed planting often results in reduced yields.

1.1.3. Adaptation to climate change in the Agriculture Sector

The IPCC (2001; 2007a) defines adaptation to climate change as "the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities". It defines vulnerability to climate change as "the degree to which a system is susceptible to, and unable to cope with adverse effects of climate change, including climate variability and extremes". Adaptation may be classified as autonomous or planned adaptation. Autonomous adaptation (also referred to as spontaneous adaptation) refers to "adaptation that does not constitute a conscious response to climatic stimuli, but is triggered by ecological changes in natural systems and by market or welfare changes in human systems" (IPCC, 2001; IPCC 2007a). It takes place without the directed intervention from a public or private agency (Aguilar, 2001). Planned adaptation on the other hand, is "the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return, maintain, or achieve a desired state" (IPCC, 2001; 2007a).

In agriculture, adaptation to climate change is already taking place (IPCC, 2007a; Kurukulasuriya *et al*., 2006; Mano and Nhemachena, 2007) as farming communities have a long record of coping and adapting to the impacts of weather and climate. According to Adger *et al*. (2003) and Burton and Lim (2005), farmers have always lived with changing climate and have shown considerable resilience to climate change and variability while Cooper *et al*. (2008) and IPCC (2007a) point out that adapting to current climate variability can increase resilience to long term climate change. However, although some adaptation to current climate variability is taking place, farmers may not necessarily display the same level of resilience in future, particularly, since according to Burton and Lim (2005), future climate changes are likely to occur at a rate faster than has been previously experienced in history. Challinor *et al*. (2007) also note that farmers have developed innovative responses to environmental changes, including climatic variability to create more sustainable production systems. However, extreme events such as droughts that have occurred in Africa especially in sub-Saharan Africa, in the last four decades, have shown that individual or community adaptation abilities may not adequately deal with these extremes (Challinor *et al*., 2007). Crop management can be altered in a number of ways to address effects of climate change. Tubiello *et al*. (2002), Challinor *et al. (*2007), Howden *et al. (*2007) and IPCC (2007a) suggest possible crop management strategies that can be employed to address effects of climate change including:

- Planting mixtures of crops and cultivars adapted to different conditions as intercrops,
- Using crop varieties that are more tolerant to climate stresses,
- Using mulch to cover the bare soil surface,
- Altering amounts and timing of irrigation and other water management practices,
- Altering the timing or location of cropping activities,
- Use of low-cost water-harvesting technologies where rainfall decreases and managing water to prevent water-logging, erosion, and nutrient leaching where rainfall increases,
- Diversifying income sources through integration with other farming activities such as raising livestock and
- Using climate forecasting to reduce production risk.

In Zimbabwe, Mano and Nhemachena (2007) identified adaptation strategies of smallholder farmers across the country to include dry and early planting, growing drought resistant crops, changing planting dates and using irrigation to cushion themselves against further anticipated adverse climatic conditions. According to Mubaya (2010) and Mubaya *et al*. (2010) current coping and / or adaptation strategies to climate variability for smallholder farmers in Zambia and Zimbabwe include winter ploughing, pot-holing, use of planting basins, ripping, resorting to cropping in gardens, resorting to off-farm sources of income and reliance on remittances from relatives working in towns or abroad. In their analyses of climate change effects on net revenues of selected African countries including Zimbabwe, Kurukulasuriya *et al.* (2006) suggest that where water is available, changing from dryland to irrigated agriculture would increase average net revenue per hectare as well as increase resilience of agriculture to climate change. However, funds for developing infrastructure would also be required. Deressa *et al*. (2009) in their study to determine farmers' choices of adaptation methods to climate change in the Nile basin of Ethiopia concluded that farmers' choices were determined by many socio-economic and environmental factors. This is confirmed by Wall and Smit (2005) who concluded that the "natural resource base of a farming system as well as the associated economic, social, cultural and political conditions determine the capacity of the s*ystem to* adapt to changing climate and weather conditions". Conclusions by Deressa *et al.* (2009) and Wall and Smit (2005) fall within the three categories of limits and barriers to adaptation to climate change that were identified by Jones (2010). These categories are:

i) Natural limits addressing both physical and ecological limits,

ii) Human and informational resource-based limits relating to knowledge, technological and economical limitations and

iii) Social barriers which comprise the psychological, behavioural and socio-institutional elements that determine how individuals and societies respond to climate stress.

Jones (2010) also notes that social barriers to adaptation are important and yet they are often neglected within wider adaptation debates. In this study (chapter 6), reasons for readiness or non-readiness by farmers in Lower Gweru area of Zimbabwe to adopt late maturing crop varieties, use of mulch and use of planting basins, in the face of climate change, will be established.

1.1.4. Importance of climate to Agriculture in Sothern Africa and Zimbabwe

In Southern Africa including Zimbabwe, agriculture is the mainstay contributing significantly to both food security and national economic development. Eighty percent of the population in this region depends on agriculture for subsistence, employment and income and the sector contributes 35% to the Gross Domestic Product (GDP) on average, for the region (Louw *et al*., 2007). In Zimbabwe, agriculture plays a pivotal role to the country's economy contributing 30-45% to total exports; 50-60% of materials required by the industrial sector and providing income and employment to 60-70% of the population (Matiza, 1999; Tekere and Hurungo, 2003; FAO, 2006). The sector also contributes 18-19.5% to the GDP and 66-70% to the labour force (FAO, 2006; CIA, 2011). According to Kinuthia (1997), southern Africa is prone to frequent droughts and uneven rainfall distribution in both time and space. Thus, in some years, the contribution of agriculture to food security and national economies in this region is reduced, these climatic factors. The climate of southern Africa is also highly variable and unpredictable. Climatic extremes including droughts and floods characterize the climate of the region and these often result in poor crop yields (Martin *et al*., 2000). In Zimbabwe 80% of total land area in the country falls within the marginal areas, Natural Regions III, IV and V and approximately 90% of communal farming land is located in these Natural Regions (Economics Division of the Ministry of Agriculture, 1996; FAO, 2006). More than 80% of Zimbabwe's total rural population consisting of smallholder farmers (communal, resettlement and small-scale commercial farmers) are located in these three Natural Regions (Bratton, 1994; Economics Division of the Ministry of Agriculture; 1996).

The influence of rainfall on crop yields can be illustrated by observed variability in the yields due to variability in rainfall. For instance in Zimbabwe, extreme variability in rainfall largely explains the 75% decline in smallholder maize production between 1980/81 and 1982/83 and the fivefold increase in production between 1982/83 and 1984/85 seasons (Rohrbach, 1989). In 1981 and 1985 unusually good rains were received whereas from 1982 to 1984 an unusually long drought was experienced. The decrease in cereal production of 5.1 million tonnes (45% reduction) experienced in the Southern African Development Community (SADC) region (excluding South Africa), due to the 1991/92 drought (FAO, 2004) also illustrates the significance of climate on agriculture in southern Africa. In Zimbabwe GDP fell by 3% and 11% after the 1983/84 and 1991/92 droughts, respectively (Kandji *et al*., 2006*)*. Droughts and prolonged dry spells, also negatively affect livestock production (Kinsey *et al*., 1998; Kandji, *et al*., 2006; FAO, 2009). In Zimbabwe, major floods do occur, but are not as frequent as droughts and they also often affect less people, but kill more people than droughts (PreventionWeb, 2012). In Zimbabwe, temperature is not as limiting as rainfall to summer agricultural production although, in the more arid areas of the country, the fairly high mean summer temperatures (18-21^{o}C) experienced, often render rainfall that is received less effective due to enhanced loss of soil water through evaporation. Mano and Nhemachena (2007) established that temperature and rainfall have significant effects (with increased temperatures having a negative effect and increasing rainfall a positive one) on net farm revenues in Zimbabwe and that farms with irrigation were more resistant to changes in climate, suggesting that irrigation is an important adaptation strategy to reduce the negative impacts of climate change.

1.2. Justification of study

There is consensus that climate is changing and that many sectors including agriculture will be affected under future climates. In Africa negative impacts are mostly expected and rural communities in this region are the most vulnerable. It is also envisaged that current coping strategies against climatic variability that the farmers are employing may not offset the impacts of future climate. The afore-stated circumstances call for action to be taken if agriculture is to continue to play its pivotal role of supporting national economies in Africa and ensuring household food security across the regions. Agriculture is particularly important to the rural communities as they rely on animal and crop production for their livelihoods. Although some research work (section 1.1.2) has estimated the likely magnitude of climate change impacts on crop productivity, these assessments have largely been at global, regional and national levels. In this study possible effects of climate change on crop productivity were examined at a more local level, the communal area level, in Natural Region III. Adaptation strategies to climate change and / or variability have been suggested by several authors (section 1.1.3). However, few studies have looked at how feasible it is for farmers to adopt these strategies or whether the current coping strategies (to climate variability) would still “work” under future climates. In addition, most of the studies on climate have not sought farmers' opinions on the envisaged future climate change scenarios. In this study farmers’ opinions on climate change and their likelihood of adopting selected strategies were also examined.

1.3. Aim and objectives of the study

1.3.1. Aim

The aim of the study is to use simulation modeling to evaluate the effects of climate change on crop growth and development and to test various adaptation strategies, under expected climate change scenarios for Lower Gweru and Lupane communal areas of Zimbabwe.

1.3.2. Specific objectives

1.3.2.1. To establish baseline data on current agronomic systems, crop production constraints, and coping / adaptation strategies to climate variability and change of farmers in Lower Gweru and Lupane communal areas.

1.3.2.2. To establish trends in extreme temperature and rainfall indices for a selected meteorological station in south western Zimbabwe.

1.3.2.3. To simulate crop growth and yields using the Agricultural Production Systems sIMulator (APSIM) model and to compare the various climate and agronomic scenarios.

1.3.2.4. To establish smallholder farmers' opinions on projected climate and test the likelihood for adoption of selected adaptation strategies for climate change, by farmers.

1.4. Outline of thesis

This thesis comprises eight chapters namely: General introduction; General materials and methods; Trends in extreme precipitation and temperature indices for Bulawayo Airport meteorological station in south-western Zimbabwe; Current agronomic practices, constraints and coping strategies of smallholder farmers in Lower Gweru and Lupane communal areas; Simulation of current and future climate effects on maize yield and soil water balance components under diffrent agronomoc scenarios, using APSIM; Simulating effects of tillage practice on soil water balance and maize yield of SC403 variety grown in Lower Gweru on a sandy soil, using APSIM; Opinions of smallholder farmers in Lower Gweru communal area on projected climate and possible adaptation strategies and Summary of findings and recommendations.

CHAPTER 2

GENERAL MATERIALS AND METHODS

2.1. Description of the study site

The research was carried out in two communal areas of Zimbabwe, namely Lower Gweru in Gweru District and Lupane, in Lupane District. Lower Gweru is located in Central Zimbabwe whereas Lupane is in the western part of the country. Choice of the communal areas was based on the International Development Research Centre / Climate Change and Adaptation in Africa (IDRC/CCAA) project (project number 104144) requirements for semi-arid areas, as the research was conducted under this project. Two wards from each communal area were selected for the study and these were Nyama and Mdubiwa wards in Lower Gweru and Menyezwa and Daluka wards in Lupane (Fig. 2.1). Nyama and Mdubiwa wards are adjacent to each other and lie about 45km north-west of Gweru city, the provincial capital of the Midlands Province. Gweru city is situated 19.42^{o} S and 29.83^{o} E. The recommended farming system in both Nyama and Mdubiwa wards is mixed farming comprising livestock enterprises combined with production of drought tolerant crops (Vincent and Thomas, 1962; Mare, 2010 - personal communication). Nyama ward has a high water table and hence more soil water is available for crop production than in Mdubiwa.

Daluka and Menyezwa wards are located about 10km south-east and about 25km north-west of Lupane town respectively. Lupane town lies at 18.93^{o} S and 27.77^{o}E and is the provincial capital of Matabeleland North Province. The recommended farming system in Lupane is semi-extensive, comprised mostly of cattle ranching, forestry and wildlife management, supported with production of drought tolerant crops.

Farmer interviews and group discussions were held with farmers from three randomly selected villages per each of the four wards (Table 2.1). Selection of wards and villages was influenced by proximity to good roads allowing access for the team.

Table 2.1. List of wards and villages from which household surveys and focus group discussions were conducted

District	Ward	Villages
Lower Gweru	Mdubiwa	Mxotshwa, Nsukunengi and Madinga
	Nyama	Matonsi, Guduza and Siyabalandela
Lupane	Daluka	Daluka, Strip road and Mafinyela
	Menyezwa	Menyezwa, Masenyane and Banda

Nearby meteorological stations are Thornhill whose latitude is19.450° S, longitude 29.850° E and at an altitude of 1429m and Lupane at latitude 18.933° S, longitude 27.767° E and at an altitude of 976m (see Fig. 2.1).

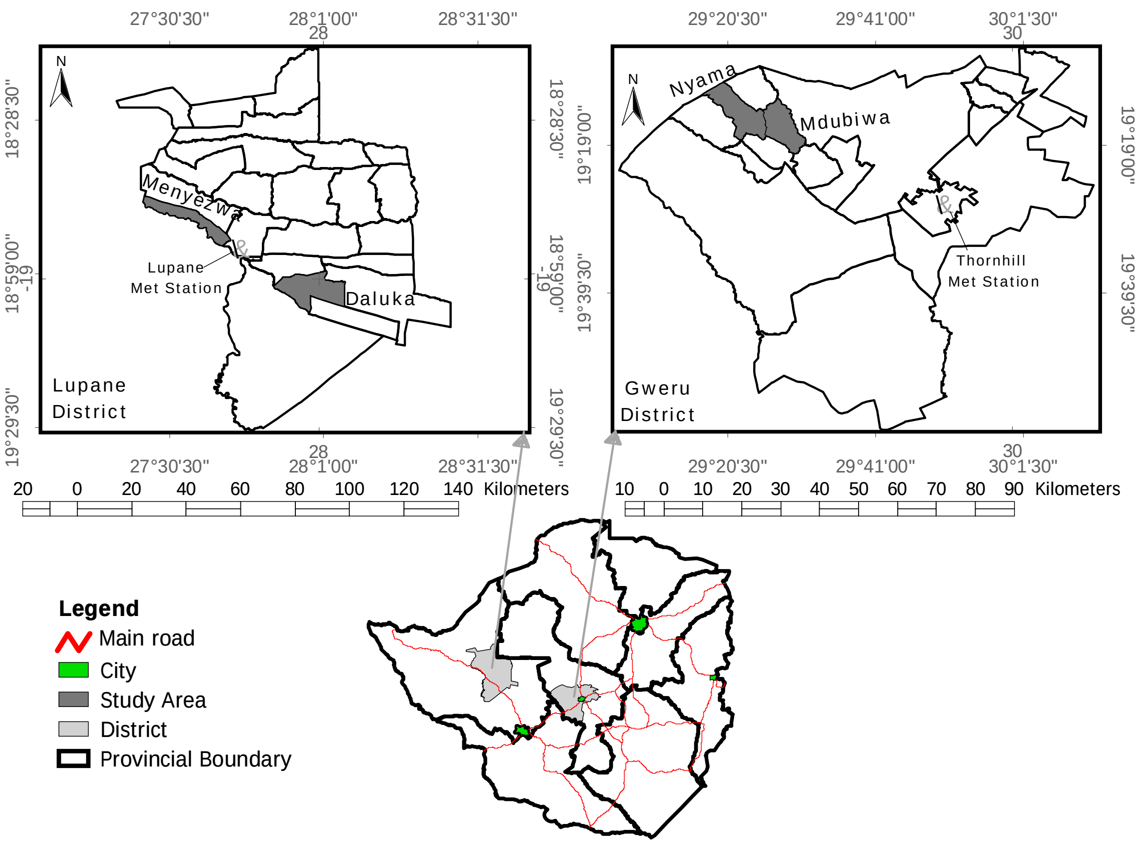


Fig. 2.1. Study area map made by the Department of Geography and Environmental Studies, Midlands State University, Gweru, Zimbabwe

2.1.1. Climate

Zimbabwe is a land locked country and lies between latitudes 15.5 and 22.5^{o} S and longitudes 25 and 33^{o} E. It experiences a sub-tropical climate. Rainfall is received in summer during the period October to April and its distribution is uni-modal with December, January and February being the peak rainfall months (Climate Handbook of Zimbabwe, 1981). Annual mean temperatures range from 15^{o}C on high ground to above 25^{o}C for low altitude areas (Climate Handbook of Zimbabwe, 1981). The country is divided into five Natural Regions (NRs), mainly according to differences in amount of rainfall received. Rainfall amount and reliability decrease while farming systems become less intensive from NR I to NR V (see Table 2.2). The study areas of Lower Gweru and Lupane, lie in NRs III and IV respectively, where in addition to relatively low rainfall, mid-season dry-spells and droughts are experienced (Vincent and Thomas, 1962). NR IV, however, experiences more dry spells and more frequent seasonal droughts than NR III. Rainfall in these regions is also characterized by infrequent short duration convective rainstorms of high intensities which often cause soil erosion. Temperatures are generally high, with annual mean maximum temperatures ranging from 20.5-30^{o}C for NR III and from 30.5-35^{o}C for NR IV (Muchadeyi *et al.,* 2007).

Table 2.2. Natural Regions of Zimbabwe and the recommended farming systems (Vincent and Thomas, 1962)

Natural Region	Land coverage (km^2)	Annual rainfall (mm)	Recommended farming system
I	7 000	>1 000	Specialized and diversified farming
II	58 600	750 - 1 000	Intensive farming
III	72 900	650 - 800	Semi-intensive farming
IV	147 800	450 - 650	Semi-extensive farming
V	104 400	<450	Extensive farming

2.1.2. Topography and soil type

Lower Gweru area is generally flat with moderate slopes. Altitude ranges from 1200-1345 m.a.s.l for both wards, with Mdubiwa being generally at a higher elevation than Nyama. Soils in both wards vary from moderately shallow greyish brown course grained sands throughout the profile to sandy loams over reddish brown sandy clay loams

(Midlands Province, Gweru District 1:250 000 soils map, 1994; Provisional 1:1 000 000 soils map of Zimbabwe-Rhodesia, 1979). The soils are derived from granitic rocks and are moderately to strongly leached. In the extreme north western and southern end of Nyama ward, there is a belt of Kalahari sands, characterised by very little or no reserves of weatherable minerals (Midlands province, Gweru District 1:250 000 soils map, 1994). Due to a high water table, much of the arable land in Nyama ward is wetland (vleis/dambos) where multiple cropping of horticultural crops as well as field crops can be carried out. There are two smallholder farmer irrigation schemes namely Mambanjeni and Shagari schemes in Mdubiwa ward. One major river, the Vungu River, a tributary of the larger Shangani River and few non-perennial streams run through the two wards.

The dominant soils in both Daluka and Menyezwa wards of Lupane are Kalahari sands. These sands comprise deep, unconsolidated and well drained tertiary sands of Aeolian origin and are highly infertile (Nyamapfene, 1991). Kalahari sands are also subject to severe wind erosion particularly if they are cropped (Thompson and Purves, 1978). Altitude for Daluka and Menyezwa wards is about 1080m.a.s.l. (Provisional 1:1 000 000 soils map of Zimbabwe-Rhodesia, 1979). There are two rivers in Menyezwa ward, Shabula to the east and Gwaai to the south, while the Lupane River traverses the Daluka ward.

2.1.3. Vegetation

Zimbabwe is characterised by Savanna woodlands interspersed with open grassed drainage lines or vleis (Shumba, 2001; Department of Agricultural Research for Development, 2009). In Lupane district the woodlands are typically *Baikiaea* (teak) and Mopane woodlands. The former woodlands are dominated by *B. plurijuga* and are predominantly found in the protected forest areas as they are of great commercial value (Shumba, 2001; Department of Agricultural Research for Development, 2009). Where the other woodlands have been degraded due to conversion to agricultural land, particularly in communal areas, there are only scattered woody spp. Other woody species found in association with *Baikiaea* woodlands include *Pterocarpus angolensis*, *Guibourtia coleosperma*, *Brachystegia spiciforrnis*, *B. boehmii, Julbernardia globiflora, Afzelia quanzensis, Kirkia acuminata, Burkea africana*, *Combretum* spp *and*

Commiphora spp (Ministry of Mines, Environment and Tourism in Zimbabwe, 1998a). Mopane woodlands are dominated by *Colophospermum mopane* and woodlands in this part of the country are described as dry early deciduous to distinguish them from Mopane woodlands found in other parts of the country (Ministry of Mines, Environment and Tourism in Zimbabwe, 1998a).

Gweru district consists predominantly of the Miombo woodlands, dominated by the *Brachystegia* and *Julbernadia* spp, in less disturbed areas. In settled areas where land has been opened up for agricultural purposes, for example, Lower Gweru, a wide range of scattered tree species exists. In Nyama ward, *Brachstegia spicimiformis*, *Julbernadia globiflora*, *Parinari curatellifolia* and *Terminalia* spp are the dominant spp whereas in Mdubiwa dominant species include *Acacia* and *Terminalia* spp. There are also scattered *C. mopane* trees in both Nyama and Mdubiwa wards and scattered *Syzygium* spp in Nyama ward. Dominant grasses in Lower Gweru include *Hyperannea* spp, *Heteropogony contotus* and *Rhynchelytrum repens* (Moyo and Musasanuri, 2010 - personal communication; personal observation).

2.1.4. Farmers' livelihoods

Livelihoods of farmers in both Lower Gweru and Lupane are derived from livestock, crop production, vegetable gardens and water sources such as boreholes and wells (Mubaya, 2010). In Lupane livestock is a more viable enterprise than cropping (Sikwela, 2008; Mubaya 2010), hence the greater contribution of livestock to food security and income generation in this communal area. Crop yields are generally low due to both low rainfall and poor soil fertility and as a result the contribution of crops to food security and income generation is relatively low. Vegetable production contributes significantly to food security and to a lesser extent, to income generation in Lupane. In Lower Gweru, horticultural production is the major livelihood, particularly in Nyama ward which has a high water table. Wetlands which are abundant in this ward, allow continuous cropping, particularly of vegetables. Exotic tropical fruits (mangoes, guavas and citrus) also contribute significantly to food security and income generation in Nyama ward. In Mdubiwa ward approximately 10% of farmers rely on smallholder irrigation schemes for production of vegetables and field crops such as maize and sugar beans (Moyo, 2010 -

personal communication). Farmers in Lower Gweru have readily available markets for these crop commodities, both locally and nearby in Gweru, as well as further away in Bulawayo.

2.2. Trends in extreme precipitation and temperature indices for Bulawayo Airport station (Chapter 3).

Historical daily temperature and rainfall data for Bulawayo Airport meteorological station (Fig. 3.1) were analyzed for significant trends. The latitude and longitude of the station are 20.017°S and 28.617°E respectively and the elevation is 1326 m.a.s.l. The length of historical observation data record available for analysis was 30 years covering the period 01/07/1978 to 31/12/2007 and the climate data were obtained from the Global Summary of the Day (GSOD) data set available from the U.S National Oceanic and Atmospheric Administration (NOAA)'s National Climate Data Centre (NCDC) (http://www.ncdc.noaa.gov/oa/ncdc.html).

Extreme temperature indices were computed from mean, minimum and maximum daily temperature and rainfall indices from daily rainfall data. The data used were obtained from the Zimbabwe Meteorological Services Department and Statistical and Regional dynamic Downscaling of Extremes for European regions (STARDEX) software (http://www.cru.uea.ac.uk/projects/stardex) was used to compute the indices.

2.2.1. NCDC data

NCDC data were obtained through the World Wide Web, http://www.ncdc.noaa.gov/oa/ncdc.html and by selecting the following options: *Data Access Tools → Global Surface Data → Map Services Data → Surface Data Global Summary of the Day → Access Maps.* Stations of interest were then selected by highlighting the area within about 100-150km radius of Gweru and Lupane towns and then picking on specific stations, by name and/ or co-ordinates. Climate variables included in the dataset for each station include temperature (minimum, maximum and mean; mean dew point); precipitation amount; mean station pressure and mean sea level pressure; wind speed and visibility. Measurements of these variables are in imperial units, so for this study units of temperature and rainfall were converted to metric units, degrees Celsius and millimetres, respectively.

The data exchange programme under the World Meteorological Organization (WMO)'s World Weather Watch Program guides provision of these data by the NCDC, according to WMO Resolution 40 (Cg-XII) (Global Daily Weather Data from the National Climate Data Center, http://www.ncdc.noaa.gov/oa/ncdc.html; and Global Summary of Day data set, http://gosic.org/ios/MATRICES/ECV/ATMOSPHERIC/SURFACE/ECV-GCOS-ATM-SURFACE-airpressure-GSOD-data-context.htm).

Before it is made available, original data are subjected to rigorous automated quality control checks (Global Daily Weather Data from the National Climate Data Center, http://www.infochimps.com/datasets/global-daily-weather-data-from-the-national-climate-data-center-; Smith *et al*., 2011). Quality control checks performed include validity checks; extreme value checks; internal (within observation) consistency checks and external (versus another observation for the same station) consistency test (Smith *et al*., 2011). Smith *et al.* (2011) also state that temperature and precipitation are among the parameters most extensively validated. The WMO (2011) provides a detailed description of these quality control checks.

2.2.2. Brief description of STARDEX

STARDEX was developed by the European Commission, to compare changes in frequency or intensity of extreme weather events between current and future climates. It is Dos-based and has two elements, a Fortran subroutine *extremes_indices* that calculates indices for a given location and a program *station_indices* that uses the Fortran subroutine to process station data in a standard input format (STARDEX Diagnostic Extremes Indices Software User Information, http://www.cru.uea.ac.uk/projects/stardex/deis/Diagnostic_tool.pdf).

The extreme climate indices are computed on a seasonal and annual basis for most indices and the default seasons are JJA (June, July and August), SON (September, October, November); DJF (December, January and February) and MAM (March, April and May), but these can be modified in *station_indices* file to suit user needs if necessary.

In STARDEX, indices can be computed from a file despite containing missing values, but the user has to specify the percentage of missing values permissible. The software also allows the user to specify the minimum number of days for which a percentile value should be calculated. The default is set at 15 days. Details of the climate indices computed and analyzed for presence or absence of trends and seasons considered in this study are explained in chapter 3.

2.3. Baseline study to establish current agronomic practices and coping/adaptation strategies used by smallholder farmers in Lower Gweru and Lupane communal areas (Chapter 4)

Current agronomic practices, constraints to crop production as well as coping/adaptation strategies of farmers in the study area were established using both quantitative and qualitative methods. Methods used to collect data include secondary data (Bless and Higson-Smith, 2000), semi-structured interviews (Bless and Higson-Smith, 2000; Mason, 2004; Flick, 2006; Gill *et al*., 2008; Newton, 2010) with agricultural extension personnel, structured interviews (Fowler, 1998; Bless and Higson-Smith, 2000; Mason, 2004; Punch, 2005; Gill *et al*., 2008; Newton, 2010) with heads of households and Focus Group Discussions (FGDs) (Steward and Shamdasan, 1998; Flick, 2006; Gill *et al*., 2008; Harrell and Bradley, 2009). A total of 48 farmers (four farmers per village) were selected for detailed household interviews, using random systematic sampling from household lists that were obtained from village headmen. FGDs were also held with farmers from the same wards and villages with five (5) farmers randomly selected from each village bringing the total number per discussion group per ward to 15. A questionnaire was developed and tested for the household survey while checklists were prepared for the FGDs. In FGDs farmers were grouped by ward and gender. Methods of data collection in FGDs included brainstorming, time charts, matrix scoring and ranking (Chambers, 1994; Sutherland, 1998). FGDs focusing on farming systems, opportunities and challenges, were carried out during October 2008 while those focusing on climate variability and change were carried out during January and February 2009 (Fig. 2.3). Household interviews were conducted at the same time as the second FGDs to solicit data on agronomic systems and practices, constraints to crop productivity as well as coping and adaptation strategies used by farmers. Frequency distribution graphs were mainly used to present quantitative data, while findings on qualitative data were narrated. Team members who participated in the 2008 FGDs included Chagonda, I; Makuvaro, V; Masere, P; Mubaya, C and Mutsvangwa, E, while, Chagonda, I; Makuvaro, V; Masere, P; Munodawafa, A and Murewi, C participated in the 2009 FGDs and farmer interviews.

2.4. Simulation of maize yields under different climate and agronomic scenarios, using the Agricultural Production Systems sIMulator (APSIM) model (Chapter 5)

The Agricultural Production Systems sIMulator (APSIM) (McCown *et al*., 1996; Keating *et al*., 2003) version 7.1 was used to simulate and compare maize (*Zea mays*) yields under different climate and agronomic scenarios for Lower Gweru. The model comprises crop, environment and management modules which interact together to simulate agricultural systems (McCown *et al*., 1996). Modules used to simulate the different agronomic and climatic scenarios include APSIM-Maize, Soil water module (SOILWAT), Soil N module (SOILN), Surface Organic matter module (SURFACEOM), Climate module and the Management module.

Maize is the staple food crop in Southern Africa. In Zimbabwe the crop is grown by more than 95% of subsistence farmers (Chiwenga, 2010) under rain-fed conditions. Of the total cereal area in Zimbabwe, maize constitutes of 75% (Smale and Jayne, 2003) and about 98% of the total maize area is under hybrid seed (Eicher, 2000 cited by Chiwenga, 2010). The per capita consumption of maize in this country is about 120kg per year (Smale and Jayne, 2003). The crop was therefore chosen for the study because of its contribution to household and national food security as well as income generation. Hybrid rather than traditional open pollinated varieties were considered because they are the most widely grown varieties in the study area.

2.4.1. Model input data

Input data required by the APSIM model include daily climate data (maximum and minimum temperature; solar radiation and rainfall), cultivar genetic characteristics, soil characteristics as well as crop and soil management data. Meteorological data used in this study were those for Thornhill Gweru station (latitude -19.45 ^{o} S, longitude, 29.85 ^{o} E and altitude of 1 429m) (Climate Handbook of Zimbabwe, 1981). The maize cultivars used were an early maturing variety SC403 and a late maturing variety SC709. SC403 is the variety grown by most of the smallholder farmers in Lower Gweru, which is a fairly dry area, whereas SC709 is currently grown under irrigation and to a lesser extent under rain-fed production in high rainfall areas of Zimbabwe. SC403 belongs to the same Seedco cultivar category, the 400 series, as SC401. The crop module in APSIM has descriptions of SC401which has parameters very similar to SC403 (Mupangwa *et al*., 2011a; Tumbo *et al.,* 2012). Similarly, the parameters of SC701 described in APSIM, are similar to those of SC709 which belongs to same cultivar category Seedco 700, as SC709. Hence parameters of SC401 and SC701 included in APSIM, were selected to describe the varieties SC403 and SC709, respectively. Soil parameters used were those of a soil typical of Mdubiwa ward, in Lower Gweru (See Tables 5.3a and 5.3b in section 5.2.8). Planting was set to occur at the first opportunity when 20 mm of rainfall was received in 5 days (Dimes *et al*., 2008). Soil N, soil water and residues were reset to initial conditions, before the start of the sowing window of each year. Simulation management details used, are provided in chapter 5. Maize yield and soil water balance components were simulated under current climate as well as future climate. For the current climate, carbon dioxide (CO_2) concentration was set at 370 ppm and temperature and rainfall changes were both set at zero. Future climate scenarios considered were based on the IPCC (2007b) A2 scenario projections (described in section 1.1.1 and in Appendix I). Two possible future climates were considered with combination of temperature and rainfall changes (Table 2.3).

Future climate scenarios were created by using the "Climate control" module in APSIM to perturb temperature and rainfall of the current climate by +3^{o}C for temperature and by -10% and -15% for rainfall and by setting CO_2 concentration at the required level of 532ppm.

2.4.2. Variables reported on and frequency of reporting

The model was set to report selected variables on a seasonal time step. The reported variables included total biomass, stover yield, grain yield, days to physiological maturity, in-crop rainfall, seasonal rainfall, surface runoff, soil evaporation, drainage and available soil water at planting.

Table 2.3. Climate scenarios used to establish climate change effects on crop productivity

Climate name	**Description**
Current climate	– Temperature change of $0^{o}C$ – Rainfall change of 0% and – CO_2 concentration of 370ppm
Future climate 1	– Temperature change of $+3^{o}C$ – Rainfall change of -10% and – CO_2 concentration of 532ppm
Future climate 2	– Temperature change of $+3^{o}C$ – Rainfall change of -15% and – CO_2 concentration of 532ppm

2.4.3. Model sensitivity analysis

A sensitivity test was conducted by simulating maize yield under varying temperature and rainfall change magnitudes as well as under varying CO_2 concentrations. The test was done to determine the range of effects of projected climate change on maize yield in the smallholder farming sector of Gweru District, in Zimbabwe. Five temperature shifts (0; +0.5; +1.5; + 2.5 and 3.5 ^{o}C) and six rainfall shifts (0; -5%; -10%; -15%; -20%; and +5%) were considered. The simulations were run under four CO_2 concentrations namely, 370, 490, 580 and 700 ppm. Details of the simulations (management practices and other input data) are outlined in section 5.2.5.

2.5. Opinions of smallholder farmers in Lower Gweru communal area to projected future climate and possible adaptation strategies (Chapter 6).

Smallholder farmers in Mdubiwa and Nyama wards of Lower Gweru area were engaged in discussions on climate change effects on agriculture. To facilitate the discussions, simulated maize yield and soil water balance components under different climate and agronomic scenarios, were shown and explained to farmers. Interactions with the farmers were made during FGDs held with the farmers over one and a half days. The FGDs were facilitated by three researchers namely, Dimes, John; Makuvaro, Veronica and Masere, Phillip. The aim of the FGDs was to seek farmers' views on the envisaged climate change projections for southern Africa, by 2050 and to establish any barriers to the adoption of identified adaptation strategies to climate change.

2.5.1. Farmer selection

A total of 36 farmers were selected from Mdubiwa and Nyama wards, with six farmers being selected from each of the selected villages in the two wards (Table 2.1). The farmers were selected using systematic random sampling from a list of 100 households for each village. Farmers were then asked to categorize themselves into three wealth groups, the "rich", "intermediate" and "poor", using criteria that they had suggested and agreed upon. Wealth ranking is a tool used widely in Participatory Rural Appraisal (PRA) (Jules *et al*., 1992; Mearns *et al*., 1992; Chambers, 1994; Loader and Amartya, 1999; Swathi Lekshmi *et al*., 2008). Criteria farmers used to group themselves in the three categories included cattle ownership, ownership of farming implements, access to labour and general appearance and/or condition of the homestead. Other researchers have used similar criteria for wealth ranking, examples being Swathi Lekshmi *et al*. (2008) in Namakkal district of Tamil Nadu, India and Ncube *et al*. (2009) in Tsholothslo, western Zimbabwe. A rich farmer was considered to be one with at least five head of cattle and with good access to either own or hired labour, owning brick houses with asbestos or zinc sheet roof and having at least a mouldboard plough and a cart. A poor farmer, on the other hand, was considered as one with zero or one animal and without any farming implements except a hand hoe. The poor farmer also normally provided labour for the rich and had poorly constructed buildings at the homestead, usually one to two grass-thatched huts.

2.5.2. Materials presented to farmers

To bring farmers to the same level (some farmers had participated in previous IDRC/CCAA climate project activities, while others had not), researchers gave a recap of the IDRC/CCAA climate change project activities that had been carried out in the wards since 2008 (Fig. 2.2). The farmers were provided with a summary of results of a survey carried out to establish farmer perceptions on climate change and variability during 2008 (Mubaya, 2010; Mubaya *et al*., 2012) and were asked whether they agreed or disagreed with those perceptions (Fig. 2.3). Climate (temperature and rainfall) projections for southern Africa by 2050 (A2 scenario) as provided by the IPCC (2007b), were then presented to the farmers. Researchers also presented APSIM simulated maize yields under current and future climates (Fig. 2.4 and 2.5). Simulated water balance components under conventional ploughing, mulch and basin were also shown to the farmers. This was done to help farmers appreciate the possible effect of climate change on the most commonly grown crop, maize and the benefits of using soil and water conservation practices.

Fig. 2.2. Researcher Veronica Makuvaro outlining previous IDRC activities in study area to farmers

Fig. 2.3. Researcher, John Dimes capturing farmers' views on perceptions of climate variability

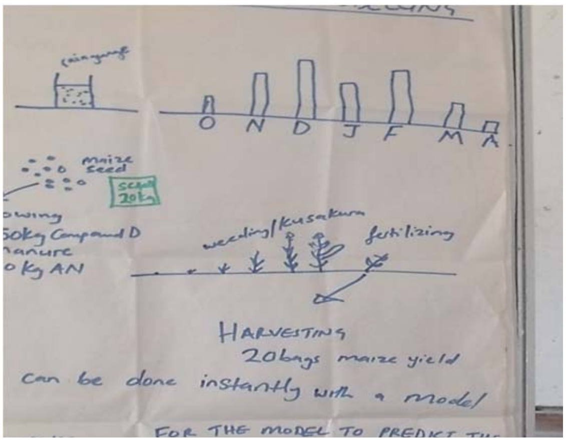


Fig. 2.4. Part of sketch diagram used to explain concept of a model to the farmers

Fig. 2.5. Farmers comparing outputs from APSIM model

2.5.3. Information solicited from farmers

Farmers were asked to give their opinion on the possible impacts that climate change could have on their farming operations, based on the climate scenarios presented with temperature and rainfall changes. They were also asked to suggest how they could reduce possible negative impacts or capitalize on any positive impacts that they had mentioned. Researchers then asked farmers whether or not they could readily adopt three strategies that could help reduce impacts of climate change. They were asked to provide reasons for readiness or non-readiness to adopt the strategies. The strategies discussed were: use of long season maize varieties, mulch and planting basins. Choice of growing long season maize varieties as a strategy was based on the researcher's finding from crop simulation modelling that there was less reduction in maize grain under climate change when a long season maize variety was used compared to a short season variety. The other two strategies were selected based on what farmers had suggested as adaptation strategies to climate change and these strategies are also components of conservation agriculture which is being promoted in the study area. Some examples of research work done on these aspects of conservation agriculture in Zimbabwe and other

Farmer responses were captured through brain storming and by letting the farmers respond to specific questions in groups formed according to the criteria described in section 2.5.1 (see Figs. 2.6 and 2.7).

Fig. 2.6. A woman farmer giving her contribution during a brain storming session

Fig. 2.7. Farmers seeking consensus for their response to a question

Individual informal interviews were also conducted with two farmers to get their views on possible adoption of the three selected strategies. One of the interviewed farmers was from Mdubiwa Ward and the other from Nyama Ward. They were interviewed at their homesteads, from which the researcher could observe and confirm some of the farmers' responses. Details of the farmers' demography and their responses are presented in chapter 6.

CHAPTER 3

TRENDS IN EXTREME PRECIPITATION AND TEMPERATURE INDICES FOR BULAWAYO IN SOUTH-WESTERN ZIMBABWE

3.1 Introduction

The subject of climate change is topical across the globe as there is growing scientific evidence that climate change is taking place (IPCC, 2007b). Climate change is characterized by increased temperature across regions, changes in precipitation, rise in sea level and increased frequency and intensity of climate extremes such as spells of high temperature, droughts and heavy storms (IPCC, 2007b). According to IPCC (2007b), global surface temperature has increased by about 0.74^{o}C between 1906 and 2005. Meanwhile, global models project further increases in magnitudes of change in the afore-mentioned climate variables (Groisman *et al*., 2005; IPCC, 2007b).

Changes in climate have an impact on natural and human systems. Most natural resource based sectors in the world, for example, fisheries, forestry, water resources management and agriculture are influenced by climate and hence any changes in climate are likely to impact on these sectors as well as natural processes such as evaporation and transpiration. It is, thus, vital to establish trends in climate variables as this will guide the nature of climate-related decisions and adaptation strategies employed by various stakeholders. In most developing countries the need to establish these trends is even more critical since these countries' economies are heavily dependent on rain-fed agriculture and the livelihoods of the majority of populations in these countries are agricultural-based (Rosegrant *et al*., 2002; Louw *et al*., 2007). In Africa, the need to establish climate trends is also quite pertinent given that Africa is deemed one of the continents most vulnerable to the effects of climate change (Adger, 2003; Kurukulasuriya *et al*., 2006; Challinor *et al.,* 2007; IPCC, 2007a; Barrios *et al.*, 2008; Mertz *et al*., 2009).

A number of authors including Mason *et al*. (1999), Groisman *et al*. (2005) and New *et al.* (2006) suggest that climate change can be better perceived through changes in extreme climate events rather than mean climate conditions. To this effect, Mason *et al*.

(1999) emphasize the need for analyses to detect changes in climate variables to focus on frequency and intensity of extreme events rather than on mean climate changes. This argument stems from the observation that discernible changes in frequency and intensity of extreme events may occur when there are only small changes in mean climate (Groisman *et al*., 2005). Chamaillé-Jammes *et al.* (2007) also highlight the masking effect of high climate variability on long-term climate, a factor which may render some statistical methods based on mean climate change, inappropriate. Groisman *et al*. (2005) also state that in comparison to annual mean changes, changes in climate extremes are likely to be detected more easily, in future climate changes.

According to Seneviratne *et al.* (2012) a climate extreme can be defined as "the occurrence of a value of a climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable." Thus, climate extremes can be probability or threshold-based (Groissman, 2005; Seneviratrie *et al.* 2012). Apart from the statistical definition, climate extremes can also be defined based on the extent of their impacts (McElroy and Baker, 2012; Seneviratrie *et al.* 2012).The analyses carried out in this study are based on the statistical definition rather than impacts of extreme climate.

Extreme precipitation and temperature events have negative impacts on human life as they can destroy infrastructure and cause loss of lives. They also negatively affect agricultural productivity and availability of water resources. Heavy precipitation may, however, be beneficial particularly with respect to recharging both surface and underground water sources. Many global, regional and country studies have been carried out to investigate extreme climate trends, (for example: Mason *et al*., 1999; Haylock and Nicholls, 2000; Brunnetti *et al*., 2001; King'uyu *et al*., 2000; Oikonomou *et al*., 2010; Klein-Tank and Können, 2003; Schmidli and Frei, 2003**;** Groisman *et al*., 2005; Moberg and Jones, 2005; Schmidli and Frei, 2005; Alexandrov *et al*., 2006; New *et al*., 2006; Aguilar *et al*., 2009; Ivanova and Alexandrov, 2012; Dimri and Dash, 2010; Mazvimavi, 2010; Mohsin and Gough, 2010, Huho *et al*., 2012)

Studies on trends of temperature extremes in parts of Africa, including southern Africa (Zimbabwe included), western and central Africa show increasing trends for warm extremes and decreasing trends for cold extremes (New *et al*., 2006; Aguilar *et al*., 2009), suggesting a warming trend for these regions. For Zimbabwe, Unganai (1997) also established net warming temperature trends at national level for the period 1933 up to 1993 and for Bulawayo and Harare stations for the period 1897 up to 1993. Mean maximum temperatures were increasing while mean minimum temperatures were decreasing over the country while for the most urbanized and industrialized cities, both mean maximum and minimum temperatures were increasing. New *et al*. (2006) showed significant positive trends for some extreme precipitation indices (average wet day precipitation; annual maximum 1-day precipitation and maximum consecutive dry days), for some stations in southern and western Africa. They also established increasing trends in heavy precipitation in southern and eastern parts of Southern Africa for example, south eastern Botswana, southern Malawi, southern Mozambique, South Africa as well as south and eastern Zimbabwe and decreasing trends for northern Botswana, Namibia and Zambia. However, for four stations, Chipinge, Bulawayo Goetz, Harare Belvedere and Harare Kutsaga in Zimbabwe, New *et al*. (2006) found no significant trends in extreme rainfall amounts or events, although mean wet day precipitation and maximum consecutive dry days showed positive trends. Similar results of non-significant trends in extreme rainfall in Zimbabwe were obtained by Aguilar *et al*. (2009), Conway *et al.* (2009) and Mazvimavi (2010). Contrary to these findings, Unganai (1996) established declining mean rainfall amounts over Zimbabwe for the period 1900-1994 while Love *et al.* (2010) also found decreasing rainfall trends for the northern part of the Limpopo basin, (in Zimbabwe), where stations used in the analyses had at least 30 years of data and the period covered ranged from 1921-2003. Groisman *et al*. (2005) found an increasing trend in annual frequency of very heavy precipitation for the eastern part of South Africa during the period 1906-1997. They also established an increasing trend in very heavy precipitation amount particularly for the period 1967-1997, for the same area. The objective of this chapter, is to establish trends in extreme temperature and rainfall using existing historical climate records for Bulawayo Airport meteorological station located in the south-western part of Zimbabwe.

3.2. Materials and Methods

Extreme temperature and rainfall indices for Bulawayo Airport meteorological station, WMO ID number 679650, were examined for significant trends. The station was selected as it is almost equidistant from the two study districts, Gweru and Lupane, being approximately 164 km from Gweru and 170 km from Lupane towns which are the district centres of the two districts respectively (Fig. 3.1). Bulawayo Airport station was also selected because its climate record is likely to be most accurate since it is located at the airport where climate records need to be accurately and regularly taken for aviation purposes by skilled personnel. The station was also selected because for the period of analysis used (1978-2007) no major changes in instrument exposure (type of shelter for instruments) took place (Unganai, 1997; Unganai, 2009 - personal communication).The station is at an altitude of 1326masl, latitude of 20.017ºS and longitude of 28.617ºE. It lies in Natural Region (NR) IV which receives annual rainfall in the range 450-650 mm (Vincent and Thomas, 1962), with mean annual temperature range of 30.5-35 ^{o}C (Muchadeyi *et al.*, 2007). NR IV also experiences mid-season dry spells and droughts. The climate record used is for the period from 01/07/1978-31/12/2007 and the period 1978-1987 was used as the base period.

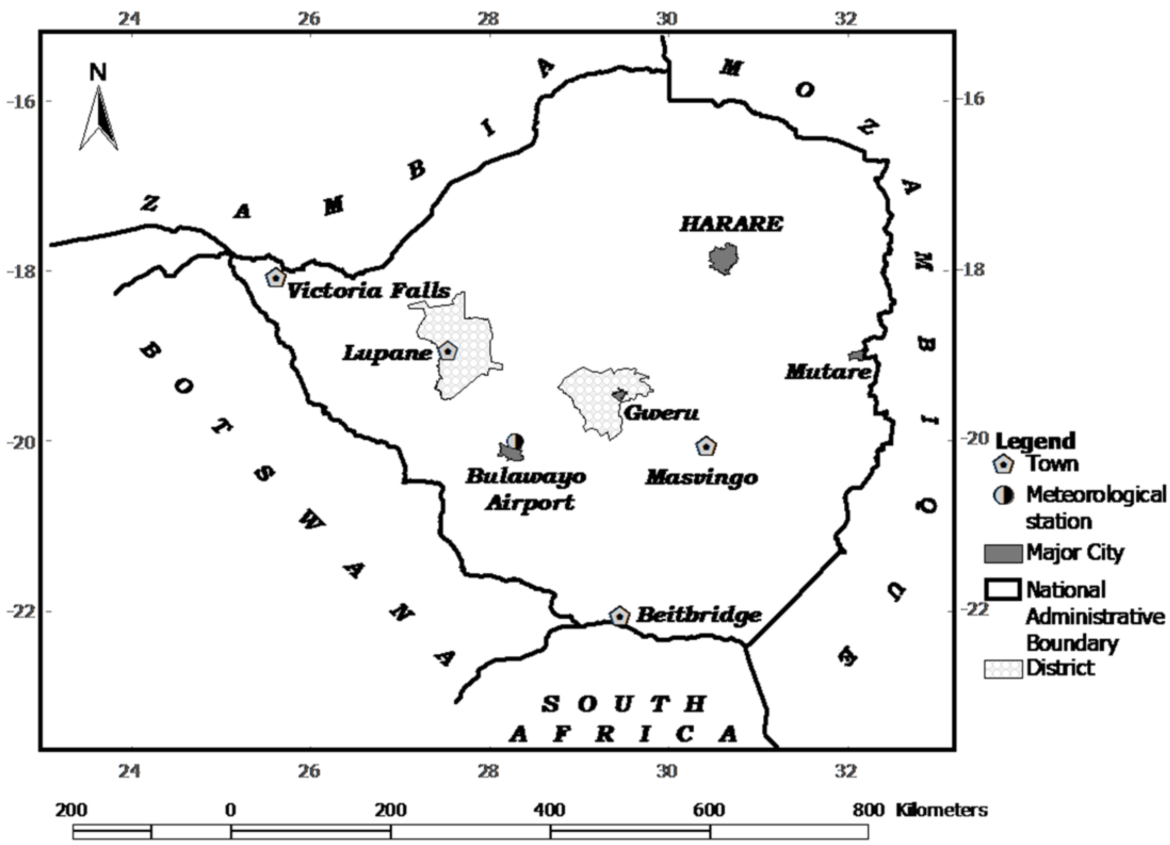


Fig. 3.1. Location of Bulawayo Airport station and districts where study was conducted. Source: Department of Geography and Environmental studies of the Midlands State University in Zimbabwe

3.2.1. Data used

Daily maximum, minimum and mean temperature were used to compute the different extreme temperature indices, while daily rainfall data were used to compute rainfall indices.

Climate data used were obtained from the Global Summary of the Day (GSOD) data set available from the U.S National Oceanic and Atmospheric Administration (NOAA)'s National Climate Data Centre (NCDC) (http://www.ncdc.noaa.gov/oa/ncdc.html) (see section 2.2.1 for details). These data, which are derived from synoptic observations transmitted over the Global Telecommunications System (GTS) have also been used by other researchers (e.g. Oikonomou *et al.*, 2008; Aguilar *et al*, 2009; Oikonomou *et al.*, 2010) to determine climate trends. This data source was used because it is readily available on-line and for Zimbabwe, the national Zimbabwean meteorological services, is obliged by the WMO, under the WMO resolution 40(Cg-XII) to provide data to the NCDC, thus the source of the NCDC data is the Zimbabwean Meteorological Services Department. The data from the NCDC have already passed through quality control (Smith *et al.,* 2011; Global Daily Weather Data from the National Climate Data Center, http://www.infochimps.com/datasets/global-daily-weather-data-from-the-national-climate-data-center) and details on quality control performed on the data are provided in section 2.2.1 of Chapter 2.

It was observed that mean daily temperature data extracted from the NCDC database, were higher than the actual value calculated from the daily maximum and minimum temperature values by about 0.5 to 1.5^{o}C. However, in this study, mean values were replaced by the calculated mean value, $\frac{(T_{max}+T_{min})}{2}$.

Extreme temperature and rainfall indices were computed and their linear trends established, using the Statistical and Regional dynamic Downscaling of Extremes for European regions (STARDEX) software version 3.3.1, described in section 2.2.2. The minimum number of days for which a percentile was calculated was 15 and the fraction of non-missing data for the computation of indices was set at 80%. The indices were calculated on seasonal as well as annual bases and significance of trends was tested using the Kendall-Tau's test (Kendall, 1975; Haylock 2004). STARDEX software has been widely used in Europe the region for which it was primarily developed for (e.g. Anagnostopoulou *et al.*, 2003; Haylock and Goodess, 2004; Hundecha and Bárdossy, 2005; Moberg and Jones, 2005) and also elsewhere in South America (Haylock *et al.*, 2006), Asia (e.g. Choi, 2004) and the Mediterranean region (Oikonomou *et al.,* 2008; Oikonomou *et al.,* 2010). Its previous applications in Africa, including Zimbabwe, are limited. However, developers of the STARDEX software have expressed their intention to extent the use of STARDEX for downscaling of climate projections to southern and western Africa (Goodess, 2007). Other software such as CLIMDEX, have been used to study trends in extreme climate in parts of Africa, including Zimbabwe, (e.g. New *et al.*, 2006; Aguilar *et al.*, 2009). Several researchers including Moberg and Jones (2005), New *et al*. (2006) and Mazvimavi, 2010), have used the Kendall-Tau test to analyze trends in climate. The advantage of the Kendall-Tau test is that it is a non-parametric test and thus does not require the assumptions of a normal distribution of the climatic data (Mohsin and Gough, 2010).

3.2.2. Temperature indices

The STARDEX default seasons are DJF (December, January, and February), MAM, JJA and SON and temperature index calculations were made for these seasons as they represent summer, autumn, winter and spring seasons respectively, with summer and winter being the more pronounced seasons in Zimbabwe. The temperature indices used (Table 3.1) were aimed at establishing whether the historical data for Bulawayo Airport station showed significant trends. This was done by considering trends in both cold and warm extremes, an approach similar to that used by previous researchers for example, Klein-Tank and Können, 2003; New *et al.*(2006) and Aguilar *et al.* (2009).

Table 3.1. STARDEX-derived indices used to determine trends in temperature extremes for Bulawayo Airport station (Adapted from Haylock, 2004)

Index name	Description / Formula
txq10 txq90 tnq10 tnq90	10th percentile of maximum temperatures (for base period) 90th percentile of maximum temperatures 10th percentile of minimum temperatures 90th percentile of minimum temperatures
txf10	% days Tmax < 10th percentile: If Tx_{ij} is the daily maximum temperature at day i of period j and $Tx_{in}10$ is the calendar day 10th percentile for a specified period. Then txf10 is determined as the percentage of time when $Tx_{ij}<Tx_{in}10$
txf90	% days Tmax > 90th percentile: If Tx_{ij} is the daily maximum temperature at day i of period j and $Tx_{in}90$ is the calendar day 90th percentile for a specified period. Then txf90 is determined as the percentage of time when $Tx_{ij}>Tx_{in}90$
tnf10	% days Tmin < 10th percentile: If Tn_{ij} is the daily minimum temperature at day i of period j and $Tn_{in}10$ is the calendar day 10th percentile for a specified period. Then tnf10 is determined as the percentage of time when $Tn_{ij}<Tn_{in}10$:
tnf90	% days Tmin > 90th percentile: If Tn_{ij} is the daily minimum temperature at day i of period j and $Tn_{in}90$ is the calendar day 90th percentile for a specified period. Then tnf90 is determined as the percentage of time when $Tn_{ij}>Tn_{in}90$
trav	Mean diurnal temperature range: $$\mathrm{Trange}_{\mathrm{mean}} = \frac{\sum_{i=1}^{I}(\mathrm{Tx}_{ij} - \mathrm{Tn}_{ij})}{I},$$ where Tx is daily Tmax and Tn is daily Tmin and Iis total days for period j.
trq10 trq90	10th percentile of diurnal temperature range 90th percentile of diurnal temperature range

3.2.2.1. Cold extremes

Four temperature indices considered for cold extremes were extreme low day temperature represented by the 10th percentile of daily maximum temperature *(txq10);* extreme low night temperature which is represented by the 10th percentile daily minimum temperature *(tnq10);* frequency of cold days *(txf10)* which is represented by percentage of days with daily maximum temperature less than the 10th percentile maximum temperature and the frequency of cold nights *(tnf10)* which is represented by percentage of days with minimum temperature less than the 10th percentile of minimum (see Table 3.1 for definition of indices).

3.2.2.2. Warm extremes

Four indices that were used to depict warm extremes were the warmest day temperature which is represented by the 90th percentile maximum temperature *(txq90);* the warmest night temperature which is represented by the 90th percentile minimum temperature *(tnq90);* frequency of days warmer than the 90th percentile maximum temperature *(txf90*) and the frequency of nights warmer than the 90th percentile minimum temperature *(tnf90)* (see Table 3.1 for definition of indices).

3.2.2.3. Diurnal temperature range (DTR)

Trends in the diurnal temperature range were also established and the associated indices used were the mean diurnal temperature range *(trav),* the 10th *(trq10)* and *90th (trq90)* percentile of diurnal temperature range (see Table 3.1 for definition of indices).

3.2.3. Precipitation indices

In contrast to the temperature indices, precipitation indices were computed for the OND (October, November, December); JFM; AMJ and JAS rather than the default STARDEX seasons. The seasons were modified in the *"station_indices"* file of *STARDEX.* These seasons were used to capture the first half (OND) and second half (JFM) of the summer rainfall season in Zimbabwe as the rainfall season is often described according to these two parts. This is for comparison purposes as most analyses of the rainfall season in

Zimbabwe and the southern African region, particularly routine seasonal rainfall forecasting, are based on these two-three months periods. Extreme rainfall indices considered (Table.3.2) included those pertaining to rainfall amount received per day for example 90th *(pq90)* percentile of rain day amounts and Simple Daily Intensity *(pint)*; those concerned with frequency of rainfall events above particular thresholds, e.g. number of events with precipitation amount greater than long term 90th percentile *(pnl90)* and those that measure proportion of rainfall from rainfall events above a given threshold, e.g. percentage of total rainfall from events greater than long term 90th percentile *(pfl90)*. Indices concerned with occurrence and persistence of dry and wet spells, for example mean spell length and the standard deviation of the spell lengths were also considered.

Table 3.2. Description of precipitation indices used in establishing precipitation trends for Bulawayo Airport station (Adapted from Haylock, 2004)

Index name	Description	Formula
pq90	90th percentile of rain day amounts (mm/day)	
pq95	95th percentile of rain day amounts (mm/day)	
Pxcdd	Maximum number of consecutive dry days	Let R_{ij} be the daily precipitation amount for day *i* of period *j*. Then pxccd is counted as the largest number of consecutive days where: $R_{ij} \leq$ wet day cut-off (wet day cut -off used in this study was 1.0mm)
Pxcwd	Maximum number of consecutive wet days.	Let R_{ij} be the daily precipitation amount for day *i* of period *j*. Then pxcwd is counted as the largest number of consecutive days where: R_{ij} > wet day_cut-off
Ppww	Mean wet-day persistence. It is the ratio of consecutive wet days to total wet days for a given period.	If *totalPwwj* is the total number of consecutive wet days for period *j* and *totalPwj* is the total number of wet days for period *j*. Then the mean wet-day persistence is given by: *Pwwj = totalPwwj / totalPwj*
Ppdd	Mean dry-day persistence. It is the ratio of consecutive dry days to total dry days for a given period	If *totalPddj* is the total number of consecutive dry days for period *j* and *totalPdj* is the total number of dry days for period *j*. Then the mean dry-day persistence is given by: *Pddj = totalPddj / totalPdj*
Ppcr	Correlation for spell lengths	*r= Pwwj-(1-Pddj),* where *Pwwj* and *Pddj* are wet and dry day persistence for period *j*, respectively.
Pwsav	Mean wet spell length (days)	If {*xi, i=1... n*} is the time series of the totals of wet spell lengths for period *j*. Then: $Mean\ of\ wet\ spell\ lengths = \frac{1}{n}\sum_{i=1}^{n} x_i$
Pdsav	Mean dry spell length (days)	If {*xi, i=1... n*} is the time series of the totals of dry spell lengths for period *j*. Then :

		$$Mean\ of dry\ spell\ lengths = \frac{1}{n}\sum_{i=1}^{n} x_i$$
Pwssdv	Standard deviation wet spell length (days)	$$Stddev. wet\ spell\ length = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$
Pdssdv	Standard deviation dry spell length (days)	$$Stddev. dry\ spell\ length = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$
pfl90	Percentage of total rainfall from events > long term 90th percentile	Let R_j be the sum of daily precipitation amount for period j and let R_{wj} be the daily precipitation amount on wet day w (R> 1.0mm) of period j and $R_{wn}90$ the 90th percentile of precipitation on wet days in the specified period. Then pfl90 is determined as: $$pfl90 = \frac{\sum_{w=1}^{w} R_{wj}}{R_j}\ , where\ R_{wj} > R_{wn}90$$
pnl90	No. of events with precipitation greater than long-term 90th percentile.	Let R_{wj} be the daily precipitation amount at wet day w (R>1.0mm) at period j and let $R_{wn}90$ be the 90th percent precipitation at wet days in the specified period. Then pnl90 is determined as the percentage of days when R_{wj} > R_{wn} 90
Pint	Simple Daily Intensity (rain per rainday in mm).	Let R_{wj} be the daily precipitation amount for wet day w (R ≥1.0mm) of period *j*, Then the mean precipitation amount at wet days is given by: $$Simple\ daily\ intensity = \frac{1}{W}\sum_{w=1}^{w} R_{wj}$$
px5d	Greatest 5-day total rainfall (mm)	Let R_{kj} be the precipitation amount for the 5 day interval k of period j, where k is defined by the last day, for example for the October-December season, the last day is day 92. Then the maximum 5 day values for period j are: $R_x5_j = \max(R_{kj})$.

Use of extreme indices was guided by the idea that under climate change, extreme events such as floods and droughts are likely to intensify in both magnitude and frequency (IPCC, 2007b) and that changes in climate are better discerned from extreme events rather than average climatic conditions. Groisman *et al.* (2005), define a "heavy" precipitation event as that which exceeds the 95th percentile value, "very heavy" as that which exceeds 97th percentile and extreme precipitation event as that which exceeds 99th percentile value for the particular station. In their study of climate extremes for central and western Europe, Moberg and Jones (2005), describe the 90th percentile value as a moderately heavy precipitation and Seneviratne *et al*. (2012), note that the 90th percentile is a commonly used threshold value for heavy precipitation in precipitation extremes studies. In this research work, one threshold was used for "extreme" rainfall, namely the 90th percentile value, to represent heavy precipitation. Heavy and very heavy precipitation events as represented by the 90th and 95th percentile of rainfall amounts, have an implication on flooding (Mason *et al.*, 1999), although it may be difficult to link them directly to floods (Groisman *et al*., 2005). On the other hand frequency and duration of dry (wet) spells may also have an implication for the occurrence of droughts (floods). Heavy precipitation, droughts and mid-season dry spells often have negative impacts on agricultural production and ecosystems in general, in arid and semi-arid areas. Hence the need to establish trends in these particular climate variables.

In this study, a wet day was defined as one with a rainfall amount greater than or equal to 1.0 mm, whereas a dry day was taken to be one with rainfall less than 1.0 mm. This threshold has also been used in other dry and wet spells studies (e.g. Sivakumar 1992 for west Africa; Tilya and Mhita, 2007 for Tanzania). Other thresholds that have been used include 0.25 mm of daily rainfall (e.g. Sawa and Ibrahim, 2011 for northern Nigeria) and 5 mm (e.g. Sivakumar*,* 1992 for west Africa; Vicente-Serrano and Beguería-Portugués, 2003 for Ebro valley in Spain; Mupangwa *et al*., 2011a for Zimbabwe).

3.3. Results and Discussion

3.3.1. *Trends in temperature*

3.3.1.1. Mean seasonal and annual temperatures for Bulawayo Airport station for the period 1978-2007

The mean temperatures presented are for the period 1978 to 2007, which is the period over which trends for extreme low and high temperatures as well as extreme precipitation were examined in this chapter. The source of the climate record used is the NCDC/NOAA described in Section 3.2.1 of this chapter and in chapter 2. Mean seasonal temperature for Bulawayo ranges from 9.10 to 17.20^{o}C with lowest temperatures being experienced during winter (JJA) and highest temperatures during mid-summer (DJF)

(Fig. 3.2). The mean annual temperature is 13.80°C. Mean maximum temperatures (mean Tmax) are highest in spring (SON)(29.50°C) and lowest in winter (JJA)(25.70 °C)(Fig. 3.2), with a mean annual Tmax of 27.7 °C. The mean Tmin is highest during mid-summer and spring (22.90 °C) and lowest during winter (16.70 °C) with an annual mean value of 20.70°C. Thus, hottest day-time temperatures occur during spring while night-time temperatures are highest during the mid-summer season. Both day-time and night-time temperatures are lowest during winter. The resultant mean diurnal temperature (DTR) is highest for winter (9.02 °C) and lowest for mid-summer (5.74 °C), while the mean annual DTR is 6.92 °C (Fig. 3.2).

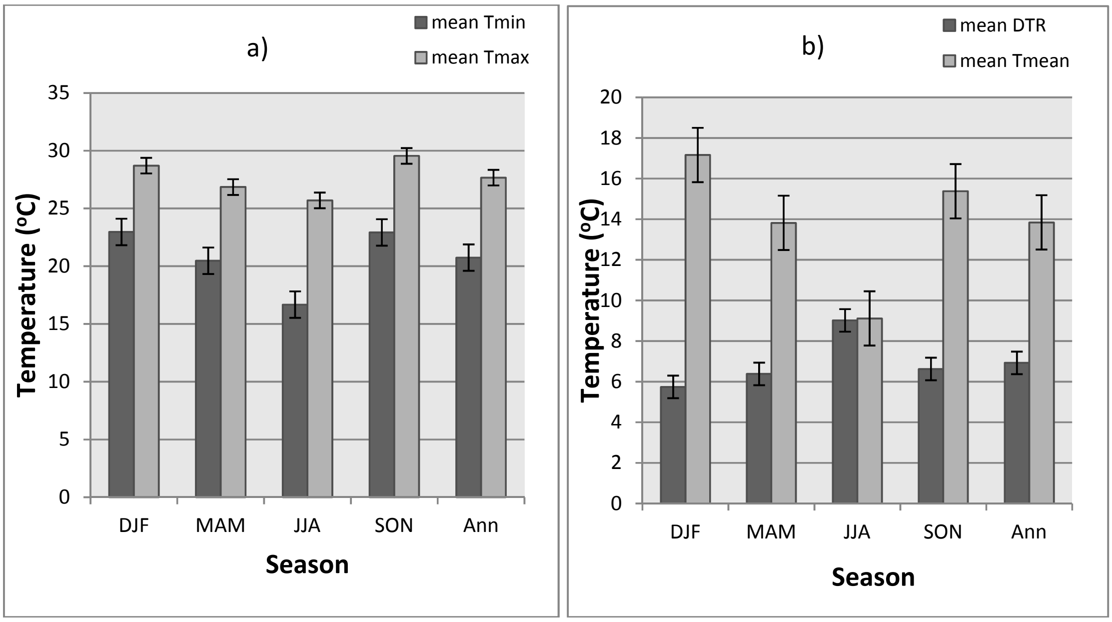


Fig. 3.2. Mean seasonal and annual temperatures for a) maximum and minimum temperature and b) mean temperature and diurnal temperature range for Bulawayo Airport station for the period 1978-2007 (error bars represent standard error)

3.3.1.2. Trends in cold extremes

Trends for all seasons namely, winter (JJA), spring (SON), mid-summer (DJF) and autumn (MAM) are positive for the extreme low night temperature (10th percentile of daily minimum temperature, *tnq10*) (Table 3.2). Except for the trend during spring (0.64°C/decade), trends for the coldest night temperature are similar for the other seasons, being about 0.25 °C/decade. The annual trend is also positive (0.29 °C/decade).

Except for mid-summer (DJF), seasonal and annual (Ann) trends are also positive for the extreme low day temperature (10th percentile of daily maximum temperature, *txq10*). The greatest increase in *txq10* occurs during autumn (0.55 ^{o}C/decade), while the annual trend is 0.34 ^{o}C/decade. Increasing trends in both *txq10* and *tnq10* are consistent with warming. However, none of the trends for these indices is significant (p>0.05).

The frequency of cold nights (nights with minimum temperature < 10th percentile minimum temperature, *tnf10*) is negative for Ann and all seasons, except autumn (MAM), also consistent with warming. The greatest decrease in number of cold nights (1.40% days in a season/decade) though non-significant, occurs in spring and this decrease is equivalent to a decrease of 1.27 days in a season/decade. The trend for the year is -0.90% days/decade (-3.29 days/decade). The trends in frequency of cold nights are, however, not significant (p>0.05). There are mixed trends for frequency of cold days (days with maximum temperature < 10th percentile maximum temperatures, *txf10*), with winter and spring exhibiting negative trends, while mid-summer, autumn and annual trends show positive trends. The greatest positive trend (1.10% days/season/decade) which is equivalent to an increase of one day/season/decade which occurs during mid-summer and the greatest decrease of 0.40% days/season/decade occurs during winter. Negative trends are consistent with warming and positive trends with cooling. However, none of the trends in frequency of cold days is significant (p>0.05).

Similar trends of increasing cold day and cold night temperatures and decreasing frequency of cold days and cold nights have been established by other researchers; for example, Kruger and Shongwe (2004) found significantly negative seasonal and annual trends in number of cold nights ($0^{o}C<Tmin\leq15^{o}C$) and in number of cold days ($Tmax\leq15^{o}C$) for some coastal and central interior stations of South Africa, for the period 1960-2003. They also established significantly positive seasonal and annual trends in hottest day and coldest day temperatures, for this period. Similarly, New *et al*. (2006) noted significantly positive annual trends in both the coldest day temperature (10th percentile maximum temperature) (0.27^{o}C/decade) and coldest night temperatures (10th percentile minimum temperature) (0.18^{o}C/decade) averaged over southern Africa and west Africa during the period 1961 to 2000. For the same period (1961-2000), New *et al*.

(2006) also found significant decreases in number of cold days and cold nights for southern Africa and west Africa. Aguilar *et al*. (2009), however, found no annual trends in coldest day temperature for Zimbabwe (average for seven stations across the country, including Bulawayo Goetz station), but significantly positive trends for Guinea (0.23^{o}C/decade) and western central Africa (0.13^{o}C/decade) during 1955 to 2006. Annual trends for the coldest night temperature were positive but non-significant ($p>0.05$) for Zimbabwe (0.02^{o}C/decade) and Guinea (0.04^{o}C/decade), while the trend was positively significant for western central Africa (0.23^{o}C/decade) (Aguilar *et al*. 2009). Findings by Aguilar *et al*. (2009) show a significantly negative annual trend in frequency of cold days (-3.83 days/decade) and cold nights (-1.24 days/decade) for Zimbabwe compared to no annual trend in frequency of cold days and non-significant negative annual trend (-2.19 days/decade) in frequency of cold nights obtained for Bulawayo Airport station, in this study, for the period 1978-2007. For stations across central and western Europe (northern hemisphere), Moberg and Jones (2005) also found warming trends for cold extremes during the period 1901-1999.

The variance in magnitude of trends for some of the cold extremes, between results obtained in this study and those obtained by other researchers for some countries or regions in Africa, particularly for Zimbabwe are most likely due to the differences in periods of analyses used as trends may vary with time as well as due to spatial coverage. Unganai (1997), in his study of surface temperature variation in Zimbabwe over the period 1897-1993, for instance, noted that there were two distinct warming phases over this period namely the 1930s to 1940 and then the 1980s onwards. Klein-Tank and Können, (2003) (for Europe over the period 1946-1999) and Kruger and Shongwe (2004) (for coastal and central interior stations of South Africa over the period 1960-2003) and Mohsin and Gough (2010) (for Toronto region in Canada for 31-162 years, depending on station) also illustrate the changes in pattern and degree of warming or cooling over different time periods within a given climate record. Whereas only one station was considered in this study, other studies looked at averages over countries or regions. Indices averaged over stations in a given geographical area may show different trends from individual station values (New *et al*., 2006), particularly if the stations are located in different climate zones or are at different latitudes and elevation.

3.3.1.3. Trends in warm extremes

Trends in hottest day-time temperature *(txq90)* and hot day frequency (% days in a season or year with Tmax > 90th percentile Tmax, *txf90*) are positive (Table 3.3; Figs. 3.3 & 3.4), consistent with warming day-time temperatures. With the exception of trends in hottest night temperature *(tnq90)* for mid-summer and in hot night frequency (% days with minimum temperature greater than the 90th percentile *(tnf90)* during Autumn, which are negative (Table 3.3), trends in *tnq90* and *tfn90* are also positive (Figs. 3.3 and 3.4), consistent with warming night-time temperatures. Trends in hottest day-time temperature and in hot day frequency are significant during winter, spring and Ann ($p \leq 0.05$). Thus, for Bulawayo, warming is evident for day-time temperature during winter, spring and Ann, with the greatest seasonal increase in hottest day temperature of 0.92^{o}C/decade and greatest increase in % of days with Tmax > 90th percentile of 7.00% days/decade occurring during winter (Table 3.3; Figs. 3.3 & 3.4). The 7.00% increase in frequency of hot days during the winter season, corresponds to an increase of 6.44 days in a season/decade. The annual trend for the hottest day temperature is +0.52^{o}C/decade, while the trend in annual frequency of hot days is +4.50% which is equivalent to +16.40 days/decade.

Trends in hottest night-time temperature and frequency of hot nights are significantly positive ($p < 0.05$) during spring (0.49^{o}C/ decade) and winter (4.60% days/decade), respectively (Table 3.3; figs. 3.3 & 3.4). The 4.60% increase in frequency of hot nights corresponds to an increase of 4.23 days in a season/decade. Annual trends, though insignificant, for hottest night-time temperature and frequency of hot nights are +0.38 ^{o}C/decade and +2.80% days/decade (+10.00 days in year per decade), respectively (Table 3.3 & Fig. 3.3).

Table 3.3. Trends for warm extremes indices for Bulawayo Airport meteorological station over the period 1978-2007

Index description	Index code	Season				
		DJF	MAM	JJA	SON	Ann
90th percentile of Tmax (°C / decade)	txq90	0.189	0.323	*0.923	*0.647	*0.518
% days with Tmax >txq90 (%/decade)	txf90	4.500	2.500	*7.000	*5.900	*4.500
90th percentile Tmin (°C / decade)	tnq90	-0.081	0.040	0.447	*0.491	0.382
% days with Tmin > 90th percentile Tmin (%/decade)	tnf90	1.600	-0.700	*4.600	4.200	2.800

*Significant at $p \leq 0.05$

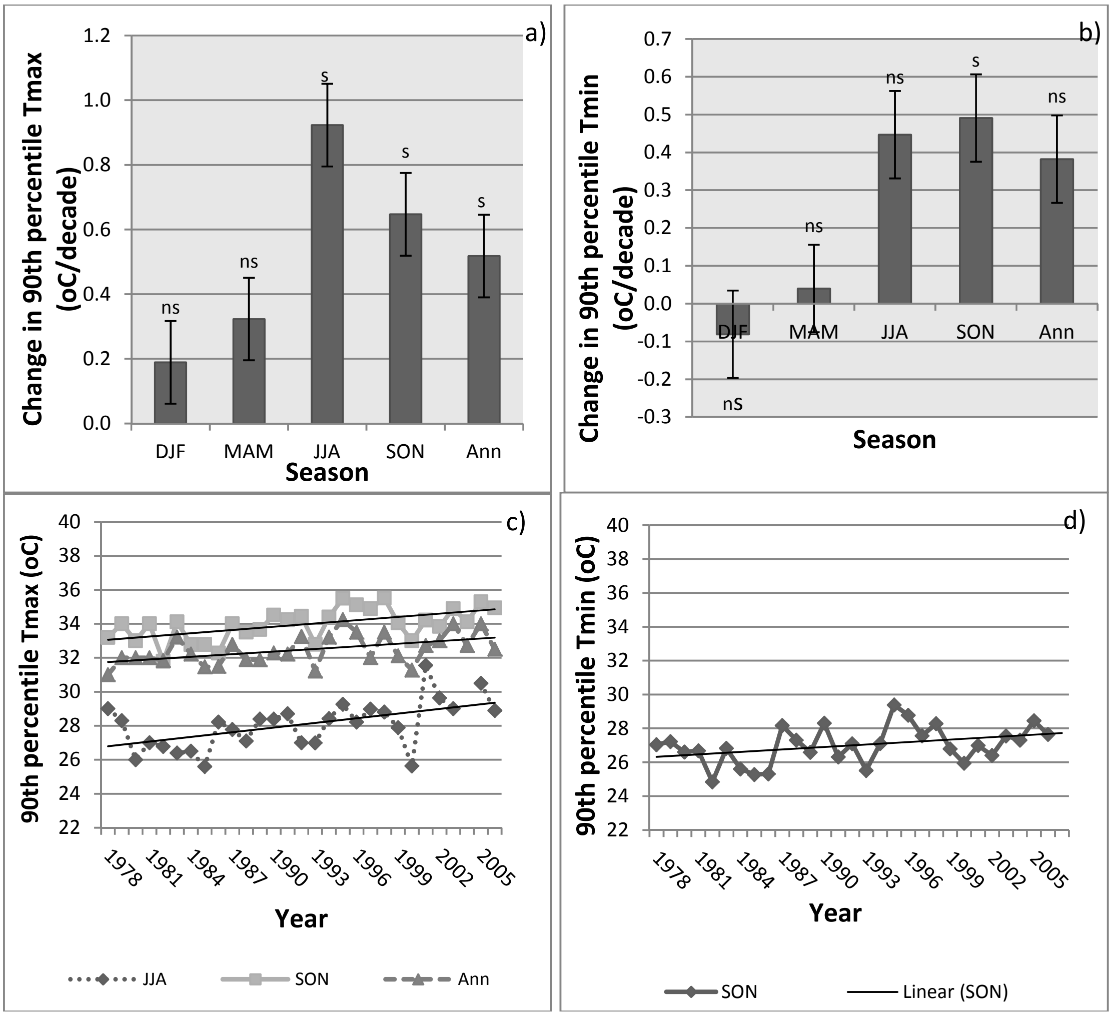


Fig. 3.3. Change in a) hottest day-time temperature, b) hottest night-time temperature and trends in c) hottest day-time temperature and d) hottest night-time temperature for seasons showing significant trends over the period 1978-2007 for Bulawayo Airport (Significant changes are denoted by s, nonsignificant by ns)

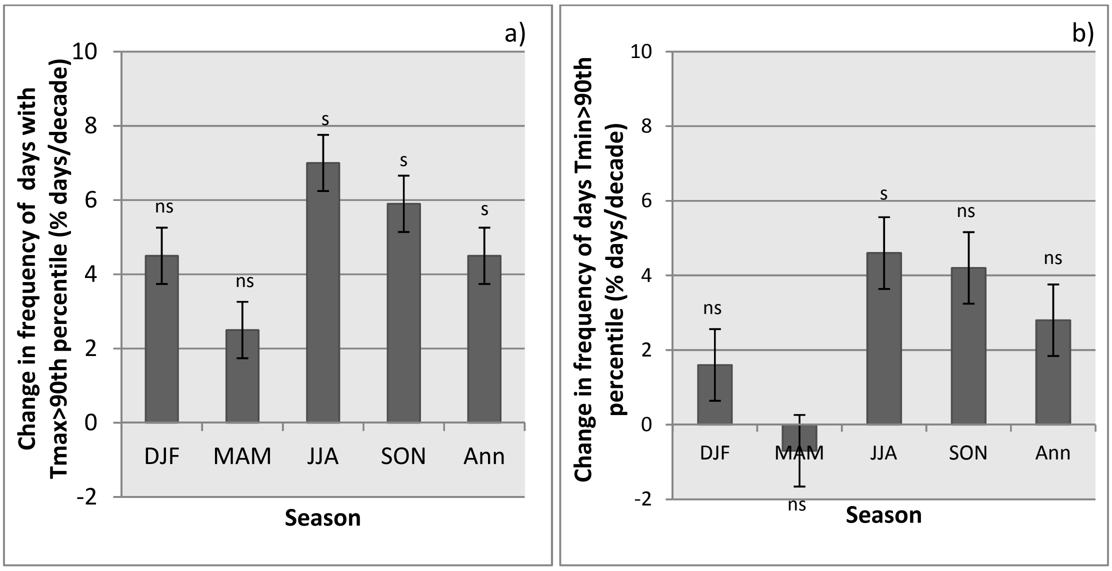


Fig. 3.4. Change in frequency, per decade of a) hot days and b) hot nights for Bulawayo Airport station, during the period 1978-2007

The generally positive trends in warm extremes, obtained in this study are consistent with increasing trends in both extreme hot day and hot night temperatures as well as in frequency of both hot days and hot nights established for Southern Africa (including Zimbabwe) and west Africa by New *et al*. (2006) for the period 1961-2000, although in this study, trends in extreme hot night temperatures and frequency of hot nights are not significant ($p>0.05$) for most of the seasons and Ann. The results are also supported by Aguilar *et al.* (2009) who established similar trends for Western Africa, Guinea and Zimbabwe for the period 1955-2006. For Zimbabwe, however, Aguilar *et al*. (2009), found positive, but non- significant trends for the extreme hot day temperature, extreme hot night temperature and for frequency of hot nights. They, however, found a significantly positive trend in frequency of hot days for Zimbabwe (1.86% days in year/decade, an equivalence of about 6.79 days/decade) for period 1955-2006. This frequency is much lower than the annual trend of about 16.40 days per decade obtained in this study for Bulawayo Airport station. The discrepancy is probably due to differences in analyses periods used and due to the fact that in the former study the indices were averaged over seven stations in different parts of the country whereas, in this study only one station located in a fairly hot region was considered. Averaging has the effect of smoothing out single station climatic characteristics which are dictated by factors such as elevation, landscape position and topography (Lundquist and Cayan, 2007). Moberg and Jones (2005) also found warming trends for warm extremes for stations across central and western Europe during the period 1901-1999.

This study established that warming, particularly in day-time temperatures, is most evident and of greatest magnitude during the winter season followed by the spring season. Similarly, Unganai (1997) established that the greatest increase in mean maximum temperature for Zimbabwe (national level) occurred in winter for the period 1933 to 1993 and in autumn and winter for Harare and Bulawayo (Goetz) stations. Mohsin and Gough (2010) also found winter to be the most consistent season in showing significant temperature increases, for the Greater Toronto region (Northern hemisphere) over 31-162 years depending on length of station record. For most of the coastal and interior stations of South Africa, however, Kruger and Shongwe (2004) found autumn to be the season consistently showing evidence of greatest warming while least warming occurred during spring for the period 1960-2003.

3.*3.1.4. Trends in diurnal temperature range (DTR)*

Trends in mean DTR (trav)

All seasonal and annual trends for the mean diurnal temperature range are positive, with the winter season showing the strongest trend (1.07^{o}C/decade) and mid-summer the weakest (0.03 ^{o}C/decade) (Table 3.4). The annual trend is 0.26 ^{o}C/decade. However, except for the trend in winter which is significantly positive ($p=0.05$), the trends are not significant ($p>0.05$) (Table 3.4). Seasonal and annual trends for both mean Tmax and mean Tmin are positive, with winter, spring and annual trends being significant for mean Tmax ($p<0.05$) (Table 3.4 and Fig. 3.5). Mean Tmin also shows a significantly positive trend of 0.39^{o}C/decade ($p<0.05$) during spring (Table 3.4 and Fig. 3.5). For each season, mean Tmax shows a relatively greater increase than the mean Tmin over the analysis period (Fig. 3.5), with the greatest increase in mean Tmax of 1.457^{o}C/decade occurring during winter (Fig. 3.5) and greatest increase in mean Tmin of (0.39 ^{o}C/decade) occurring during winter and spring. Thus, there is an overall increase in diurnal temperature range across all seasons, namely mid-summer (DJF), autumn (MAM), winter (JJA) and spring (SON).

Trends in10th percentile diurnal range (trq10).

The smallest difference between mean Tmax and mean Tmin (10th percentile diurnal range, *trq10*) shows an increasing trend for all seasons and Ann, except for mid-summer which has a negative trend. The greatest increase (0.115^{o}C/decade) occurs during winter (JJA). None of the trends is, however, significant ($p>0.05$) (Table 3.4).

Trends in 90th Percentile Diurnal Range (trq90)

The greatest difference between mean Tmax and mean Tmin (90th percentile diurnal range, *trq90*) shows an increasing trend for all seasons and for Ann, with Autumn having the greatest increase (0.26 ^{o}C/decade) (Table 3.4). However, none of the trends is significant ($p>0.05$).

Table 3.4. Trends for diurnal temperature range indices for Bulawayo Airport stations over the period 1978-2007 (^{o}C/decade)

Index description	Index code	Season				
		DJF	MAM	JJA	SON	Ann
Mean diurnal range (^{o}C/decade)	trav	0.031	0.258	*1.068	0.086	0.258
10th percentile diurnal temperature (^{o}C/decade)	trq10	-0.088	0.091	0.115	0.096	0.022
90th percentile diurnal temperature (^{o}C/decade)	trq90	0.086	0.262	0.138	-0.062	0.022
Mean minimum temperature (^{o}C/decade)	tnav	0.081	0.113	0.388	*0.387	0.262
Mean maximum temperature (^{o}C/decade)	txav	0.111	0.371	*1.457	*0.475	*0.521

*Significant at $p\leq0.05$

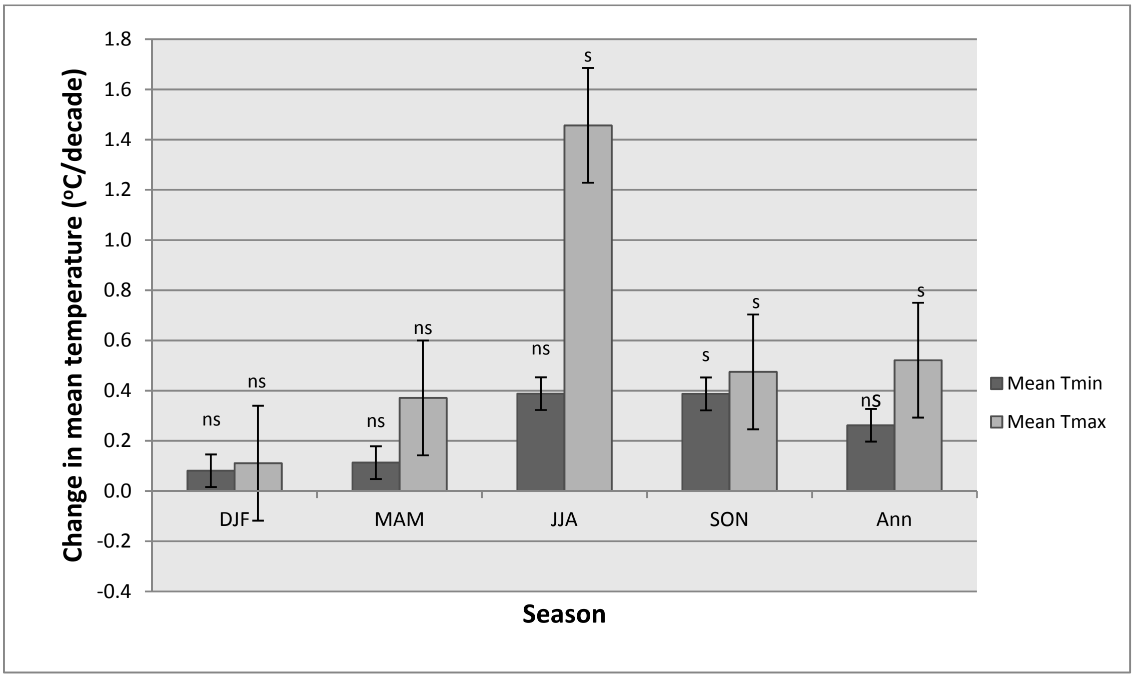


Fig. 3.5. Trends in mean maximum and minimum temperatures over the period 1978-2007, for Bulawayo Airport station

Overall, the least difference (10th percentile diurnal temperature range - trq10) and greatest difference (trq90) between daily maximum and minimum temperature, as well as the mean diurnal temperature show positive trends, indicating an increase in diurnal temperature. This is contrary to the findings of most research work on global diurnal temperature trends, which have suggested decreasing trends, largely due to greater warming for daily minimum temperatures compared to maximum temperatures (e.g. Karl *et al*., 1993, Horton, 1994, Dai *et al.,* 1999, Easterling *et al*., 1997 and Price *et a1*., 1999 for the period ranging from 1951 to the early 1990s and Geerts, 2003 for the period 1968 to 1996 and IPCC, 2007b for the period 1950-2004). Decreasing trends could also be due to daily minimum temperatures decreasing at a slower rate than daily maximum temperatures (Karl *et al*., 1993; Easterling *et al*., 1997). For Bulawayo Airport, however, both mean maximum and minimum temperatures show positive trends during the period 1978-2007. However, the annual maximum temperature is warming at a rate twice that of minimum temperature while the greatest seasonal difference in warming between mean maximum and mean minimum temperatures occurs in winter, where the maximum temperature increases at a rate 3.75 times that of the minimum temperature (Fig. 3.4).

Thus, the resultant DTR is positive. An increasing trend in diurnal temperature range obtained in this study for Bulawayo Airport station, though not statistically significant, is consistent with New *et al*. (2006)'s findings that, although there were inconsistencies in diurnal temperature range trends over southern and west Africa, trends for Zimbabwe, Zambia and Mozambique were largely positive. Aguilar *et al.* (2009) also established that the annual diurnal temperature range for stations across Guinea and Zimbabwe were slightly increasing and the trends were significant for Zimbabwe (0.11^{o}C per decade), while Hulme *et al*. (2001), also established an increase in mean diurnal range of 0.5 to 1.0 from 1960 to 1997, for Zimbabwe. For stations in coastal and interior central South Africa, Kruger and Shongwe (2004) found mixed positive and negative trends for DTR. A similar pattern of mixed trends was also established for Eastern Africa, particularly south of 5^{o} S, due to wide variability among stations with respect to minimum temperatures (King'uyu *et al*., 2000). However, for the northern part of this region, DTR showed a decreasing trend due to night-time warming and day-time cooling. For India, Rai *et al.* (2012) found increasing annual trends in DTR during the period 1901-2003, while for Europe Makowski *et al*. (2008) show a reversal of trends in DTR, from negative to positive over the1950 to 2005 period. Since global warming is associated with greater increases in night-time temperatures compared to day-time temperatures, the temperature increases particularly for day-time temperatures, noted for Bulawayo Airport station may not be due to climate change effects per se. Other factors that may lead to temperature changes for a given locality include changes in land surface cover, urbanization and industrialization as well as changes in cloud cover (e.g. Karl *et al*., 1993; Unganai, 1997; Dai *et al*., 1999; Braganza *et al*., 2004; Zhou *et al*., 2009; Mohsin and Gough, 2010).

Positive trends in DTR obtained for Bulawayo Airport, are also consistent with trends established for non-urban area stations, compared to trends for urban stations where the DTR shows a decreasing trend (e.g. Kruger and Shongwe, 2004 for coastal and interior stations in South Africa; Mohsin and Gough, 2010 for the greater Toronto region in Canada). Negative trends in DTR have been attributed to greater warming for night-time temperatures than for day-time temperatures due to the greenhouse effect caused by urbanization and industrialization effects in urban areas. Unganai (1997) found greater warming in night-time temperatures than day-time temperatures for Harare and Bulawayo (Goetz station) the two largest cities in Zimbabwe during 1893-1993. In this study, Bulawayo Airport station did not show such evidence of urbanization and industrialization effects, presumably because it is located on the outskirts of Bulawayo city rather than within the city like Bulawayo Goetz station. These results are supported by Kruger and Shongwe (2004) who showed that in South Africa most stations located at the airports, being on the outskirts of major cities were not affected by urbanization and industrialization effects.

Temperature has effects on agricultural and natural ecosystems and hence a significant change in this climate variable will affect these systems: For example, grain crops, which are the major food crops and source of income in many parts of the world, have temperature thresholds above which yields will drop (Hitz and Smith, 2004) and Schlenker and Roberts (2009) established this threshold to be 29^{o}C for maize. In their review of model-based analyses of climate change effects on crop yields, Hitz and Smith (2004), concluded that there were increasing adverse global effects beyond temperature increases of 3-4^{o}C, while Lobell and Field (2007) established that maize, wheat and barley yields across the globe have been adversely affected by global warming, since 1980. The UNFCCC (2007) also estimated that rain-fed crop yields could be halved by 2020 in some countries in Africa, as a result of the combined changes in temperature and rainfall. Higher temperatures, particularly in winter, could also lead to increased occurrence of pests (Sombroek and Gommes, 1996; Rosenzweig *et al*., 2001; Tubiello *et al.*, 2007). Some climate change studies have estimated combined and/or single factor effects of changes in temperatures, precipitation and CO_2 concentrations effects on crop yield losses (e.g. du Toit *et al.*, 2000; Schlenker and Lobell, 2010; Dimes *et al*., 2008), and on availability of water resources (e.g. Arnell, 1999; Love *et al*., 2010). For Zimbabwe, Makadho (1996) found a reduction in maize yield due to climate change for stations in four of the five Natural Regions of the country. Using data from Bulawayo Goetz station (Western Zimbabwe) Dimes *et al.* (2008), also found a decline in both cereal (maize and sorghum) and legume (groundnut and pigeon pea) crops due to climate change, with temperature having the greatest grain yield reduction of as high as 25% for the staple crop, maize. Positive trends in temperature will require strategies such as breeding for varieties with higher temperature tolerance level or thresholds (e.g. Abrol and Ingram, 1996; Hitz and Smith, 2004; Decoteau, 2005) to be put in place.

Changes in DTR may affect crop growth, for example through effect on the balance between respiration and photosynthesis. Higher night temperatures, for example, may increase dark respiration thereby reducing net-biomass production (Sombroek and Gommes, 1996). There seems to be different views on the degree to which DTR may influence crop growth and development: For example whereas Roberts and Summerfield (1987) suggest that the mean DTR, within levels of base temperature and optimum growth temperature, is the most important factor influencing flowering compared to separate day and night temperatures, for annual crops; Phillips *et al.* (2011) found that asymmetric warming (greater increase in Tmin than Tmax - synonymous to an increasing DTR) did not have an effect on photosynthesis and respiration of a grassland ecosystem containing species native to Oregon, USA. They concluded that change in mean temperature alone was sufficient to affect growth and development of the grassland species (Phillips *et al.,* 2011). However, in this study, it is only the trend in mean DTR for the winter (JJA) season which was significant (p=0.05). Thus, the effect of a changing DTR in Zimbabwe, may have an influence on crop growth and development of irrigated winter crops such as wheat and barley.

3.3.2. Trends in precipitation

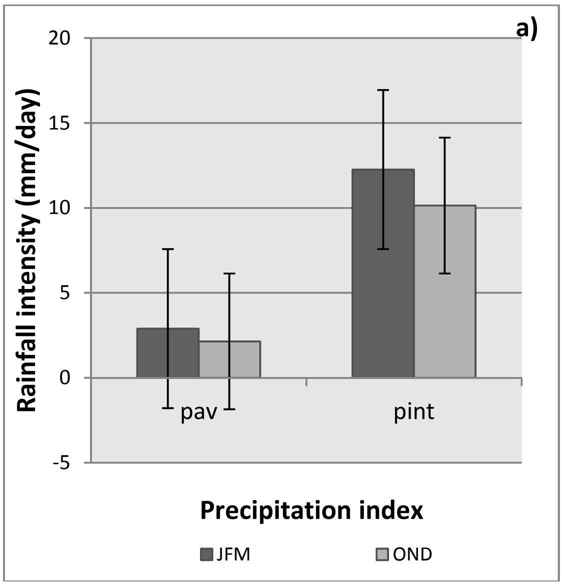
3.3.2.1. Mean precipitation for Bulawayo over the period 1978-2007

The rainfall season in Zimbabwe extends from October to March and in this study, changes in extreme rainfall indices were considered on a seasonal (JFM, AMJ, JAS and OND) and annual basis. In this section mean rainfall conditions at Bulawayo during the first half (OND) and second half (JFM) of the summer rainfall season are described, for the period 1978-2007. Mean precipitation indices considered in this study indicate generally wetter conditions for the JFM season than for the OND season (Table 3.5). Mean daily rainfall amount (all days in a season considered) (*pav*) and mean daily rainfall per rainy day (*pint*) are of about similar magnitude being between 2-3 mm and between 10-12mm/day respectively for the two seasons, with JFM having slightly higher daily rainfall amount (Table 3.5, Fig. 3.6). The highest amount of rainfall received over five days (*px5d*) is significantly higher for JFM than for OND (Fig. 3.6).

Mean dry spell is longer for OND than for JFM, being about 9 days and 5 days respectively for the two seasons. However, the mean wet spell length is about the same duration (approximately two days/season) for OND and JFM seasons (Fig. 3.7). The longest dry (wet) spells are about equal in duration for the two seasons, being about 17 (4) days (Fig. 3.7). Dry days show greater persistence (ratio of consecutive dry days to total number of dry days in a season) than wet days (ratio of consecutive wet days to total number of wet days in a season), for both seasons, with OND having greater (lower) dry-day (wet-day) persistence than JFM (Fig. 3.7), signifying generally drier conditions for Bulawayo. Standard deviation for dry and wet spell lengths show that there is greater (lower) variability in dry (wet) for the OND than JFM season (Table 3.5 and Fig. 3.7), implying that dry (wet) spell lengths during the first half of the rainfall season (second half of the season) can be predicted with relatively less (greater) certainty.

Table 3.5. Mean annual precipitation indices for Bulawayo for the period 1978-2007

Rainfall index	**Index code**	**Season**				
		JFM	**AMJ**	**JAS**	**OND**	**Ann**
Mean daily rainfall amount (mm)	pav	2.90	0.51	0.24	2.15	1.44
Simple rainfall intensity (rain per rainy day) mm	pint	12.26	9.28	13.77	10.14	11.38
90th percentile of rainday amounts (mm/day)	pq90	28.22	-	-	22.21	27.22
Maximum number of consecutive dry days	pxcdd	18.30	40.17	49.38	16.90	68.93
Maximum number of consecutive wet days	pxcwd	4.67	1.86	0.72	3.63	5.13
Mean dry-day persistence	ppdd	0.79	0.94	0.99	0.91	0.92
Mean wet-day persistence	ppww	0.43	0.38	0.06	0.35	0.42
Mean wet spell length (days)	pwsav	1.81	1.80	0.63	1.59	1.71
Mean dry spell length (days)	pdsav	4.62	11.69	22.48	8.71	9.08
Standard deviation wet spell lengths (days)	pwssdv	1.20	0.92	0.02	0.80	1.12
Standard deviation dry spell lengths (days)	pdssdv	4.11	10.47	23.64	10.26	14.39
% total rainfall from events > 90th percentile	pfl90	0.30	0.19	0.10	0.34	0.39
No. events > 90th percentile	pnl90	2.16	0.45	0.19	1.87	4.99
Greatest 5-day rain amounts (mm)	px5d	83.48	32.57	12.88	65.92	102.81



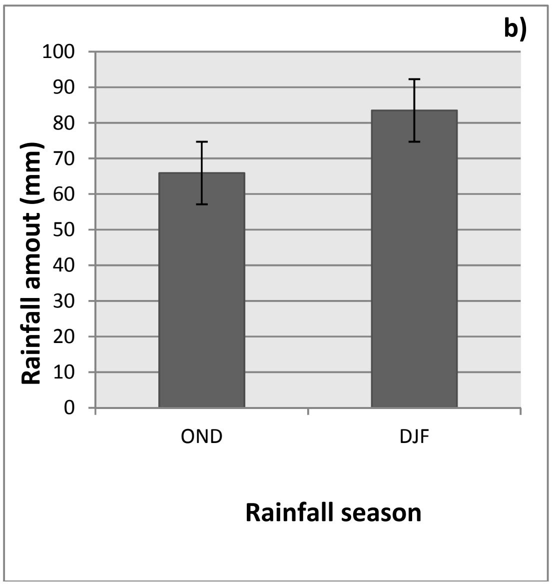


Fig. 3.6. Mean rainfall intensity for Bulawayo for period 1978-2007 a) daily intensity and b) greatest amount of rainfall received in 5 days (px5d) for the summer

3.3.2.2. Trends in heavy precipitation

Trends in long term 90th percentile of rain day amounts (pq90)

The 90th percentile of rainy day amounts (*pq90*) shows an increasing trend during the rainfall season being 0.103 mm/rainy day/decade for OND and 4.168 mm/rainy day/decade for JFM. Indices for the dry season (AMJ and JAS were not computed because the rainfall data for these seasons did not meet the non-missing data requirements). The annual trend, was negative being -0.263 mm/rainy day/decade and the negative trend is due to the fact that both the wet and dry seasons are considered. All the trends are, however, not statistically significant ($p>0.05$). Thus, there is no evidence of heavy rainfall during the rainfall season as well as for the whole year, for the period 1978-2007.

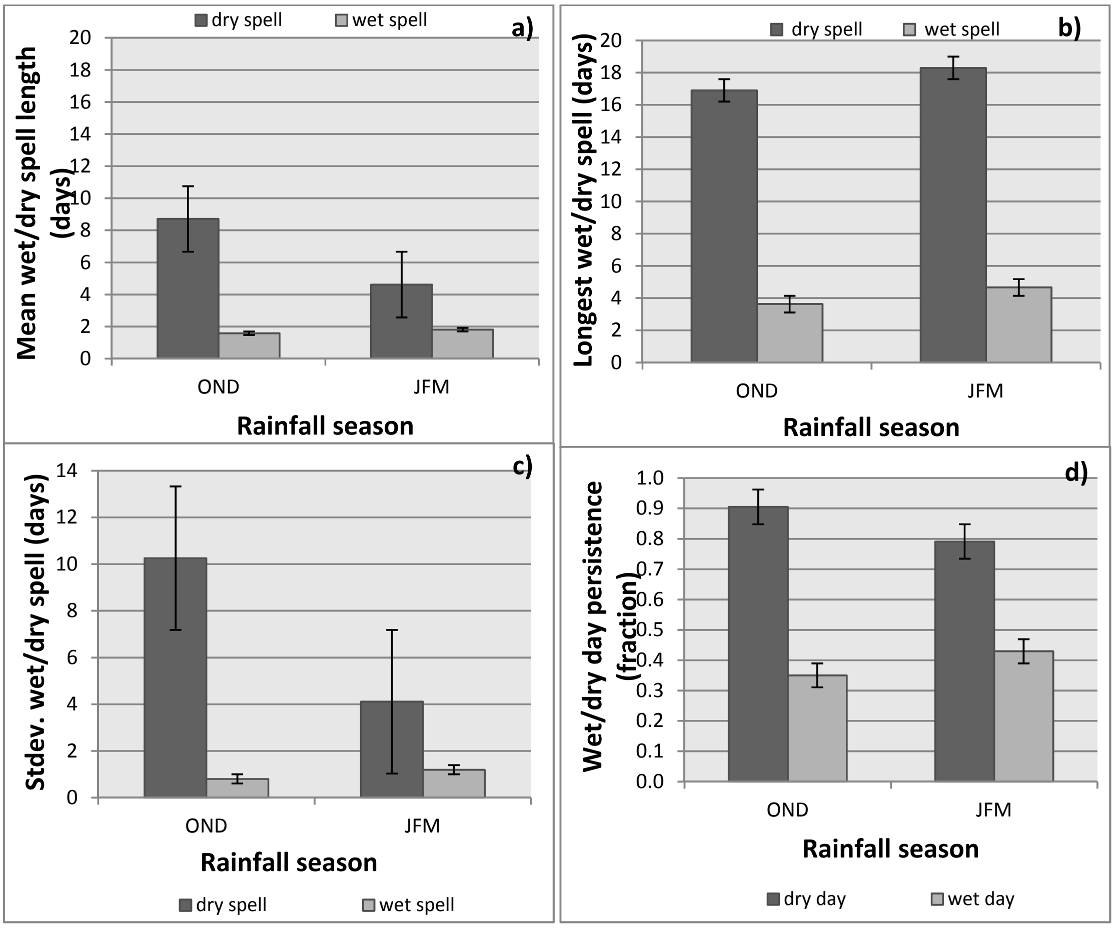


Fig. 3.7. Characteristics of wet/dry spells for Bulawayo during 1978-2007 a) mean spell length, b) longest spell, c) standard deviation mean spell length and d) wet/dry-day persistence for summer months

Trends in number of events with precipitation greater than the long-term 90th (pnl90)

The trend in number of events with rainfall amount exceeding the 90th percentile of the 1978-2007 period is negligible for all seasons and Ann, with JFM showing a positive trend of 0.833events /decade. The other seasons and Ann have negative trends ranging between -0.020 for Ann and 0.213 for OND. None of the trends is, however, significant ($p>0.05$). Therefore, there is no evidence of change in frequency of heavy precipitation events for Bulawayo, during the period 1978-2007.

Trends in percentage of total rainfall from events greater than the long term 90th percentile (pfl90)

Similar to trends in *pnl90*, trends for the percentage of total rainfall from events greater than the long term 90th percentile *(pfl90)* show an inconsistent pattern across seasons with JFM, AMJ and Ann having positive trends, while JAS and OND show negative trends. The greatest increase of 7.60% per decade occurs during JFM, while the greatest decrease of 3.90% per decade occurs during JAS. During the first half of the rainfall season (OND), a decrease of 3.00% occurs while the annual (Ann) trend is +2.00% per decade. Both seasonal and annual trends are, however, not significant ($p>0.05$). Lack of significant trends in *pfl90* is an indicator for no change in extreme rainfall amounts and/or frequency of heavy rainfall events.

The general lack of statistically significant trends in heavy precipitation is consistent with New *et al*. (2006) who found increasing but non-significant regionally (southern and west Africa, including Zimbabwe) averaged trends for heavy precipitation, for the period 1961 to 2000. For Zimbabwe, they found a significant increase in *pq95* for only one station (Beitbridge, located in a very dry area south of the country) out of the four stations they considered for this country. New *et al*. (2006) also found non-significant, positive trends in total rainfall from heavy events for the southern Africa and west Africa region. Similarly, Aguilar *et al*. (2009), found non-significant increases in heavy precipitation for stations in Zimbabwe, but found decreasing trends in heavy precipitation for Central Africa for the period 1955 to 2006. The results obtained in this study are also supported by Conway *et al*. (2009), who noted a stable rainfall series between 1931-1960 to 1961-1990 for the Zambezi and Okavango river basins in Southern Africa, represented by Victoria Falls and Mohembo rainfall stations, respectively. Mazvimavi (2010) also found no evidence of changes in heavy seasonal and annual precipitation as well as in medium and low precipitation for 40 stations across Zimbabwe during varying periods (start period of 1892-1941 to 2000) for the different stations. For Bulgaria, Alexandrov *et al*. (2006) and Ivanova and Alexandrov (2012), also found generally weak and insignificant extreme precipitation trends for the 20th century. On the contrary Unganai (1996) using linear regression methods, based on means, found significant decreases in average rainfall across Zimbabwe for period 1900-1993. The differences between Unganai (1996)'s findings and results obtained in this study could be due to different times series considered in the analyses and the spatial coverage he used across Natural Regions. For some regions and other countries, increasing trends in extreme precipitation have, however, been established, for example; Mason *et al*. (1999) established increases in intensity of heavy rainfall events for stations in South Africa between 1931-1960 and 1961-1990, while Groisman *et al*. (2005) found a significant increase in the proportion of total precipitation from heavy precipitation events for the USA and increase in the frequency of very heavy precipitation for South Africa during the period 1906-1997. Moberg and Jones (2005) also found significant increases in heavy precipitation during the winter season for Central and western Europe for the period 1901-1999. Heavy precipitation has implications on flooding. Communities around Bulawayo are thus at low risk of flooding, as trends in heavy precipitation are not significant.

3.3.2.3. Trends in daily and short-term rainfall intensity

Trends for rainfall received per rainy day *(pint)* are weak and positive during the rainfall season with the first half of the season (OND) showing a decrease of 0.090 mm/decade and the second half (JFM) a decrease of 0.960 mm/decade). Trends for the drier seasons, AMJ and JAS are however negative, being -1.550 and -1.910 mm/decade, respectively. This implies that the dry seasons are getting drier, with respect to amount of rainfall received during these seasons. The season AMJ is, however, relatively wet as the rainfall season sometimes extends into April, while JAS is typically dry with light showers ("*guti*" weather) experienced during the main winter months (June and July). The annual trend is -0.380 mm/decade. Both seasonal and annual trends are, however, non-significant ($p>0.05$). Negative/positive trends in *pint* indicate that the mean rainfall amount for Bulawayo Airport station increased (decreased) during the rainfall season (dry season) though insignificantly, over the analysis period (1978-2007). Similarly, New *et al*. (2006) found increasing trends in daily rainfall intensity for most of the stations in southern Africa and west Africa although only few of the stations had significant trends. Unlike with individual stations, averaged trends (over the southern Africa and west Africa region) were significantly positive for the daily rainfall intensity (New *et al*., 2006). Results for trends in daily rainfall intensity, are supported to an extent by Tadross *et al*. (2009) who found limited spatial consistency for trends in this index, with only a few stations showing significant trends in Malawi, Mozambique, Zambia and Zimbabwe, over varying periods, depending on station (rainfall data records used varied from 1900-2005).

The trend in greatest amount of rainfall received during five days *(px5d)* is negative for all seasons and Ann, being -6.250, -10.580, 5.990, -3.00 0and -13.100 mm/decade for JFM, AMJ, JAS, OND and Ann, respectively. None of the trends are, however, significant (p>0.05). In their analysis of rainfall extremes, New *et al*. (2006) found mixed annual trends in *px5d* for four stations in Zimbabwe, and found a significant negative annual trend in *px5d* for only one station, Belvedere, in north of the country. They however, found non-significant positive trends for the regionally (southern and west Africa) averaged trends. Cumulative rainfall over short-term periods (five days in this case) may have implications for flooding (Achberger and Chen, 2006). The negative seasonal and annual trends in this index for Bulawayo may therefore be an indicator for reduced risky of flooding during the 1978-2007. Negative trends in this index could have implications on timing and effectiveness of operations such as planting, fertilizer application and weed management operations since timing and success of these operations are heavily influenced by soil moisture availability and/or absence of rainfall in short term periods.

3.3.2.4. Trends in dry spells

Trends in mean dry and wet spell lengths

Over the period 1978-2007, there is a decreasing trend in mean dry spell length *(pdsav)* during all seasons except OND which has a positive trend (Fig. 3.8). The annual trend is also negative (-0.62 days/decade). The greatest decreases occur during the dry season being -3.28 and -2.69 days/decade for AMJ and JAS, respectively. For the rainfall season, a decrease of 0.51 days/decade occurs during the second half of the season (JFM), while an increase of 0.16 days/decade occurs during the first half of the season (OND). All seasonal trends except for AMJ (part of dry season) and the annual trend are, however, not significant (p>0.05) (Fig. 3.8). Whereas there were contrasting (negative and positive) and non-significant trends during the first and second halves of the rainfall season in this study, findings from Tadross *et.al*. (2009), show increases in mean dry spell length over Zambia, Malawi and Zimbabwe during the rainfall season. The significant trend in *pdsav* obtained for part of the dry season (AMJ) in this study, may have limited value with respect to dry spell effects on agricultural productivity. However, as suggested by New *et al*. (2006), a decreasing trend in dry spell length in such a case, may imply lengthening of the rainfall season. This is because AMJ is the season immediately after the main rainfall season and a decrease in *pdsav* is likely to be due to rains extending into April, thereby lengthening the rainfall season. Thus, for Bulawayo, there is an indication of lengthening of the rainfall season, for the period 1978-2007 due to a decrease in dry spell duration post the main rainfall season. In fact, rains normally extent to April although compared to March, the rainfall amount received during April is often lower. The extended rainfall season, may allow farmers to consider growing later maturing varieties, provided other rainfall conditions remain unchanged. An extended rainfall season could also lead to deterioration of grain quality due to effect of late rains on the mature crop.

Similar to the trends in mean dry spell length, trends in mean wet spell length *(pwsav*) are also negative for all seasons except OND. The annual trend is also negative (-0.05 days/decade). The greatest seasonal decrease of 0.29 days/decade occurs during AMJ while during JFM the decrease is 0.11 days/decade and during OND, the increase in *pwsav* is only 0.04 days/decade. None of the trends is, however, significant ($p>0.05$).

Trends in maximum consecutive dry days (longest dry spell) *(pxcdd)* are negative for JFM (-1.27 days/decade) and AMJ (-5.33 days/decade), but positive for JAS (4.30 days/decade), OND (3.20 days/decade) and Ann (2.76 days/decade). The trend for OND is significant ($p=0.013$), while trends for the other seasons and Ann are not significant ($p>0.05$) (Fig. 3.9). Similar to the increase in longest dry spell length obtained in this study, significantly positive trends in longest dry spell duration were also established for the southern Africa and west Africa region (regionally averaged trends), although individual stations in this region, showed non-significant positive trends during 1961-2000 (New *et al*., 2006). For the longest wet spell *(pxcwd)*, there are decreasing seasonal and annual trends, with the greatest decrease of 0.87 days/decade occurring during the second half of the rainfall season and the least decrease (-0.03 days/decade) during the first half of the season. The annual trend is -0.48 days/decade. None of the trends in *pxcwd* are, however, significant ($p>0.05$). New *et al*. (2006), also found a decreasing but non-significant annual trend for the longest wet spell length for Bulawayo Goetz station, which is about 25km from the Bulawayo Airport station. New *et al.* (2006) also found positive, though non-significant trends for three other Zimbabwean stations they considered in their analyses, while Aguilar *et al*. (2009) also found positive but non-significant trends averaged over eight stations in Zimbabwe, for the longest wet spell.

Extended periods of dry (wet) conditions may indicate likelihood of getting droughts (floods) in an area. Hence for Bulawayo, the likelihood of getting droughts during OND season for the period 1978-2007 was high. The increase in duration of the longest dry spell during the first half of the rainfall season (OND) signifies drying conditions. Dry conditions have an implication on agricultural productivity, particularly on rain-fed cropping in areas such as Bulawayo, which are already dry. Such changes during the first half of the rainfall season (OND) impact negatively on crop establishment, as germination and emergence percentages may be low, leading to poor crop stands. An increase in duration of the longest dry spells also has implications on water availability for other purposes, including irrigation, fisheries as well as livestock and human consumption.

Drying conditions as depicted by increasing trends in dry spell length call for farmers to embark on or strengthen existing coping strategies such as rain water harvesting and/or mulching technologies (e.g. Mupangwa *et al*., 2006; Oweis and Hachum, 2006; Ibraimo and Munguambe, 2007; Ibraimo, 2009; Ali *et al*., 2010; Rockström, 2010; Bunclark and Lankford, 2011) and perhaps growing short season crops and/or varieties. As noted by Bunclark and Lankford (2011) and in chapter 4 of this thesis, there is need to review adoption of water conservation technologies among small holder farmers and this is particularly important in Zimbabwe and other parts of Africa, where adoption rates have been established to be low.

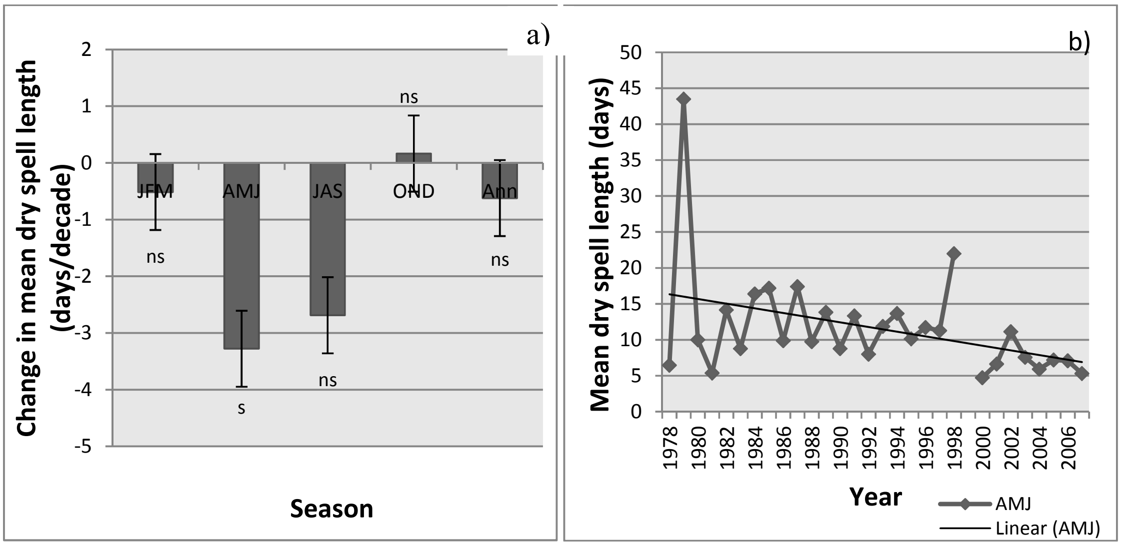


Fig. 3.8.a) Seasonal and annual changes in mean dry spell length, and b) trend in mean spell length during AMJ season for Bulawayo Airport station during 1978-2007

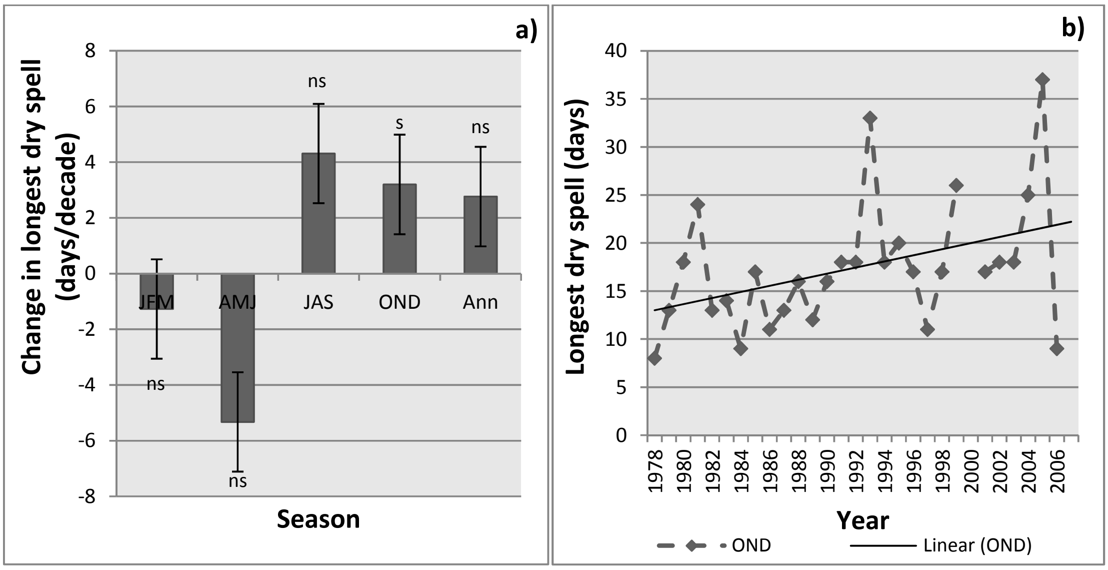


Fig. 3.9. a) Change in duration of longest dry spell and b) trend in longest dry spell during OND over the period 1978-2007, for Bulawayo Airport station

Trends in standard deviation for mean dry and wet spell lengths

The standard deviation for dry spell length *(pdssdv)* shows decreasing trends for JFM (-0.35 days/decade), AMJ (-0.78 days/decade) and for Ann (-0.23 days/decade), while trends for JAS and OND are positive, being 1.05 and 0.83 days/decade respectively. All the trends are, however, not significant (p>0.05). For the wet spell length, the standard deviation *(pwssdv)* shows negative trends for Ann and for all seasons, except OND. The greatest decrease in *pwssdv* of 0.20 days/decade occurs during the second half of the rainfall season (JFM), while the annual trend is -0.09 days/decade. The trend is +0.01 days/decade for the first half of the rainfall season (OND). Thus, trends in standard deviation of the mean spell lengths are generally weak, particularly for the wet spell length. All the trends are also not significant ($p>0.05$). Hence there is no evidence of change in year to year variability in both mean dry and wet spell lengths. Thus, during the rainfall seasons, wet and dry spell lengths can be predicted with unchanged certainty.

Trends in mean dry-day and wet-day persistence

Trends for the ratio of the number of consecutive dry days to the total number of dry days in a season (dry-day persistence*, ppdd*) are negative for JFM (-3.10% per decade), AMJ (-0.60% per decade) and for Ann (-0.10% per decade). These trends translate to decreases in consecutive dry days of 2.79, 0.55 and 0.37 days/decade for JFM, AMJ and Ann, respectively. For JAS and OND the trends are positive being 0.60% or 0.55 days and 1.00% or 0.92 days/decade respectively. The trends are, however, not significant ($p>0.05$). Except, for JAS, seasonal and annual trends in ratio of the number of consecutive wet days to the total number of wet days in a season (wet-day persistence*, ppww*) are negative. For the rainfall season, it is JFM which has the greater decrease in wet day persistence (-3.78 days/decade) compared to OND which has a decrease of 0.18 days/decade. The decrease during AMJ is 5.37 days/decade, while the annual trend is -8.76 days/decade. The trend is +0.64 days/decade for JAS. Similar to dry-day persistence, the trends for wet-day persistence are not significant ($p>0.05$), indicating that there is no evidence of change in probability of getting consecutive dry and wet spells during the period 1978-2007, for Bulawayo. However, the correlation for wet and dry spell lengths *(ppcr)* for the JFM season as given by: *ppww-(1-ppdd)*, has a significantly negative trend ($p=0.032$), the trend being -0.073/decade (Fig. 3.10). Trends in both consecutive dry and wet days are negative and this is also reflected in the correlation for spell lengths. This suggests that rainfall is becoming more intermittent during the second half of the rainfall season (JFM period) (Goodess, 2013 - personal communication).

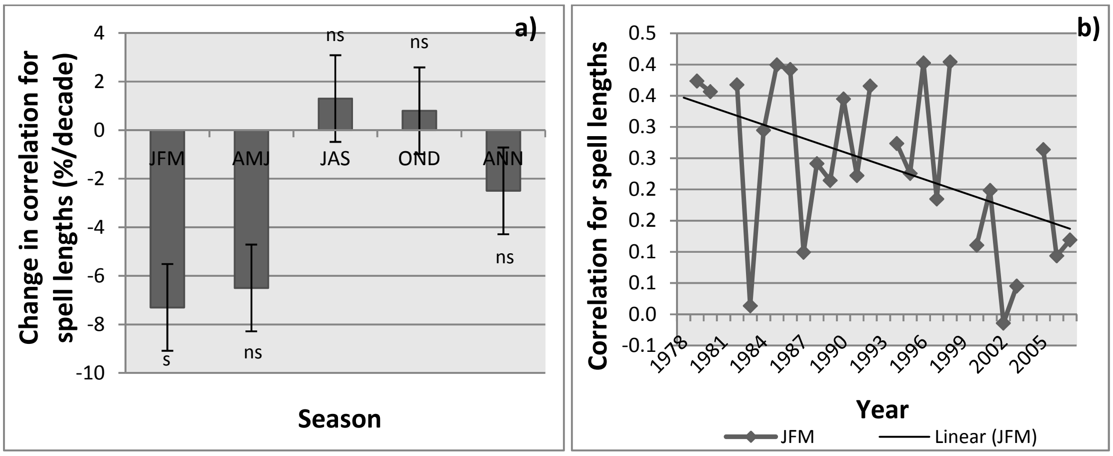


Fig. 3.10.a) Change in correlation for spell lengths and b) Trend in correlation for spell lengths during JFM over the period 1978-2007 for Bulawayo Airport station

Related to findings in this study, Mupangwa *et al*. (2011a) found no significant changes in number of wet days during the rainfall season, for stations in the Mzingwane catchment in southern Zimbabwe, for varying periods ranging from 50-71 years and covering the years 1921-2008. On the contrary, Tadross *et al*. (2009) found significant decreases in frequency of wet days, during the rainfall season for Zambia, Zimbabwe and Malawi. These results are at variance probably because in Tadross *et al*. (2009) most of the stations considered for Zimbabwe are in the northern and eastern parts of the country where rainfall amounts are relatively high compared to stations used in Mupangwa *et al*. (2011a) and Bulawayo Airport used in this study located the southern and western parts of the country. Differences in observed trends could also be due to different periods of analyses.

3.4. Conclusion and Recommendations

3.4.1. Trends in extreme temperature

Trends in both cold and warm extreme indices indicate that warming took place during the period 1978 to 2007, for Bulawayo Airport area, south of Zimbabwe. The warming is more evident from warm extremes than from cold extremes and it is extremes in day-time rather than in night-time temperatures where most significant increases in temperature occur. Significant and greatest warming mostly occurs during the winter (JJA) and spring

(SON) seasons. Trends in night-time temperatures do not show evidence of the greenhouse effect due to global warming, as they are not warming any faster than day-time temperatures, hence the positive changes in temperature established for Bulawayo, may not be due to climate change per se. Urbanization and industrialization effects on temperature appear not to influence temperatures around the Bulawayo Airport area.

3.4.2. Trends in extreme precipitation

Trends for heavy rainfall, show no evidence of change over the period 1978-2007, for Bulawayo. There is no evidence of change in mean rainfall amounts as indicated by lack of trends in mean daily rainfall amount (all days in season or year considered) or in daily rainfall amount per rainy day.

Mean dry and wet spells do not change significantly during the rainfall season and for the whole year. However, for the period April to June, the period following the second half of the major rainfall season, the trend in mean dry spell length is significantly negative. The longest dry spell has a significantly positive trend for the first half of the rainfall season, signifying drying conditions for this period. Farmers should prepare for such conditions, by resorting to crops and varieties that are adapted to drier conditions, early planting to allow the crop to use any available rain water and using moisture conservation techniques. Results from analyses of trends in extreme rainfall indices, also show no evidence of change in variability in both mean dry and wet spell duration. In addition, the probability of getting consecutive dry or wet days does not change significantly over the analysis period, 1978-2007, for Bulawayo. However, during the second half of the rainfall season (JFM) the correlation for wet and dry spells shows a significantly negative trend confirming the negative trends for both consecutive wet and dry days.

There is temporal variation in direction and significance of the trends for some of the precipitation indices considered in this study, between the two halves of the rainfall season (OND and JFM). Examples are fraction of total rainfall above annual 90th percentile (*pf90*), duration of longest dry and wet spells and the variability in wet spell length.

Trends in temperature and rainfall extremes that were obtained for Bulawayo are to a large extent, consistent with findings from other past research work, although there may be differences in magnitude of the trends. In future work, the researcher intends to consider more stations in the southern and western parts of the country, where rainfall is already limiting agricultural productivity, to improve validity of results obtained. Trends in extreme temperature indices also need to be established for several stations throughout Zimbabwe. The analysis period should ideally be extended to the current year, if data are available.

CHAPTER 4

CURRENT AGRONOMIC PRACTICES, CONSTRAINTS AND COPING STRATEGIES OF SMALLHOLDER FARMERS IN LOWER GWERU AND LUPANE COMMUNAL AREAS

4.1. Introduction

Farming is the major livelihood of most rural households in Zimbabwe. These households practice mixed farming, comprising animal rearing and production of crops, with crop production being confined to summer (FAO, 2006). Most of the arable land available to these rural farmers is allocated to food crops, and this is particularly so in the more marginal areas of the country for example in Natural Regions IV and V (FAO, 2006). Cereal crops are the major crops with maize being the staple crop. The majority of the rural population belongs to the smallholder farmer category, which comprises farmers in communal, resettlement and co-operative areas. The second broad category of farmers in the country is the large scale commercial farmers, who differ from smallholder farmers in the type of land ownership, scale of operation and the level of inputs they use. There is also an intermediate category, the small scale commercial farmers who operate on relatively smaller farms compared to the large scale commercial farmers, but like the large scale farmers they have title deeds to the land they use. Following the land redistribution exercise which started around 2000, however, the size of the large scale commercial farming sector has decreased, while more land is now being cultivated by smallholder farmers.

The target group for this study is the smallholder farmers in the traditional communal areas of Gweru and Lupane districts of Zimbabwe. The majority of communal areas in this country lie in low agricultural potential regions, III, IV and V, where more than 80% of the rural population lives (FAO, 2000). Agricultural potential decreases from region I to V and a detailed description of these regions is provided in Table 2.1. Approximately 17% of the communal land area is located in Natural Region III, 45% in region IV and 29% in region V (Chiremba and Masters, 2003; FAO, 2006). The study areas of Lower Gweru and Lupane lie in regions III and IV, where soils range from vertisols to sands and are less weathered compared to those in higher rainfall areas and hence tend to be shallower (Thompson and Purves, 1978). Although a wide range of soils exit in regions III and IV, most soils in these regions consist of shallow, coarse grained sands, which have a low production potential (Thompson and Purves, 1978; Grant, 1981; Mashiringwani, 1983; FAO, 2006; Ncube *et al*., 2009). The soils are also subject to fast depletion in fertility (FAO, 2006). A considerable area of deep, fine grained sands (Kalahari sands) is also found to the west of the country, which includes Lupane (Thompson and Purves, 1978). These soils are relatively infertile and subject to severe wind erosion particularly if they are cropped.

Communal farmers have no title deeds to the land they use. They are entrusted with this land by the state through local leadership (headmen), who allocate the land to them. Most of the resources and infrastructure they use are communally owned, for example, grazing land, boreholes and dip tanks. Arable land holdings in communal areas are usually less than 2.5 ha (Rukuni, 1994; Chiremba and Masters, 2003) and for Natural Regions III and IV, covered in this study, average arable land holdings are 2.0 ha and 3.2 ha, respectively (Mushunje, 2005). These land sizes are smaller than the land size that is considered viable (able to provide enough food for a family for a whole year) as they are even less than the minimum land size of 4 ha recommended for medium to high potential agricultural areas of Zimbabwe (Kinsey, 2002). Smallholder farmers are generally characterized by a limited resource base and Waddington *et al.* (2004) characterized smallholder productivity as "low input – low output" farming. According to Rockstrom (1999), small-scale farmers in water scarce tropical regions of sub-Saharan Africa are "generally risk minimizers rather than yield maximizers". For semi-arid Zimbabwe, Ellis-Jones and Mudhara (1995), point out that these farmers face great challenges as they are required to respond to a wide range of environmental and economic variables which include low and erratic rainfall, generally infertile soils and difficulties in acquiring production resources such as agronomic inputs, labour and draft power. Production systems of communal area farmers in Zimbabwe are also labour intensive and characterized by use of ox-drawn implements (FAO, 2006).

Despite the biophysical and economic challenges they encounter, smallholder farmers continue to rely on agriculture for their livelihoods in these areas where, according to FAO (2000), good crop yields are only obtained one year out of every four to five years. Smallholder agricultural productivity in communal areas of Natural Regions III and IV is already marginal, and climate variability and change are likely to render farmers in these areas more vulnerable to food and nutrition insecurity. Farmers in the study areas ascertain that they have observed some changes in land and vegetation cover, crop and livestock productivity and water sources, over the years, as a result of climate variability and change (Munodawafa *et al*., 2009). Their perception of climate change and variability is that rainfall has become more and more unpredictable, with seasons starting late and ending early, while amount of rainfall received is getting less (Mubaya, 2010; Mubaya *et al*., 2012). The farmers also claim that droughts and floods have become more frequent and summer seasons have become hotter (Mubaya, 2010; Mubaya *et al*., 2012). However, communities across the world have always adapted to climatic and other environmental factors (Adger *et al.*, 2003) and according to Wall and Smit (2005) "Climate and weather conditions are a good example of factors that require on-going adaptation with climate change they take on even more significance". The level of adaptation has not been the same across communities, with some communities being more vulnerable than others (Adger *et al.*, 2003). Communities in Africa, for example, are considered to be among the most vulnerable in the world due to their heavy reliance on agriculture which is among the most sensitive sectors to climate change and due to limited capacity to adapt to climatic changes (Kurukulasuriya and Mendelsohn, 2008b; Mendelsohn, 2009).

The objective of this chapter is to establish farmers' current agronomic practices, their crop production constraints and the strategies they use to cope with and/or adapt to these constraints. Strategies currently used to cope/adapt to current climate variability will also be described. Identified agronomic practices, for example crop varieties grown and management practices (e.g. planting density, fertilizer rates, timing of operations etc) will be used as crop model input data for simulating crop yields under current and future climate scenarios in Chapter 5. Other model input data required are climate and soil data. Agronomic practices as well as coping and adaptation strategies that farmers are currently using, may guide in suggesting possible strategies that farmers may use to reduce impacts of climate change. Appropriate recommendations for the target group of farmers, smallholder farmers in Lower Gweru and Lupane areas of Zimbabwe in this case, can only be made if the circumstances under which the farmers are operating are known, hence the current objectives.

4.2. Materials and Methods

The study area comprises Lower Gweru and Lupane communal areas, in Gweru and Lupane districts of Zimbabwe (Fig. 2.1). Most of Lower Gweru lies in Natural Region III while Lupane is in region IV. Natural Region III is a semi-intensive farming region receiving annual rainfall of 550-700 mm while Region IV is semi-extensive and receives annual rainfall of 450-600mm (Vincent and Thomas, 1962). Both quantitative and qualitative methods were used to collect data and information on current agronomic practices, constraints to crop production and on coping and adaptation strategies employed by farmers in the study area. Data were collected from structured interviews (Fowler, 1998; Bless and Higson-Smith, 2000; Mason, 2004; Punch, 2005; Gill *et al*., 2008; Newton, 2010), semi-structured interviews (Bless and Higson-Smith, 2000; Mason, 2004; Flick, 2006; Gill *et al*., 2008; Newton, 2010) and Focus Group Discussions (FGDs) (Steward and Shamdasan, 1998; Flick 2006; Gill *et al*., 2008; Harrell and Bradley, 2009).

Structured interviews are a quantitative research technique which involves use of pre-determined and standardized questions (Bayer *et al.*, *undated*; Bless and Higson-Smith, 2000; Balnaves and Caputi, 2001; Mason, 2004; Punch, 2005; Flick 2006; Gill *et al*., 2008; Newton, 2010). The questions and responses are largely closed, although open-ended questions may be used (Punch, 2005). Structured interviews can be used in many types of research, ranging from case studies to interviews (Bayer *et al.*, *undated*). One major advantage of using this technique is that comparisons between sample sub-groups and/or between survey periods are possible (Bryant, *undated*), since exactly the same questions are asked and in the same manner, each time the interviews are conducted. Conclusions about the subject being investigated can then easily be made with confidence. The method is also relatively quick and questionnaires are easy to administer, since there is no probing (Gill *et al*., 2008). However, compared to other methods, the method is less flexible (Mason, 2004; Punch, 2005; Gill *et al*., 2008) and the method is not as useful where in-depth knowledge and understanding are required (Gill *et al*., 2008). Unlike using structured interviews, in semi-structured interviews not all questions are pre-determined (FAO, 1990; Newton, 2010) and most questions and responses are open-ended (FAO, 1990; Newton, 2010). Interviews start off with more general questions, based on an interview guide or check list. The interviews use questions, conversation and discussion to get in-depth understanding of the subject being investigated (Newton, 2010) and success of the method is highly dependent on the relationship and rapport established between interviewer and interviewee (FAO, 1990; Newton, 2010). Semi-structured interviews are suitable for relatively small groups or populations e.g. case studies (Balnaves and Caputi, 2001). Compared to structured interviews, semi-structured interviews are more flexible (FAO, 1990, Mason, 2004; Gill *et al*., 2008). They also allow researchers to discover important aspects of the subject (being investigated), which they may originally not have thought as being relevant (Gill *et al*., 2008). However, it may be difficult to control discussions during semi-structured interviews (Gill *et al*., 2008), thereby leading to more time being spent in conducting the interviews than originally intended. It may also be difficult to come to conclusions, since the questions asked are unlikely to be exactly the same with each individual as in a structured interview.

Focus group discussions (FGDs) are appropriate for probing people's views and behaviour (Barbour and Schostak, 2005; Punch, 2005) and insight into these issues cannot be easily obtained through individual interviews (Barbour and Schostak, 2005). Unlike with interviews, where the researcher's main role is to ask questions, in group discussions the researcher acts more as moderator (Punch, 2005). FGDs are relatively inexpensive (Punch, 2005; Flick, 2006) and they also provide a lot of data and are "flexible, elaborative and stimulating" (Punch 2005). Limitations of the method include the fact that findings of the research work cannot be applied beyond that group (Harrel and Bradley, 2009). During FGDs it may also be difficult to have balanced group interactions (Punch, 2005) as some participants can dominate the discussions, while other participants may fail to express their views (Flick, 2006). FGDs may also be inappropriate for investigating sensitive topics (Gill *et al.,* 2008).

Mixed research methods (MRMs) were thus used in this study and according to Balnaves and Caputi (2001) and Flick (2006) this approach allows for data triangulation and thus checking for validity of data. Johnson and Onwuegbuzie (2004) reckon that the multi-methods nature of the MRM approach often results in enhanced research. In this study, however, for certain specific aspects of the investigations, some of the research techniques were used as stand-alone methods, for example ranking of farmer constraints to crop production and ranking of crops, which were done during FGDs. Data on agronomic practices, nature of crop production constraints and coping strategies were determined using all three methods. Whereas household interviews (structured interviews) and FGDs were held mainly with heads of households, semi-structured interviews were held with key-informants from the Zimbabwe Department of Agricultural Research and Extension Services (AGRITEX), namely area supervisors and extension officers. Secondary data (Bless and Higson-Smith, 2000; Hox and Boeije, 2005) were mainly used to better understand characteristics of smallholder farmers in the study area and their biophysical environment, recommended agronomic practices as well as farmer perceptions of climate variability and change. Sources included maps, reports, published refereed articles and farm management handbooks. Two wards were selected from each communal area and these were Mdubiwa and Nyama Wards for Lower Gweru, and Daluka and Menyezwa Wards for Lupane (Fig. 1.1). In each ward, three villages were selected (Table 4.1).

4.2.1. Semi-structured interviews with key informants

Interviews were carried out with area supervisors and extension officers from the Department of AGRITEX, of the Ministry of Agriculture, on agricultural productivity in the smallholder sector in Gweru and Lupane districts of Zimbabwe. Most of these key informant interviews were carried out before the individual farmer interviews and group discussions. A check list was prepared and used in the interviews (Appendix IIb).

4.2.2. Focus Group Discussions (FGDs)

The first FGDs (one per ward) focused on farming systems and crop production constraints and were carried out in October, 2008, while the second FGDs (one per ward) focused on adaptation and coping strategies to rainfall variability and were carried in January and February, 2009. For each FGD, five farmers were randomly selected from each village bringing the total number per discussion group to 15 and the number of participating farmers for each period of investigations to 60. Where possible, farmers were further grouped by gender within a focus group to allow men and women to express their views freely. Notable exceptions were the focus groups for Daluka Ward in Lupane for the 2008 FGDs and the focus group for Menyezwa Ward in Lupane during the 2009 FGDs. These groups were dominated by women and men respectively. The year 2008 was characterized by economic hardships and high food insecurity levels as the country experienced a cumulative decline in economic output starting from the year 1999 (Kramarenko *et al*., 2010; World Bank, 2013). The period 1999-2008 saw a weakening in Zimbabwe's revenue collection (a decrease in total revenues of about 25% of GDP) and public service delivery, due to a reduction in economic output and hyperinflation (Kramarenko *et al.*, 2010) and the reduction in economic output between 1999 and 2008 was estimated at more than 45% (World Bank, 2013). In addition, the 2007/08 rainfall season was generally poor with some farmers in both study areas of Lower Gweru and Lupane stating that they received excessive rains during this season (Mubaya *et al*., 2012). According to FAO/WFP (2010) maize production in Zimbabwe was just above 500 000 tonnes, for the 2007/08 season, an amount which is far less than a possible 2 500 000 tonnes under favourable socio-economic and climatic conditions (FAO/WFP, 2010) By the time of the second FGDs and household interviews (February, 2009), the economic situation in the country had improved slightly as witnessed by improved availability of food in retail outlets and more realistic prices of goods. These observations are supported by Kramarenko *et al*. (2010) and the World Bank (2013) who report that the economy of Zimbabwe started to recover during the year 2009, following a significant improvement in economic policies (Kramarenko *et al*., 2010). During the period 2009-2011, real GDP increased by 20.1%, mainly due to significant growth in the mining, agriculture and services sectors (World Bank, 2013). The 2008/09 rainfall season was a relatively poor season in Daluka Ward of Lupane, as both the first half (October, November and December) and second half (January, February and March) of the season received below normal rainfall (Chagonda, 2013; Chagonda *et al*., 2013). Menyezwa Ward (Lupane) and the two wards in Lower Gweru, namely, Mdubiwa and Nyama had above normal rainfall during both the first and second parts of the rainfall season (Masere, 2011; Chagonda, 2013; Chagonda *et al*., 2013). The second half of the season in the later three wards had well above normal rainfall season (Masere, 2011; Chagonda, 2013; Chagonda *et al*., 2013) which resulted in crops, particularly those in low-lying areas, succumbing to waterlogging. Generally, low crop yields were thus obtained by farmers in these areas during this season. Check lists were developed for the FGDs and methods of data collection used in the FGDs included brainstorming, time charts, matrix scoring and ranking (Chambers, 1994; Sutherland, 1998).

4.2.3. Household structured interviews

Household interviews were held at the same time as second FGDs, that is, during January and February, 2009. A total of 48 farmers were selected using random systematic sampling from a household list that had been compiled for the International Development Research Centre-Climate Change Adaptation in Africa (IDRC-CCAA) project baseline survey carried out in the same wards and villages during 2008. A questionnaire with coded responses for most of the questions (see Appendix IIa), was developed, tested and then used to collect data on agronomic practices, constraints to crop production and coping strategies to rainfall variability.

Table 4.1. Wards and villages from which participating farmers for both individual interviews and FGDs were drawn

Communal area	Ward	Villages
Lower Gweru	Mdubiwa	Nsukunengi Madinga Mxotshwa
	Nyama	Guduza Mathonsi Msingondo
Lupane	Daluka	Daluka Mafinyela Strip road
	Menyezwa	Banda Masenyane Menyezwa

4.2.4. Data analysis

Data from household interviews were analysed by determining frequency distribution of the number of farmers carrying out the various practices, while results from qualitative methods, were mostly narrated. Graphs and tables were used to present most of the results.

4.3. Results and Discussion

4.3.1. Agronomic Practices

Soil type

Farmers in Lower Gweru and Lupane wards are knowledgeable about the types of soils in their fields and they narrated the various soil types in vernacular language. The researcher, with assistance from local expert soil scientists from the IDRC/CCAA project (project number104144) as well as local AGRITEX officers matched farmers' soil description with the conventional soil descriptions used herein. Soils in Lower Gweru wards are variable with granitic sandy loams *("inhlabathi"),* red clay soils *("isibomvu")* and sodic soils *("isikwakwa")* in both Mdubiwa and Nyama Wards. Dark clays (pseudo vertisols) *("isidhaka")* are also found in Mdubiwa. The dominant soil type in Lupane wards is Kalahari sands *("gusu")*. Black clays *("isidhaka")* and *"bhemba"* (mixture of "*gusu*" and black clays) are also found in both Daluka and Menyezwa Wards. Sandy loam soils *("inhlabathi")* are dominant in Menyezwa village of Menyezwa Ward while some red clays are found in parts of Daluka Ward. The farmers' verbal description of soils generally agrees with what is known from the literature about soils in the Natural Regions in which they occur, for example, the description by Thompson and Purves (1978). Farmers acknowledged that their soils were low in fertility and also cited poor soil fertility as one of the major limitation to high crop productivity. This is in agreement with Waddington *et al.* (2004)'s findings that smallholder farmers on their own perceive poor soil fertility as a major constraint to crop production, suggesting that there are other reasons for low adoption of fertilizer use, rather than their lack of knowledge. Most farmers reported that they had different soil types in different fields and for some of them, inherent soil fertility levels, among other factors, influenced their cropping decisions. In Lupane, for example, "*isidhaka"* black clay soil, confined to river banks, is fertile and retains moisture, is often planted to maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), pumpkins (*Curcurbita* spp) and sugarcane (*Saccharum officinarum* L.). Pearl millet (*Pennisetum glaucum* (L.) R. Br.), cowpeas (*Vigna unguiculata* (L.) Walp), groundnuts (*Arachis hypogea L.*) and bambara groundnuts (*Vigna subterranean* (L.) Verdc) are often grown on sandy "*gusu"* soils, while on "*bhemba*" and "i*siwomvu*" maize, sorghum and sweet potatoes (*Ipomea batatas* L.) are normally grown. "*gusu"* soils are particularly good for groundnut pod development and ease of lifting during harvest operations. Maize and sorghum are grown across all soil types for food security reasons as the most preferred soils are limited in extent. According to these farmers, change in rainfall does not influence what crop to grow on the different soils. Mudhara (1995) suggests that ear-marking certain soils for maize production by some farmers in Chivi (Zimbabwe), similar to what the farmers in this study area do, results in limited or lack of rotations on some fields and/or soil types.

Tillage systems

The predominant tillage system in both Lower Gweru and Lupane communal areas is conventional tillage (Fig. 4.1) with the ox-and/or donkey-drawn mouldboard plough, being the most commonly used tillage implement. However, this may not be over all the fields for some of the farms, as more than half of the farmers in Lupane also use "*gatshompo"* (planting basins), with more farmers in Daluka Ward than Menyezwa Ward, using this practice (Fig. 4.1). In Lower Gweru, only five percent of the farmers use planting basins. Zero tillage (digging a hole on unploughed land in which to place the seed) is practised by approximately 29% of farmers in Lower Gweru on some or all of their fields, while about 10% of farmers in this communal area also resort to *"chibhakera"* (hand digging of the whole field and then planting) (Fig. 4.1). Thus some of the farmers use more than one tillage system on their farms for land preparation and planting, according to soil type and labour availability.

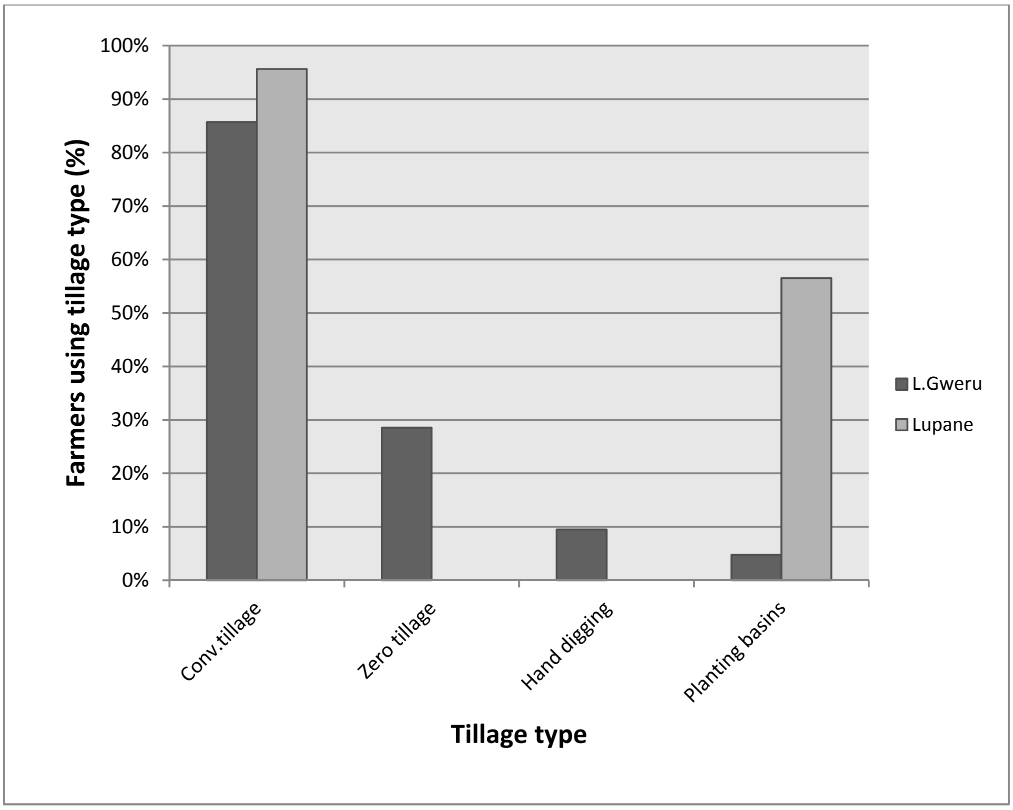


Fig. 4.1. Tillage systems used by farmers in Lower Gweru and Lupane communal areas during the 2008/09 cropping season

Ploughing is mostly carried out just prior to planting, during early summer, with only about 30 percent of the farmers in these areas ploughing in winter. The plough, particularly the mouldboard plough, has been in use in Zimbabwe since 1920s (Alvord, 1926; Elwell, 1993; Kramer, 1997; Baudron *et al*., 2012) and continues to be used by the majority of smallholder farmers across the country, despite some disadvantages associated with conventional ploughing. Annual conventional ploughing, promotes soil degradation, has a high draft force requirement and contributes to loss of crop productivity (Vogel, 1994). Planting basins were introduced by Non-Governmental Organizations (NGOs) in Zimbabwe in the 2003/04 season, as part of the Conservation Farming (CF) tillage package. This type of tillage is suitable for farmers with inadequate draft power and implements, which is the case in Lower Gweru and Lupane. In addition, the use of basins spreads labour for land preparation over the dry season, promotes timely planting and reduces the risk of crop failure, even under drought conditions, due to the concentration of water and available fertilizer in the basins (Hove and Twomlow, 2007; Twomlow *et al*., 2008b, 2008c; Thierfelder and Wall, 2009). The use of mulch on the basins, if available, also enhances moisture retention and improves crop productivity. Twomlow *et al*. (2008b) established that crop yields increased, on average, by 15 to 300% across 13 pilot districts in Zimbabwe over three seasons (2004/05 to 2006/07) of planting basin use. The magnitude of yield increase depended on rainfall pattern and amount, soil type and soil fertility. The adoption rate for use of planting basins is higher in Lupane than Lower Gweru (Fig. 4.1), presumably due to more intense extension effort in the former area where rainfall inadequacy and unreliability are more critical. In fact, Lupane district is one of the eight districts partaking in conservation agriculture programmes spear-headed by NGOs and run in collaboration with Government extension agencies (Twomlow *et al*., 2008b) in which planting basins are a key component. Farmers who use zero tillage and those who use hoes to dig the whole field, usually lack draft animals and implements and/or have limited capacity to hire these resources.

Type of crops grown

The range of crops grown by farmers in Lower Gweru and Lupane is wide and almost similar (Fig. 4.2). The difference lies in the extent to which the crops are grown in terms of area planted to a crop and/or the number of farmers who grow a crop. Crops grown include maize, sorghum pearl millet, finger millet (*Eleusine coracana* L.) groundnuts, cowpeas, groundnuts, melons (*Citrullus lanatus* (L.) Thunb), pumpkins (*Curcubita maxima* L.), sugar beans (*Phaseolus vulgaris*) and sweet potatoes. Farmers ranked crops they consider important according to their contribution to food security, improved livelihoods and income generation as well as according to the number of farmers growing the crop and the number of uses of the crop. The overall ranking (Table 4.2) shows that in Lower Gweru, the most important cereal crop is maize while finger millet and sorghum are grown to a lesser extent. In Lupane, the main cereal crops are maize, pearl millet and sorghum and in Daluka Ward, these were ranked 1 to 3 respectively, while in Menyezwa Ward pearl millet is the most important cereal, followed by sorghum and then maize. The sour melon "*amajodo*", a type of melon that is cooked and consumed on its own or boiled and consumed together with maize grain, was ranked as first and second crop based on contribution to food security (from a food availability view point) as well as income generation by men and women respectively, in Menyezwa Ward during the 2008 FGDs. However, results from individual farmer interviews and semi-structured interviews with local extension officers did not indicate that the sour melon was in any way, the most important crop in this ward. The crop, however, yields quite well in relatively dry years as compared to wet years, resulting in its high abundance in dry years. The most probable explanation for the high ranking of the sour melon by the Menyezwa group of farmers is that, during the 2008 season, when the FGDs were conducted, farmers in this ward depended heavily on this cultivated food crop for survival as other crops had failed. At the time of the 2008 FGDs local vendors could be seen along the adjacent highway road to Victoria Falls selling a lot of these melons. In these dry areas of Lupane, the sour melon is usually intercropped with other crops, particularly cereals. The main legume crop in Lower Gweru is groundnut, while in Lupane groundnuts and cowpeas are the main legume crops being grown by about the same number of farmers (Fig. 4.2). Farmer interviews did not reflect the high priority that was given to sugar beans by Mdubiwa farmers during the 2008 FDGs. This is probably because only a few of the farmers that were interviewed own plots in the two irrigation schemes in this ward, where the crop is grown in rotation with maize. In Lupane, results of household interviews also did not show that farmers in the area grow sugar beans, but from FGDs and extension worker interviews it emerged that the crop was grown by very few farmers who got seed from an NGO promoting agricultural production in the area. In Lower Gweru sweet potatoes are grown for both consumption and for sale locally and in nearby Gweru city markets, while in Lupane the crop is mostly only grown for household consumption. The small grain crops (pearl millet and sorghum), melons (especially the sour melon) and cowpeas are grown by a higher percentage of farmers in Lupane than in Lower Gweru because of their relatively high tolerance to soil water deficits. Hence they are more suitable for production in the drier Lupane than Lower Gweru. Although the success of growing maize is minimal in Lupane, being one year in every four to five years (FAO, 2000), all farmers grow the crop because it is preferred as food, is easier to process and in good years gives higher yield than small grains (Sukume *et al.,* 2000). Maize is also preferred over sorghum and pearl millet because it gives higher stover yield which is an important source of animal feed during the dry season (Alumira and Rusike, 2005). However, for food security reasons, sorghum and pearl millet are the more suitable crops in Lupane and other dry areas. Smallholder farmers in both Lower Gweru and Lupane mainly grow crops for subsistence and only sell when they have surplus. Hence none of their crops are purely cash crops.

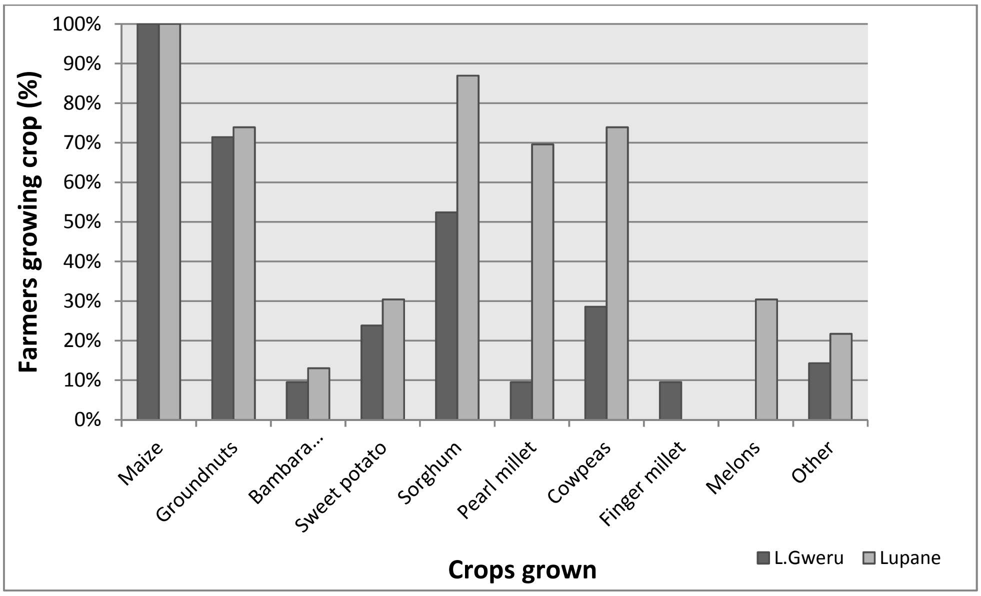


Fig. 4.2. Percentage of farmers growing different crops in Lower Gweru and Lupane communal areas during the 2008/09 growing season

Table 4.2. Ranking of crops by women and men in Mdubiwa and Nyama Wards (L.Gweru) and Daluka and Menyezwa Wards (Lupane) during FGD in 2008

Crop	Ranking by women				Ranking by men		
	Mdubiwa ward	Nyama Ward	Menyezwa ward	Daluka ward	Mdubiwa ward	Nyama Ward	Menyezwa ward
Maize	2	1	5	1	2	1	4
Pearl millet	-	-	2	2	-	-	2
Sorghum	-	-	4	3	-	-	3
Finger millet	-	4	-	-	-	5	-
Groundnuts	3	3	-	5	4	3	-
Cowpeas	4	5	3	4	5	4	5
Bambara groundnuts	-	6	-	7	-	6	-
Sugar beans	1	-	-	-	-	-	1
Sweet potato	5	2	-	6	3	2	-
Sour melon ("*amajodo*")	-	-	1	-	-	-	1

Varieties of main cereal and legume crops

Farmers indicated that their choice of variety is normally governed by factors such as shortest time to maturity, tolerance to drought, yield potential, ease of management and good storability. Short statured varieties, for example, are generally preferred over tall varieties for easy harvesting while the "red cob" an Open Pollinated Variety (OPV) (variety which is produced under non-controlled pollination, through continuous selection for uniformity until a uniform stand is obtained (Tinsley 2009a) unlike a hybrid variety which is produced through controlled pollination) of maize is preferred over other varieties, due to its good resistance to weevil attack. However, in recent years, farmers have had little varietal choice, due to the economic situation, and what they grow is mainly dictated by what is available, provided it suits their water stress environments. Farmers in the study areas use a wide range of crop varieties (Table 4.3) and within one season a farmer often grows more than one variety of a crop as a way of spreading risk of complete crop failure in these water stressed environments. For maize, hybrids as well as OPVs are grown in both communal areas. In Lupane an equal number of farmers (approximately 75%) grow hybrid varieties and traditional OPVs, while in Lower Gweru about 90% of farmers use hybrid maize seed while traditional OPVs are used by 40% of the farmers. Improved OPVs yield higher than traditional OPVs, but are used to a lesser extent compared to unimproved OPVs, with only about 20 and 10% of the farmers growing improved OPVs in Lupane and Lower Gweru, respectively. Early maturing (110-130d) hybrids are grown in Lupane while in Lower Gweru the range stretches to medium (130-140d) maturity varieties. Although hybrids generally have a higher yield potential than OPVs for varieties in the same maturity group (Chiduza *et al*., 1994; Pixley and Bänziger, 2001), farmers in the study areas continue to choose to grow OPVs for a number of reasons. They are relatively cheap to grow and planting seed is readily available. When maize is grown from hybrid seed retained from previous harvests, there is non-uniformity of the crop in the field as well as reduction in yield, due to segregation of characteristics of the individual parental plants. In contrast, OPV seed can be retained for several years without incurring significant yield reductions (Chiduza *et al.*, 1994; Pixley and Bänziger 2001; Tinsley, 2009a). Use of seed retained from previous harvests is a factor that has cushioned farmers in the study area against shortages of planting seed on the market during certain seasons, including the 2007/08 and 2008/09 when this study was carried out.

The use of improved varieties of sorghum and pearl millet by communal farmers in western Zimbabwe, including Lupane, was reported to be low (Ahmed *et al.,* 1997). The study has established that about 60 percent of the farmers in Lupane use improved varieties of either crop, with Pearl Millet Variety 3 (PMV3) being the main pearl millet variety and Macia (white), the main sorghum variety. Interviews with agricultural extension officers in Lupane also indicated that improved sorghum varieties SV1 and SV2 are grown by farmers, but on a limited scale due to shortage of seed. The traditional "unimproved" pearl millet variety most commonly grown is “Harare” while for sorghum it is was unclear what the main traditional variety is, since some farmers were not sure of the names of traditional varieties they were growing. There is an indication that use of improved small grain varieties has increased and this is most likely due to their earliness to reach maturity, a favourable trait in low and erratic rainfall areas together with promotion of the varieties by seed companies, NGOs and Government extension agencies.

Groundnut seed is often in short supply and farmers normally grow any varieties made available to them. Results from household interviews showed that about 30% of farmers in each of the communal areas, grow the Natal Common variety, 20% Valencia Red and 5% Valencia White. The majority of farmers were not sure of the names of varieties they were growing, although from their description of the varieties, it appears they are growing Natal Common. Interviews with agricultural extension officers also confirmed that most of the farmers grow this variety. Most farmers have for a long time grown these varieties using seed retained from previous seasons and fortunately self-pollinating crops, like groundnuts do not lose genetic purity when retaining the seed from generation to generation (Tinsley, 2009b). Improved varieties such as Nyanda and Falcon*,* released in the 1980s and 1990s, have been in short supply since their release and it was unclear from farmers in Lupane and Lower Gweru, whether they grow them or not. However, some extension officers in Lower Gweru claimed that these varieties were being grown by some of the farmers in this communal area. Farmers in both communal areas grow both spreading and upright varieties of cowpeas. However, most farmers prefer the upright variety IT18, popularly known as *"Mupedzanhamo"* as it matures quite early (about 90d) providing food before most crops are mature and ready for consumption. The variety is also high yielding.

Table 4.3. Crop varieties for crops commonly grown by farmers in Lower Gweru and Lupane communal areas of Zimbabwe

Crop	Varieties grown	
	Lower Gweru	**Lupane**
Maize	SC403(very early maturing hybrid) SC407 (very early maturing hybrid). SC521 (early maturing hybrid) SC513 (early maturing hybrid) ZM521 (improved OPV) "*Bogwe*"-white cob (local OPV)	SC403 SC513 "*Bambadhla*" red cob (local OPV) "*Bambadhla*" white cob (local OPV)
Pearl millet	Bird proof, "*Tsholotsho*" bearded (traditional variety) "Long plane" (traditional variety with long head) "Short plane" (traditional variety with short head & large seed)	Bird proof, "*Tsholotsho*" bearded (traditional variety) "*Harare"(*traditional variety) Pearl Millet Variety 1(PMV1) & PMV2 (hybrids)
Sorghum	*"Tsheta"(*traditional variety) Red Swazi-"*Chibuku"* (hybrid) Macia white (improved variety) Sila (improved variety)	*"Tsheta"* (traditional variety) Red Swazi-"*Chibuku"* (hybrid) Macia white (improved variety) Sorghum Variety1 (SV1) and SV2 (hybrids)
Groundnuts	Natal common (early maturing, pink seeded) Valencia (early red & late pink, seeded varieties) Makulu red (grown mainly in wetlands/dambos & irrigation schemes; late maturing)	Natal common (early maturing, pink seeded) Valencia (early red & late pink seeded varieties) Red Congo (matures early & grown by few because seed is not readily available)
Cowpeas	IT 18 *("Mupedzanhamo*")-upright & very early maturing hybrid; spreading indigenous types (white and red seeded varieties)	IT 18 ("*Mupedzanhamo")*-upright & very early maturing hybrid; spreading indigenous types (white and red seeded varieties)
Sugar beans	Mostly speckled variety; PAN 148 & PAN 138 (seed in short supply)	Mostly speckled variety
Bambara groundnuts	Black-eyed Susan (black & yellow seeded) Red-eyed Susan (red & yellow seeded)	*"Nyembesi"* (black & white mostly grown) Red variety from Zambia (brought into country in 1997)
Sour melon "*amajodo*"	Traditional varieties	Traditional varieties

Planting

The majority of farmers who use conventional ploughing either plant behind the plough as illustrated in Fig. 4.3 or open up planting furrows in winter ploughed fields, at the start of planting season, when first effective rains are received. With the former method, variable row spacings are achieved, depending on the number of furrows skipped before the planting furrow and the plough width used (Table 4.4). As an example, maize is planted every third row and the plough width is adjusted to 30 cm to give an inter-row spacing of 90 cm. Farmers then use an intra-row spacing of 25-30 cm resulting in plant population of 37 000-44 000 plants ha^{-1}.

Fig. 4.3. Nicholas Chimusoro (stripped shirt) of Mxotshwa village in Mdubiwa ward and family planting maize using the "planting following the plough" method, during the 2008/09 season

Table 4.4. Inter-row spacing and plant densities achieved when planting behind the plough and with the plough width adjusted to 30 cm, for major cereal and legume crops (Source: Lower Gweru and Lupane farmer interviews, 2009**)**

Crop	**Number of furrows skipped before next planting row**	**Inter-row spacing achieved (cm)**	**Intra-row spacing used (cm)**	**Plant population (plants/ha)**
Maize	2	90 *(90)*	25-30 *(30)*	37 000-44 000 *(37 000)*
Sorghum	1	60 *(90)*	10-25 (after thinning) *(7-10 after thinning)*	66 000-167 000 *(111 000-160 000)*
Pearl millet	1-2	60-90 *(50-75)*	10-25 (after thinning) *(20-30 after thinning)*	~44 400-167 000 *(53 300-100 000)*
Groundnuts	0-1*	30-45 *(50-75)*	7-10 *(5-7.5)*	~ 222 200-476 000 *(178 000-400 000)*
Cowpeas (upright varieties)	0-1*	30-45 *(45)*	10-15 *(15)*	~150 000-333 300 *(~150 000)*

Figures in brackets and italics are recommended spacing and populations from the Ministry of Agriculture.
* When a row is skipped the plough width is maintained at standard width of 20 cm

However, if land is prepared in autumn or winter, farmers open up planting furrows at start of the cropping season using a plough pulled by animals harnessed to a cultivator yoke (Fig. 4.4) which is 240 cm wide (full length) and 180 cm between pegs (skeis) to achieve a 90 cm inter-row space. This yoke is used when opening up furrows to plant maize, sorghum and pearl-millet, while a plough yoke (similar in design, but shorter than the cultivator yoke)(Fig. 4.4) with a distance of 90 cm between skeis is used when opening up furrows to plant groundnuts and cowpeas as its use results in a narrower inter-row spacing of 45 cm. With this method of planting it is relatively easy to achieve the desired inter-row spacing as there is no requirement for adjusting the plough width, hence farmers should be encouraged to winter plough their fields. Ploughing in winter also conserves moisture from the previous season, promotes early crop establishment and reduces weeds (Sibanda, 2005; Mpatane *et al.*, 2012). Over and above recommendations from the Ministry of Agriculture, farmers are also guided by the method of weed control they use, in their choice of inter-row spacing e.g. if the animal-drawn cultivator (Fig. 4.4) is used, a wider spacing is required than when the hand hoe is used.

Fig. 4.4. Photographs of a) plough and b) cultivator yokes and associated implements (mouldboard plough and cultivator) belonging to farmer Benjamin Mpala (black T-shirt) of Nsukunengi village in Mdubiwa Ward. In Fig 4.4. c) Extension officer Mirirai Musasanuri explains the design of the cultivator yoke to woman researcher, Veronica Makuvaro while extension officer Alfred Pawadyira d) demonstrates how the animal drawn cultivator is adjusted to achieve the desired operation width

For the maize crop, the inter-row spacing of 90 cm used by farmers in both study areas matches that which is recommended for these medium to low agricultural potential areas. However, the intra-row spacing of 25-30 cm used by farmers gives a population range whose lower limit is equal to and upper limit about 20% higher than the recommended population (Table 4.4). To achieve the recommended plant population farmers can adopt the recommended intra-row spacing of 30 cm for upland maize production, while farmers such as those Nyama Ward, who grow crops in wetlands where soil water is less limiting may use an intra-row spacing of 25 cm.

Farmers drill sorghum and pearl millet in furrows by hand and then thin emerged plants to about 10-25cm within the row. For sorghum, the inter-row space they use is smaller and the intra-row space bigger than is recommended, resulting in a wider plant population range whose lower and upper limits fall outside the recommended range of 111 000-60 000 plants ha^{-1} (Table 4.4). Recommendations from the Ministry of Agriculture also stipulate that sorghum plant populations below 90 000 plants ha^{-1} should be avoided (Ministry of Agriculture, Mechanization and irrigation Development in Zimbabwe, 2011). On the contrary, Ismail and Ali (1996) in their study on effects of plant population on sorghum yield in dry-land farming systems, established that grain sorghum yield decreased with increase in plant population from 53 000-106 000 to the range 166 000-333 000 plants ha^{-1} (the same inter-row spacing of 60cm was used for both ranges, with the first range being for an intra-row spacing of 30cm and the second for an intra-row spacing of 10cm, while the lower range values are for one plant per station and the upper range values for two plants per station). This suggests that populations less than 90 000 plants ha^{-1} could still give good yields in low cropping potential areas such as Lower Gweru and Lupane. The tillering nature of the sorghum plant will compensate for the relatively low plant population under wider spacing regimes and farmers can thus use relatively low seeding rates. To achieve populations within the recommended range, farmers could maintain their practice of planting sorghum every second furrow (to give an inter-row spacing of 60 cm) and adopt an intra-row spacing of about 15 cm. For pearl millet, the 90 cm inter-row that some of the farmers use is outside the recommended range, while the 60 cm that others use is within the recommended range. However, the intra-row spacing they usually use is wider than what is recommended. The recommended plant population could be obtained by farmers adopting an inter-row spacing of 60 cm, as other farmers are already doing and by using an intra-row spacing of 15-20 cm, instead of 10-25 cm. Farmers are using about the same plant populations for sorghum and pearl millet, whereas recommended populations show differences between the two, with sorghum having a lower and upper limit population which is about double and one and a half times greater than that of pearl millet, respectively. A lower population is expected for pearl millet since it produces many tillers and therefore requires wider spacing compared to sorghum. Farmers are thus likely to be getting below optimal grain yields for pearl millet due to crop competition for available water, light and nutrients although according to M'Khaitir and Vanderlip (1992), pearl millet grain yield is less sensitive to changes in plant population than other grain crops e.g. sorghum.

The practice of planting groundnuts and cowpeas every furrow results in an inter-row spacing of 30 cm which is much narrower than the recommended 50-75 cm and 45 cm for groundnuts and cowpeas, respectively. Using the narrow inter-row spacing of 30 cm in combination with 7-10 cm and 10-15 cm intra-row spacing for groundnuts and cowpeas, respectively results in higher plant populations than what is recommended implying that for both crops farmers could be getting lower yields than optimum, due to intra-specific competition for available resources. By using these populations farmers could also be wasting seed which is already in short supply. However, if farmers plant every second furrow and do not adjust the plough width, as some of them are already doing, they achieve the recommended inter-row spacing.

The recommendations provided by the Ministry of Agriculture, are based on field experiments where effect of different combinations of inter-and intra-row on grain yield are tested and the combination that gives optimum yields then recommended. For farmers who plant behind the plough, it appears to be relatively easy to attain the recommended inter-row spacing if they skip the correct number of furrows before planting and if they correctly adjust the plough width. They can then achieve the correct plant population by adopting the recommended intra-row spacing. The variations in plant populations between farmer and recommended practices (varying from seemingly small e.g. for maize to large e.g. for pearl millet), may require on-farm field experiments to verify whether there are significant grain yield differences due to the different plant populations and to establish the associated economic implications (e.g. higher unnecessary input costs). Farmers should be encouraged to plough their fields in winter so that they can open furrows to sow seed on onset of the rains using a plough drawn by animals harnessed to the cultivator yoke or plough yoke depending on the intended inter-row spacing. The advantages of this system being that it is easy to achieve the correct inter-row spacing, moisture is conserved, labour is spread, correct planting depth is easy to achieve and seed can be better covered using a harrow (Moyo, 2012 - personal communication).

Other planting methods used by farmers include the use of wires or ropes to mark out rows followed by hand hoe planting or planting in basins. Both methods are suitable for relatively small fields. Planting basins generally measure 15 x 15 x 15 cm (Hove and Twomlow, 2007; Twomlow *et al*., 2008b; Thierfelder and Wall, 2009) and farmers in Zimbabwe use short hand hoes to dig them (Mazvimavi and Twomlow, 2009; Thierfelder and Wall, 2009). They are dug during the winter period to reduce peak labour demand during planting time in early summer (Hove and Twomlow, 2007; Mazvimavi and Twomlow, 2009; Thierfelder and Wall, 2009). The basins are commonly used for maize and are spaced either 75 x 75 cm or 90 x 60 cm and the recommendation is to plant three seeds per basin (Hove and Twomlow, 2007; Twomlow *et al*., 2008b). Thinning should then be done after emergence to remain with two plants per basin, giving a target population of about 37 000 plants per ha (Fig. 4.5). The practice of initially planting three seeds per basin and then thinning out the third seedling where 100% seedling emergence is achieved, may be considered wasteful by farmers particularly for hybrid seed which is relatively expensive and sometimes not readily available and has generally high germination rates. To reduce the loss, extension officers encourage farmers to thin out extra plants when the soil is wet and transplant them onto another piece of land (Musasanuri and Pawadyira, 2013 - personal communication).

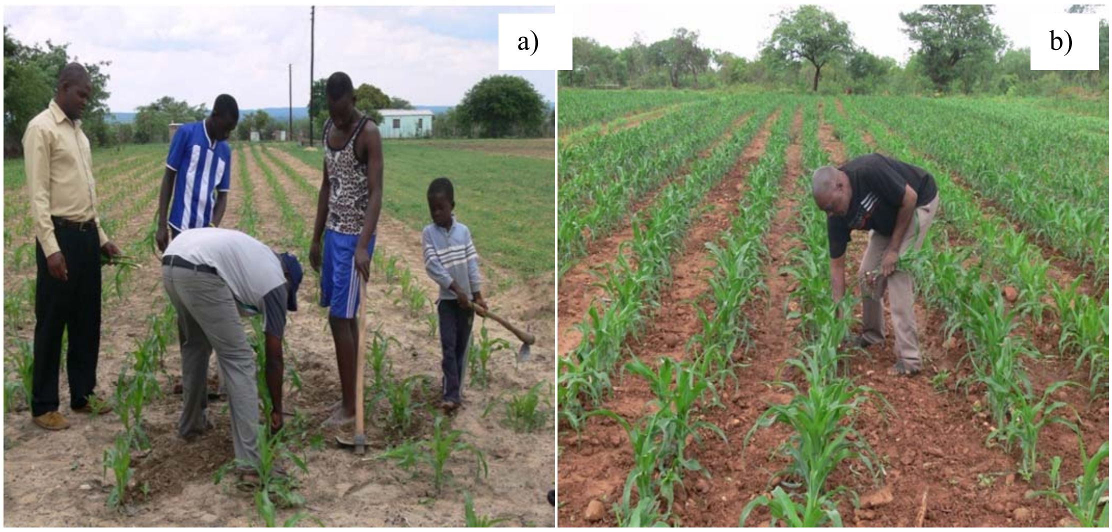


Fig. 4.5.a) Extension officers Mirirai Musasanuri (bending) and Alfred Pawadyira demonstrate and discuss thinning maize on a crop grown in planting basins to farmer Getrude Bonde's sons, in Mlotshwa village of Mdubiwa ward, while in b), Mr. Benjamin Mpala of Nsukunengi village is thinning maize by hand in his basin planted crop

Farmers indicated that planting dates were dependent on a number of factors including availability of soil water, seed and draft power. If there is delay in the availability of any of these resources, it delays planting. Norton (1988) reckons that the ability to plant on time as affected by tillage system, is probably the most important factor determining the success of small scale production in Zimbabwe. Farmers are aware of the importance of early planting, given their water stressed environments. They thus, aim to plant most of the crops with the first rains or dry plant before the rain comes. In Lower Gweru maize, groundnuts and finger millet are sown first, while in Lupane it is maize and pearl millet that have first priority. Shumba (1989) shows that delaying planting of maize by up to 21 days after first effective rains reduces yield by about 30% in Mangwende District in northern Zimbabwe and located in Natural Region II. Due to late planting, the crop is unable to intercept full sunlight radiative load available since, by 22 December when the sun is overhead, the crop will not have developed full canopy. Other disadvantages of delayed planting are reduced soil and water conservation due to delayed crop cover (Norton, 1995). Dry planting, which is also meant to reduce labour demand for planting at the start of the rainy season, is mostly done in October. According to the farmers, crops that they normally dry plant are maize, pearl millet and groundnuts. In Lupane, almost all of the pearl millet is dry planted. Farmers in this area argue that dry planting of this crop results in early establishment of the crop and allows it to mature at the same time as wild grasses, a factor that reduces crop damage/loss from bird attack as the birds will not only be feeding on the crop at that time, but on wild grasses as well. Staggering of planting dates is a characteristic feature of the planting process for most farmers.

Cropping calendars drawn up by the farmers (see Table 4.5 for an example) showed that planting in uplands (as opposed to vleis) stretches from as early as late October (mostly dry planting) to as late as the first dekad of January in both study areas, depending on rainfall pattern. In general most of the planting is done during the period from the second dekad of November until the second dekad of December.

Table 4.5. Calendar of farmers' main activities for Daluka Ward in Lupane communal area recorded in October, 2008

Activity	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**
Land clearing											+√	
Manuring		+√										
Winter ploughing										√	√	√
Ploughing (main)			+√	+√	+√	+√						
Planting			+√	+√	+√	+√						
Weeding				+√	+√	+√	+√					
Fertilizer application					+√	+√						
Harvesting										+√	+√	+√
Threshing/processing	+√	+√										+√
Earthing-up groundnuts					+√							
Lifting groundnuts							+√					
Making yokes from wood		√	√									
Fencing fields (repairing)			√									
Training oxen										√	√	
Livestock rearing				+√	+√	+√	+√	+√	+√	+√		
Plastering houses especially kitchens, with ant-hill soil	+											
Gardening (ploughing over/ re-establishing crop)									+√			
Craft work/clubs (sewing; making mats; crocheting)	+	+										
Ritual ceremonies (e.g. unveiling of tombstones memorial services etc)	+√	+√										

Key: √ activities mainly done by men; + activities mainly done by women

Weeding

Crop competition with weeds is always a major constraint as weeds use water, nutrient and solar radiation resources and yet they do not contribute to production, but rather reduce crop yield. Hand hoeing is carried out by all the farmers in the study areas, consistent with the findings of Chatizwa and Nazare (2000) that all farmers in the different farming sectors of Zimbabwe carry out hand weeding. Farmers with draft animals and equipment also use cultivators to remove weeds in-between plant rows and about 50% of the farmers use these cultivators in both Lower Gweru and Lupane communal areas. However, where farmers use planting basins, the weeding method is predominantly hand hoeing.

At least 70% of farmers in the study areas weed twice during each growing season while less than 15% weed once under the conventional tillage system (Fig. 4.3). The practice of weeding twice is in agreement with the Zimbabwe Ministry of Agriculture recommendation to combine fertilizer with weed free management through three tillage operations per crop (Snapp *et al.,* 2003). The three operations being ploughing and planting plus two weeding operations. Mudhara (1995) also found that most farmers in semi-arid Chivi communal area in southern Zimbabwe weed twice. Similarly, a survey conducted during the 2009/10 and 2010/11 seasons in 15 districts across different Natural Regions of Zimbabwe, showed that under the conventional tillage system, the majority of smallholder farmers weed their fields twice, irrespective of Natural Region (Nyamangara *et al*., 2013). Field experiments, for example by Kumwenda and Kabambe (1995) in Malawi and Mabasa and Nyahunzvi (1995) in both low and high rainfall areas of Zimbabwe suggest that weeding twice has yield benefits. However, from field experiments conducted at the University of Zimbabwe farm located in northern Zimbabwe under Natural Region II, Mashingaidze (2004) established that there was no grain yield benefit from increasing the frequency of hand hoe weeding from once to twice or thrice during the 1998/99 season and no significant difference in grain yield between a maize crop weeded once and one weeded twice during the 1997/98. The experiments were conducted over four cropping seasons from 1995/96 to 1998/99. Results from simulation modelling also show that in risky environments such as Lupane, only the first weeding is critical and that a second weeding does not have detectable benefits (Dimes *et al*., 2002).

In this study it was apparent that, in the majority of cases, farmers who use planting basins, also have fields where they practise conventional tillage. They weed three times on the basin plots, but only twice and rarely once on conventionally tilled fields. The high frequency in weeding on planting basins is consistent with Nyamangara *et al*. (2013)'s findings that farmers in different Natural Regions of Zimbabwe, who use planting basins, weed at least three times. Thus, the frequency of weeding varies according to tillage practice used and some farmers use more than one tillage practice. Weeding three times on planting basin plots is consistent with the observation that weed infestations are high under minimum tillage (Mabasa *et al.,* 1999; Twomlow *et al*., 2008b). Thus, farmers who use planting basins need more labour during the season as well as during land preparation and their labour source is mostly family labour. However, with planting basins, weed pressure is reduced in subsequent years (Twomlow *et al*., 2008b).

The method and frequency of weeding depends on the availability of equipment, draft power and the type of tillage system used. Given that labour is a significant constraint, farmers in the study areas who use conventional tillage may not necessarily maintain the tradition of weeding twice. They could, instead, only weed once due to the expected low return per dollar invested in these dry areas, particularly in Lupane. As suggested Mashingaidze (2004) and IIRR and ACT (2005), smallholders farmers, particularly those who rely entirely on hand-hoeing to remove weeds can embark on cultural practices such as intercropping with good cover crops, reducing inter-row spacing and early planting to control weeds thereby reducing the need to weed more frequently. The use of planting basins with its associated benefits could be limited due to high labour requirements for weeding and other operations such as making the basins.

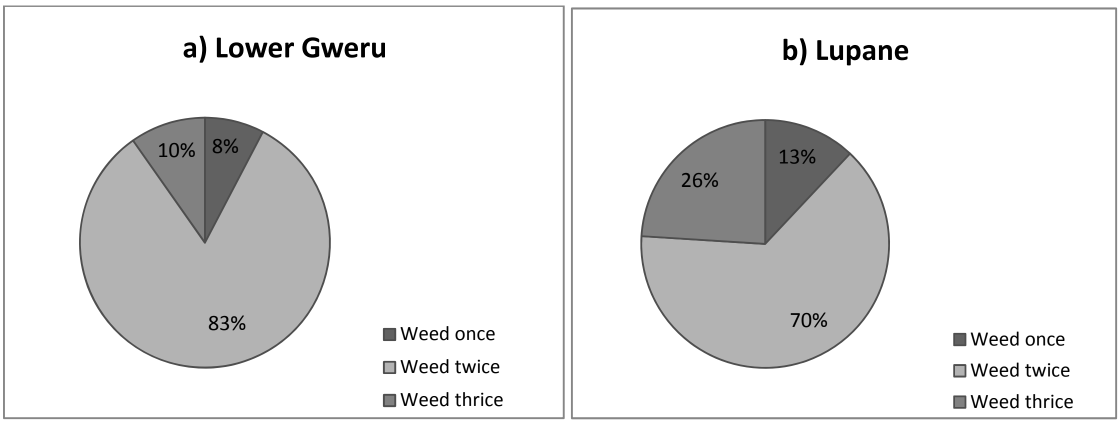


Fig. 4.6. Frequency of weeding by farmers in a) Lower Gweru and b) Lupane communal areas

Fertilizer use

From the household survey, it emerged that farmers in the study areas generally apply little fertilizer to their fields in most seasons, mostly because fertilizers are expensive and/or unavailable, with around 10% admitting to not using fertilizer at all. They also use less fertilizer because of limited available soil water in these areas. The main soil ameliorants used during the 2009/10 season are cattle manure and inorganic fertilizers (compound D, with N:P:K = 7:14:8 and Ammonium nitrate, N =34.5 % or urea, N = 46 %), while leaf litter, anti-hill soil and ash are used to a lesser extent in both communal areas (Fig. 4.4).

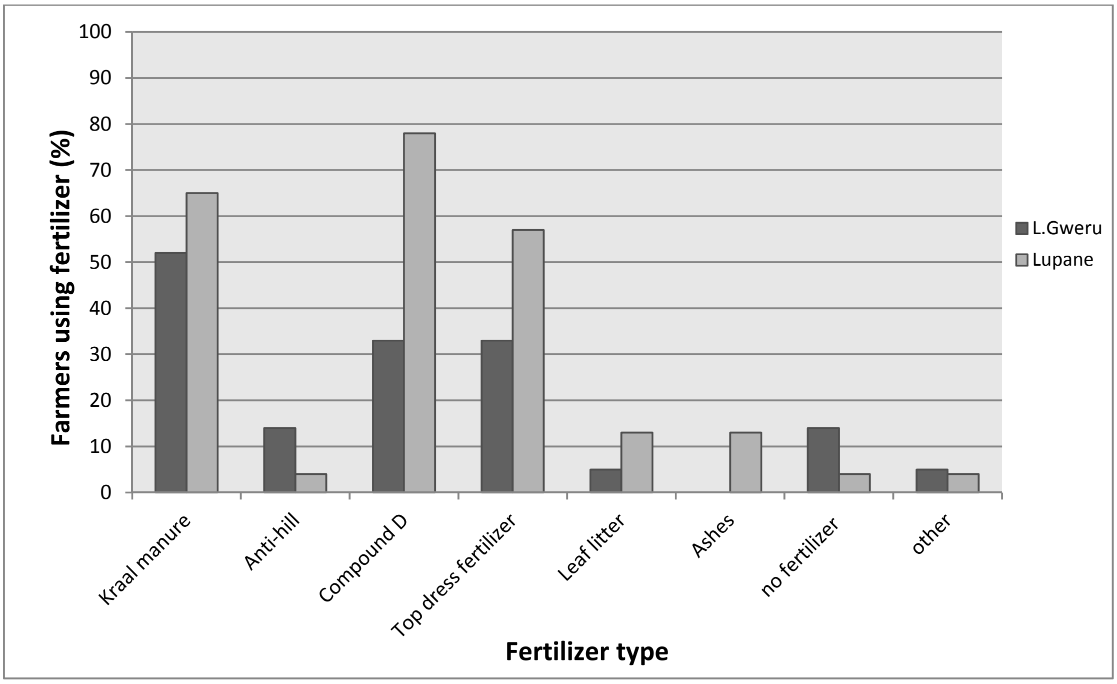


Fig. 4.7. Fertilizer types used by farmers in Lower Gweru and Lupane communal areas during 2008/09 cropping season

Although about 15% of the farmers in Lower Gweru and 60% in Lupane own donkeys, they do not use donkey manure because they believe that the manure burns crops, due to high nutrient content presumably high N and lack of decomposition. Manure and inorganic fertilizer rates used are quite diverse and most farmers use amounts that are below the recommended rates. The majority of farmers who use inorganic fertilizers use 100 kg ha^{-1} of compound D and a top dressing of 50-100 kg ha^{-1} of Ammonium Nitrate or 50 kg ha^{-1} of urea on maize in both communal areas. Farmers who use both organic and inorganic fertilizers, either use manure or Compound D (inorganic) as basal fertilizer and then top dress with either Ammonium Nitrate or Urea. Blanket fertilizer recommendations given by extension officers are 200-300 and 150-200 kg ha^{-1} compound D (basal) for Natural Region III (where Lower Gweru is mostly located) and

IV (where Lupane is located) respectively (Ministry of Agriculture, Mechanization and Irrigation Development in Zimbabwe, 2011). Corresponding recommended top dressing fertilizer rates are 150-200 and 100-150 kg ha^{-1} Ammonium Nitrate for region III and IV respectively. The general recommendation for cattle manure is 20-30 t ha^{-1}, but due to limited supplies farmers often apply considerably less than this. The use of blanket recommendations rather than specific recommendations that could take into account the cropping history of the land as well as biophysical and economic factors that affect resource poor farmers in semi-arid regions, has been considered as one reason for low adoption rates of fertilizer use (Snapp *et al*., 2003; Giller *et al*., 2006). The use of planting basins allows precision application of the limited fertilizers and as a result of this and other benefits associated with use of these basins, it was found that more farmers in Lower Gweru and Lupane are adopting the practice. Some of the farmers and agricultural extension officers pointed out that there were some farmers who use inorganic fertilizers only when they get them from government or NGO drought relief programmes. This is in agreement with what Ahmed *et al*. (1997) reported and came to the same conclusion regarding some farmers in south-western Zimbabwe, including Lupane district. Ellis-Jones and Mudhara (1995) established that nearly all communal area farmers in Zimbabwe used fertilizers over the period 1992-94 when fertilizer was provided at no cost, under the government drought relief and recovery programmes. Extension officers in the study areas confirmed that there was a decline in fertilizer use in these areas from the late1990s to the early 2000s, following the phasing out of drought relief programmes. With the launch of new government input schemes such as "*Maguta*", "Champion Farmer" and the SADC input scheme (Mare, 2010 - personal communication), inorganic fertilizer use is likely to increase, but probably only temporarily, and in the targeted communal areas which include both Lupane and Lower Gweru. Some farmers in Lupane are skeptical about using inorganic fertilizers as they believe that these fertilizers "kill" the soil. This observation is consistent with Ahmed *et al*. (1997)'s findings regarding perceptions of some farmers in western Zimbabwe on fertilizer use. Of the commonly used inorganic fertilizers, compound D and Ammonium Nitrate, it is the former that they believe to be more detrimental to the soil especially when one does not use it continuously (every season) in a particular field. According to the farmers, "the problem is worse if one does not apply the fertilizer every season". A similar perception by some smallholder farmers in Western Kenya is highlighted by Misiko *et al*. (2011) where the farmers believe that fertilizers "spoil" the soil in that "the soil gets addicted to the fertilizer" so much that if it (the soil) is not fertilized, the crop (maize) yields drop drastically. The perception that fertilizer "kills" the soil probably arises as a result of increased soil acidity due to use of inorganic fertilizers, particularly nitrogenous fertilizers which leads to reduced or non-availability of nutrient elements to the crop. To this effect, farmers should be advised to apply organic fertilizer (manure) or liming agents every 3 to 4 years to maintain the soil at near optimum pH levels.

Cropping systems and patterns

The "true" rotations that farmers practise are basically cereal-legume rotations and these are practised by about a third of the farmers in each of the communal areas. Maize-groundnut-maize rotation is the most common rotation in Lower Gweru while in Lupane maize, sorghum or pearl millet is rotated with cowpeas. In Lower Gweru, maize-bambara groundnut rotation is popular with women farmers. Other crop sequences include maize - pearl millet - maize, maize – sorghum - maize, sorghum – groundnut - sorghum and fallow - bambara groundnuts (i.e. bambara groundnuts grown on a newly ploughed field). Some farmers in the study areas, allocate certain fields or soils to particular crops, for example, in Lupane some farmers plant maize, continuously on the more fertile and high soil water holding capacity "*isidhaka"* soils. This practice is a limitation to the implementation of rotations. In Lupane, farmers believe that pearl millet revives the soil because of its high tillering ability (more roots are developed) and for this reason, they alternate it with maize, so that maize benefits from the improved organic matter content of the soil. However, alternating maize with pearl millet cannot be as good as rotating maize with a legume crop. Inclusion of a legume in the rotation improves soil fertility through biological nitrogen fixation by the legume. The disadvantages of growing maize and millet in sequence are that there could be carry-over of insect pests and diseases from season to season and proliferation of weeds, since the two crops belong to the same botanical family and therefore may have similar pests. The two cereals may also have similar nutrient requirements and thus a cropping system where the two are alternated, may require the farmer to apply relatively high quantities of fertilizer. This is in contrast with the advantages of improving soil fertility through biological nitrogen fixation by the legume.

It was found that although most farmers are aware of the benefits of a good crop rotation, they do not practise effective rotations and the rotations they use do not have a consistent pattern. These findings are consistent with Mudhara (1995), who concludes that in the third year, farmers in Chivi communal area (southern Zimbabwe) rotate only 40% of the area planted to maize in the previous year with other crops such as pearl millet, finger millet, groundnuts and sunflower. Chuma *et al*. (2001) also highlight the point that smallholder farmers in Zimbabwe do not practise effective rotations. One reason for ineffective and/or inconsistent rotations is their decision to allocate more land to grain cereals in an attempt to achieve household food security each year. This is in line with Ahmed *et al.* (1997)'s findings that most smallholder farmers in south-western Zimbabwe allocate most of their cropping area to cereals, namely maize, pearl millet and sorghum. So, where cropping land is limited, priority is given to these staple crops. Seed shortages and labour constraints lead to a reduction in area planted to grain legumes, groundnuts in particular, and this contributes to ineffective and inconsistent crop rotations in these communal areas. Shumba (1983) highlights the shortage of groundnut seed as a major constraint to groundnut production in communal areas of Zimbabwe while labour shortage is another important constraint, especially for the resource poor farmers (Shumba, 1983, Waddington and Karigwindi, 2001; Zingore *et al.,* 2009).

Farmers in Lower Gweru and Lupane predominantly practise sole cropping, although pumpkins, sweet reeds (family Gramineae) water melons (*Citrullus lanatus)* and sour melons are often sparsely intercropped with the main cereal crops. A few farmers alternate single rows or strips of groundnuts, cowpeas or bambara groundnut with cereal grain crops, especially maize. In Lupane, some farmers are forced to intercrop due to shortage of planting seed, since they will not have adequate seed of one crop to plant the whole intended cropping area. Others intercrop sorghum with maize due to shortage of land, but they do not intercrop pearl millet with maize as they believe that the two crops are "not compatible". In fact, the farmers ascertain that maize dies when intercropped with pearl millet. Extension officers in Lupane verified that the common practice is to mix sorghum and maize and not pearl-millet and maize, but they were not sure why this was the case. Although pearl millet has been found to have allelopathic effects on germination and growth of certain weeds, for example as was established by Narwal *et al*. (1998) in weed suppression experiments, the possibility of direct allelopathic effects of pearl millet on maize germination and growth may be ruled out in this case since farmers who practise sole cropping indicated that they usually grow maize after pearl-millet and get a good maize crop. The ability of pearl millet to tiller effectively and fast (Mahalakshmi and Bidinger, 1986; Maman, *et al*., 2004), may compensate for possible grain loss from the main stem under intermittent drought (Mahalakshmi and Bidinger, 1986; Vadez *et al*., 2012). This characteristic of pearl millet probably gives the crop an advantage over non-tillering cereal crops such as maize under intermittent droughts and when soil water stress occurs just prior to or during flowering. This may explain farmers' views on the performance of maize and pearl millet when the two are grown together in Lupane where, moisture stress is often experienced as a result of prolonged mid-season dry spells or droughts. However, farmers' claims of a negative interaction between maize and pearl-millet when the two crops are grown together in a field, could provide a basis for a detailed crop physiology study.

Water management practices

Inadequate soil water is a limiting factor to crop productivity in both Lower Gweru and Lupane, although both flooding and waterlogging are occasionally experienced. Water management, particularly as it relates to soil water conservation and water harvesting goes a long way in improving water availability in these water stress environments. Farmers in the two communal areas employ various forms of water management techniques (Fig. 4.5).

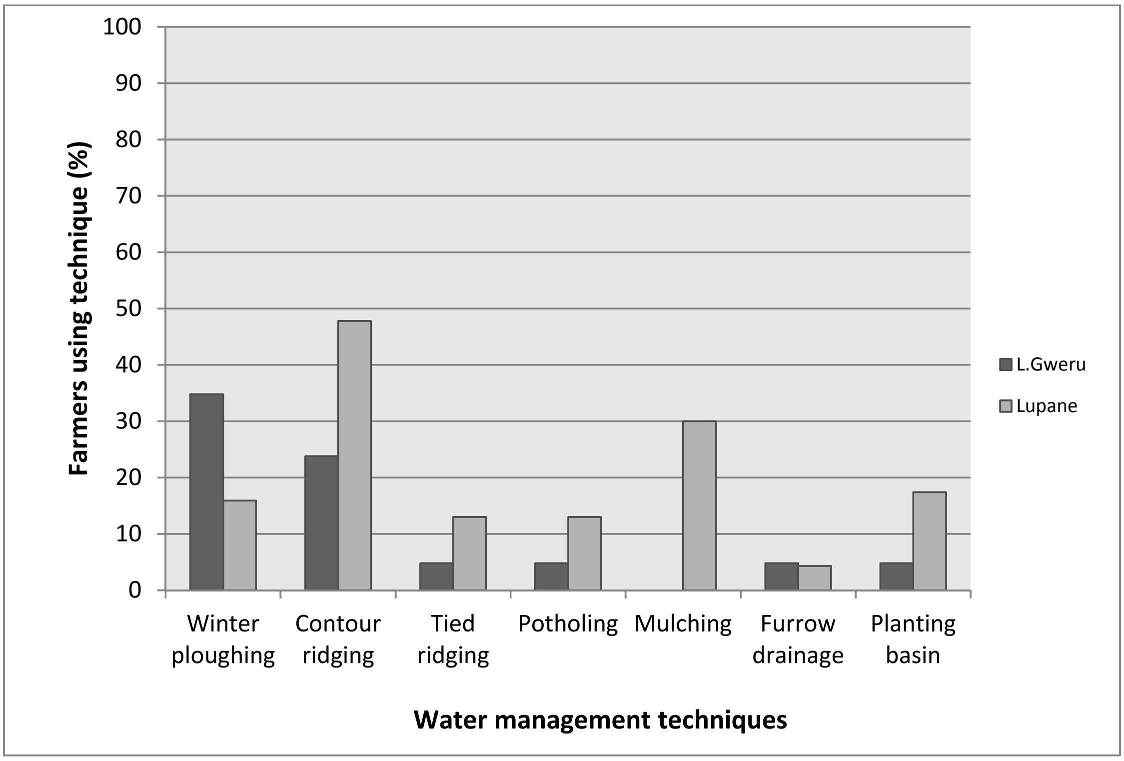


Fig. 4.8. Water management techniques employed by farmers in Lower Gweru and Lupane communal areas according to results from interviews conducted during 2009

Less than 50% of farmers use any one form of water conservation measures in either communal area. However, overall, more farmers in Lupane than in Lower Gweru use some of the techniques. This scenario is expected since rain water is scarcer in Lupane than in Lower Gweru. Contour ridges followed by winter ploughing are the main water managing techniques used by farmers in Lupane, while in Lower Gweru, winter ploughing is the major water management technique, followed by contour ridging (Fig. 4.5). About 48% of farmers in Lupane and 24% in Lower Gweru use contour ridges while winter ploughing is practised by 16% and 35% of farmers in Lupane and Lower Gweru respectively. It was encouraging to note that most of the farmers who used contour ridges had moved away from the traditional graded contour ridges to the zero gradient contour ridges which are more suitable for retaining water in the field rather than the graded ones which drain away excess water from the field. Planting basins, which farmers dig by hand during the winter season and then plant crops, particularly maize, at the start of the rainfall season (Twomlow *et al.*, 2008b; Thierfielder and Wall, 2009) conserve soil water as the water is concentrated in the basins. These basins, which should ideally measure 15x15x15 cm (Twomlow *et al*., 2008b; Thierfielder and Wall, 2009) are used by 55% of the farmers in Lupane (Fig. 4.1). However, because not all of the farmers who use basins readily consider them as a water conserving measure, the number of farmers reportedly using planting basins as shown in Fig. 4.5 is only about 18%. According to most of the farmers, the major reason for using planting basins is to reduce the need for draft animals and to save inputs, particularly fertilizer. Some of the farmers who use planting basins also apply mulch to the basins when it is available, hence the use of mulch by 30% of farmers in Lupane where basins are more commonly used. Although in Zimbabwe the concept of planting basins was developed as early as the late 1980s by Oldrieve (Oldrieve, 1993; Twomlow and Hove, 2006; Twomlow *et al*, 2008b), the greatest initiatives to promote the technology were made in the early 2000s when a Conservation Agriculture Task Force led by the Food and Agriculture Organization (FAO), was formed in 2003 to spearhead conservation agriculture in the country (Twomlow and Hove, 2006; Twomlow *et al*. 2008b). The taskforce comprised donor organizations such as DFID (United Kingdom's Department for International Development), NGOs (Non Governmental Organizations), CIMMYT (International Centre for Maize and Wheat Improvement), ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), FAO and the Department of Agricultural Research and Extension (AREX). Lupane district is one of the 15 pilot districts for this initiative which initially covered southern Zimbabwe (Twomlow and Hove, 2006; Twomlow *et al*. 2008b).

Potholing (a practice where small holes are dug in-between the growing crop usually using a hoe, to harvest and conserve water (University of Zimbabwe, 2006) and tied-ridging are both used by a few farmers (less than 15%) in both communal areas (Fig. 4.5). Low adoption rates for water conservation techniques such as use of tied-ridges and potholes is not unique to Lower Gweru and Lupane communal areas, as the adoption of these technologies by smallholder farmers elsewhere in Zimbabwe and Africa are also slow and low (Chuma *et al.,* 2001; Mutekwa and Kusangaya, 2006; Chiputwa *et al*., 2011; Marongwe *et al*., 2012; Nyamadzawo *et al*., 2013). Reasons for low adoption rates include high labour requirements for implementing some of the technologies, e.g. contour ridging and making planting basins; limited land size, lack of suitable implements, inadequate institutional support and lack of credit (Chuma *et al.,* 2001; Mutekwa and Kusangaya, 2006; Kabamba and Muimba-Kankolongo, 2009; Mazvimavi and Twomlow, 2009; Nyagumbo, 2009; Nyamadzawo *et al*., 2013). Nyamadzawo *et al*. (2013) also attribute low adoption rates for soil and water conservation technologies to blanket recommendations given for different biophysical environments, despite availability of knowledge on the biophysical requirements for effective implementation of the different technologies (Nyagumbo, 2009; Places and Deews, 1999, cited in Chiputwa *et al*., 2011). Some technologies result in waterlogging during periods of high rainfall (Mutekwa and Kusangaya, 2006) and this discourages farmers from adopting such technologies despite their advantages during dry spells or droughts.

4.3.2. Constraints to crop production

Farmers ranked the constraints they face in crop production according to the extent to which the constraints affect food security and income generation as well as according to the number of households affected. This was done during the FGDs held during 2008. The overall ranking based on a combination of these criteria reveals that the major constraints common to both communal areas are shortage of planting seed, shortage of draft power as well as low and/or unreliable rainfall (Table 4.6). Approximately 60% of interviewed farmers cited the problem of shortage of planting seed in both communal areas, while shortage of draft power was cited by 50% and 25% of farmers in Lower Gweru and Lupane, respectively.

Table 4.6. Ranking of farmer constraints by ward and gender during focus group discussions, 2008. IDRC/AACC project (*1 represents the most important or serious problem)*

	Ranking by women				*Ranking by men			
Constraint	Nyama	Mdubiwa	Menyezwa	Daluka	Nyama	Mdubiwa	Menyezwa	Mean across groups
Unavailability and/or late supply of seed and fertilizer	1	2	3	1	3	3	5	2.6
Lack of transport	2				4			3.0
Inadequate rainfall/high rainfall variability	6	1	2	4	1	1	1	2.3
Unavailability of crop chemicals	3				2			2.5
HIV and AIDs pandemic	4				5			4.5
Shortage of draft power	5	4	1	2	6	2	3	3.3
Poor maintenance of roads		3				4		3.5
Lack of capital to buy seed			5				4	4.5
Poor soils			4				2	3.0
Lack of farm implements				3				3.0
Crop damage by elephants				5				5.0

*There were no male farmer participants from Daluka Ward.

Unavailability of planting seed on the formal market, especially of hybrid maize seed, has been a problem only in recent years due to political and economic challenges. Over the years, it is the shortage of legume and improved small grains seed that has been a problem in communal areas (Shumba, 1983; Chuma *et al.,* 2001). While sunflower was reported to be an important cash crop in the western parts of the country which include Lupane (Ahmed *et al*., 1997), the crop is no longer grown by most farmers in Lupane and Lower Gweru, mainly due to seed shortage. About 30% of farmers interviewed in Lower Gweru indicated that they used maize grain that had been donated for consumption by some non-governmental organizations (NGOs) in the area, as planting seed during the 2008/09 season, a clear indication that planting seed was in short supply. Farmers in both Lupane and Lower Gweru have maintained their traditional Open-Pollinated maize Varieties (OPVs) over the years. The use of these varieties has gone a long way in alleviating the problem of shortage of hybrid maize seed, since these OPVs are readily available locally. Farmers in the study areas "trust" these OPVs particularly "*Bogwe"* (in Lower Gweru) or "*Bhambadhla"* (in Lupane) which most believe yield very well under high rainfall, but still give reasonable yields when rainfall is low. Other research work has also established that smallholder farmers in other semi-arid areas, of Zimbabwe for example those in Uzumba-Maramba-Pfungwe District in northern Zimbabwe (Progressio, 2009) prefer growing OPVs of maize due to their better performance in a variable climate, compared to hybrids. In general, farmers retain seed even of hybrid varieties, from previous harvests to plant the following year. However, at times they are forced to consume the seed before the start of the subsequent cropping season due to food shortages. Drought relief programmes have in some seasons, for example 1993/94, 1994/95 and 1999/2000 seasons, provided farmers in these areas with some planting seed, particularly maize and small grain seed. Recently introduced drought relief programmes, such as the "*Maguta"* and SADC input schemes which were introduced in 2005/06 and 2008/09 seasons respectively, are providing farmers with groundnuts and cowpea seed in addition to cereal grain seed (Mare, 2010 - personal communication). However, these programmes, just like previous relief programmes have been characterized by late disbursement of inputs, resulting in late plantings.

Draft animals, which provide about 90% of the draft power requirements of smallholder farmers in Zimbabwe (Norton, 1995), are inadequate as most farmers own few or no cattle or donkeys. The draft animals are also sometimes too weak to pull the plough due to inadequate and poor quality grazing prior to the start of the cropping season. This problem, which intensified following the severe drought of 1991/92 season, is well recognized (Shumba, 1984; Ellis-Jones and Mudhara, 1995; Francis *et al*., 1999; Tsimba *et al*., 1999). Farmers in the study areas cope by hiring and sharing draft animals, exchanging labour for draft power and by practising minimum or zero tillage. These findings are consistent with those of Wolmer and Scoones (2000) and Tsimba *et al.* (1999). In addition, farmers also supplement natural grazing with stover, when available, while others send their animals to neighbouring commercial farms for grazing. Closely related to the shortage of draft animals, is the shortage of draft implements as highlighted by the farmers in Daluka ward (Table 4.6).

Other problems cited by farmers across all wards during household interviews, but that were not mentioned in FGDs held in 2008, are shortage of labour, cited by about 67%

and 20% of the farmers in Lower Gweru and Lupane, respectively and unavailability of fertilizers which was cited by 75% and 30% of the farmers in Lower Gweru and Lupane respectively. From FGDs held in 2009, it emerged that farmers reduce labour bottlenecks by working together as groups *"majangano"* in each other's fields. This practice of farmers organizing themselves into self-help groups to enhance their access to labour and other resources has been reported by previous researchers, for example Bratton (1986) and Doré (2012) in Zimbabwe and Macoloo *et al*. (2013) in Kenya. Some of the farmers also hire labour. Farmers in both communal areas realize the need to fertilize their fields and more than 50% of the interviewed farmers highlighted that fertilizer unavailability was a major constraint to crop production. Precision farming, where fertilizer is applied at the plant station and use of small quantities of both organic and inorganic fertilizers in water stress environments such as Lower Gweru and Lupane (Twomlow *et al*., 2006; Ncube *et al*., 2007; Twomlow *et al*., 2008c; Twomlow *et al*., 2010), appears to be an effective way of using the scarce fertilizers and should be recommended for adoption by more farmers in the study areas and other semi-arid areas of Zimbabwe and across southern Africa.

The problem of high inter- and intra-annual variability of rainfall is not uncommon to the semi-arid areas of Zimbabwe and southern Africa (Kinuthia, 1997; Mason and Jury, 1997; Hulme *et al*., 2001; Unganai and Mason, 2001). The problem was ranked highly by both men and women farmers in Mdubiwa Ward (Lower Gweru) as well as by men in Nyama (Lower Gweru) and Menyezwa (Lupane) Wards. However, farmers in Daluka (Lupane) rated this problem fourth out of the five constraints they listed and their reason for the low rating was that they did not have control on the rainfall amount or pattern as it was God-given, consistent with the findings of Mertz *et al.* (2009) in rural Sahel. Women in Nyama Ward rated the problem of variability in rainfall last, presumably because most of them derive their livelihoods from vegetable gardens where they rely on wetlands (that usually have a high water table throughout the year) and on fruit trees which are less prone to soil water shortages than annual field crops. Hence these farmers are not so severely affected by poor rainfall pattern or amount.

The problem of crop damage by elephants is unique to Lupane as the area is in close proximity to the Hwange Game Reserve as well as to the border with Botswana. Although this problem was only reported by farmers in Daluka Ward during FGDs, about 50% of the farmers in both wards of Lupane highlighted the problem during household surveys. Farmers have no means to prevent crop damage by elephants except to report to the Department of National Parks, who they expect to take the animals back and try to keep them in the game reserves. However, according to the farmers, for years, the Department has not done much to assist them. Farmers try and harvest crops as soon as they can to reduce the level of damage by the elephants.

Farmers in Lupane (Menyezwa Ward) also cited poor soils as a major challenge to crop production. This finding is consistent with findings of soil fertility studies carried out in most communal areas located in semi-arid Zimbabwe. The studies concluded that low soil fertility and poor soil fertility management are major reasons for low yields in these areas (Grant, 1981; Mashiringwani, 1983; Ncube *et al*., 2009). Shortage of transport and unavailability of crop chemicals were highlighted as problems by farmers in Lower Gweru (Nyama Ward). These problems are peculiar to Lower Gweru, especially Nyama Ward, where transportation of horticultural produce to the markets is critical and crop chemicals essential for high yield and good quality vegetable production. Closely related to the transport issue raised by farmers in Nyama Ward, is lack of road maintenance reported by farmers in Mdubiwa Ward. Farmers in Nyama Ward (Lower Gweru) also reported that the HIV and AIDs pandemic affected agricultural productivity. This problem surfaced in FGDs, but not in household surveys, presumably because individuals were not free to mention this problem, lest they or their family members would be labeled as victims of the pandemic, as most people in Zimbabwe are not willing to reveal their HIV/AIDS status. This scenario is contrary to the view of Gill *et al.* (2008) that individual interviews are more appropriate for investigating sensitive topics than group interviews or discussions. The HIV and AIDS pandemic affects agricultural production in two main ways: first it reduces the capacity to invest in cropping as some of the funds will be diverted to health expenses; and secondly it reduces the amount and availability of labour (Zimbabwe Vulnerability Assessment Committee, 2005).

4.3.3. Coping and adaptation strategies to climate variability and change

Climatic factors, among other biophysical and socio-economic factors influence farmers' decisions. Farmers in the study areas cited crop choice, amount of fertilizer to use, timing of application of top dress fertilizer as well as weeding frequency and timing, as the rainfall-based decisions they make (Fig. 4.6). More farmers in Lupane than in Lower Gweru indicated that they make such climate-based decisions. This is probably because rainfall pattern is more erratic and less adequate and therefore more critical in Lupane than Lower Gweru. Although cropping potential is higher in Lower Gweru than Lupane, farmers in Lupane appear to value growing of field crops more than farmers in Lower Gweru who have more alternative livelihoods. Some farmers did not readily acknowledge climate as a factor influencing their decisions presumably because they had more critical/pressing issues to consider, for example availability of seed and draft power as decisions that they considered they had some control over. With some of the farmers, it only became apparent that some of their decisions were dependent on rainfall, when they gave reasons for deviations in agronomic practices in the "current" (2008/09) season compared to the usual practices, for example, planting more sweet potatoes in the "current" season due to high and persistent rainfall. This indicates that in general, farmers are aware of the weather patterns and that their reactions are so instinctive and engrained that they do not really notice this relationship. Therefore these could hardly be classified as responses to 'climate change' but more appropriately considered as part of a wide variety of options which are then used when needed during a particular rainfall season.

As indicated earlier, farmers in the study area adjust timing of agronomic operations, quantities of inputs used and crop type and/or variety used, depending on prevailing climate or weather. The short term adjustments (from one season to another or within a season) are typical of the short term and tactful strategies that most researchers have acknowledged as practical applications of seasonal climate forecasts (e.g. Ziervogel, 2004; Patt *et al*., 2005; Chagonda *et al*., 2013, Churi, *et al*., 2013).

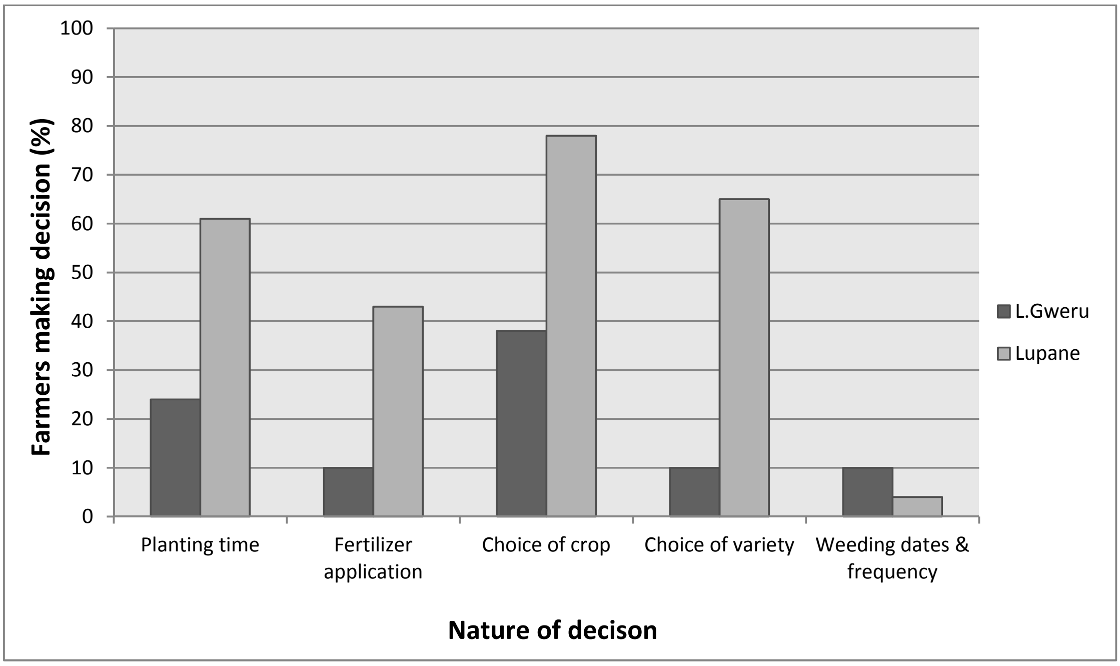


Fig. 4.9. Climate-based cropping decisions made by farmers in Lower Gweru and Lupane communal areas as collected during the 2009/10 season

Farmers presented a wide array of rainfall-related concerns. These included low rainfall amount, short season length, late start of the season, abrupt end of the rainfall season, mid-season dry spells, excessive rainfall, rainfall unreliability especially with regard to start and end of rainfall season, as well as drought. The diverse rainfall patterns clearly indicate the wide intra- and inter-annual rainfall variability experienced in these areas. According to the farmers' poor crop yields, hunger, shortage of grazing, low animal productivity and weak draft animals are some of the direct impacts of the poor rainfall pattern on their farming systems. Summer temperatures were also reported to be too high, causing rapid drying out of the soil and farmers indicated that there was nothing they could do about this problem. A number of coping and adaptation strategies are used by farmers to cope with and adapt to climate variability and change (Table 4.7).

Table 4.7. Strategies that smallholder farmers in Lower Gweru and Lupane communal areas of Zimbabwe use to cope and adapt to rainfall variability (Source: Focus group discussions and household interviews, Jan/Feb 2009)

Driver of coping / adaptation	**Coping / Adaptive Strategies**
Low rainfall amounts	1. Winter plough to retain soil moisture; 2. Grow short duration crops & varieties; 3. Use of contour ridges; 4. Concentrate on growing vegetables in gardens; 5. Plant early; 6. Cultivate deeply; 7. Dry plant; 8. Grow drought tolerant crops; 9. Use planting basins (conservation farming); 10. Use less fertilizer; 11. Apply mulch (especially on planting basins)
Mid- season dry spells	1. Concentrate on growing vegetables in gardens; 2. “No plan”; 3. Use mulch; 4. Stagger planting dates; 5. Open up furrows to capture water; 7. Carry out cultural cleansing exercises e.g. clearing bushes of dead animal bones & trees struck by lightning
Short season length	1. Grow short duration varieties/crops; 2. Grow drought tolerant crops; 3. Concentrate on gardening; 4. Early procurement of inputs + early land prep; 5. Winter plough to retain moisture; 6. Dry plant; 7. Early plant; 8. Use less fertilizer
Late start of the rainfall season	1. Grow short season varieties/crops; 2. Concentrate on gardening; 3. Dry plant; 4. Grow drought tolerant crops; 5. Conduct traditional ceremonies such as "*mukwerere*"(beer brewing to appease ancestors) & praying for rains
Abrupt end of rainfall season (Earlier than normal)	1. Concentrate on gardening; 2. “No plan”
Extremely high rainfall	1. Apply more fertilizer if available; 2. Grow more sweet potatoes; 3. Grow more maize (in Lupane)
Waterlogging	1. Open up furrows to drain excess water (furrow drainage); 2. “No plan”
Crop failure, drought or hunger	1. Sell livestock to buy food & get cash for other uses; 2. Buy items such as soap & sugar & exchange for maize grain; 3. Get money to buy food from non-farming activities such as basket making, brick moulding & gold panning; 4. Buy grain from the Grain Marketing Board (GMB) if available; 5. Migrate to other areas; 6. Get food aid from government & NGOs; 7. Rely on remittances from children and/or relatives working locally or in Diaspora; 8. Get assistance from local/community social groups; 9. Reduce number of meals per day
Shortage of grazing	1. Supplement natural grazing with stover, if available; 2. Take animals to neighbouring commercial farms for grazing
Weak draft animals	1. Rely more on donkey than oxen-draft; 2. Reduce number of tillage operations; 3. Supplement natural grazing with stover, if available

Farmers have a broad spectrum of strategies that they use to cope with rainfall variability (Table 4.6) and these can be grouped into crop and varietal choice, choice of planting date, adjustment of crop input levels, soil water management techniques, use of alternative sources of food or income and resorting to traditional and religious ceremonies. These strategies are similar to findings by Mubaya (2010), in a study to establish adaptation strategies to climate variability in Zambia and Zimbabwe, with the difference that in this study farmers specified the problems associated with the rainfall pattern and provided strategies they adopted for each of them. Choice of crop and planting date as well as adjusting amount of inputs used (especially with regard to amounts fertilizer used) are the most commonly used strategies. Choice of crop and variety by farmers in the study areas supports findings from other researchers including Kurukulasuriya and Mendelsohn (2008b) who showed that African farmers have adapted their crop choice to climate and Salick and Byg (2007) who reported that over the years, indigenous people have used biodiversity to cushion themselves against environmental changes and disasters. With the exception of use of contour ridges and winter ploughing, adoption of other soil moisture conservation techniques such as use of planting basins and mulch is fairly low due to availability of limited labour and of inadequate mulching material. Winter ploughing conserves soil water as there are no weeds to transpire and use the water and is the major adaptation strategy to low rainfall that farmers currently use.

As described in section 4.2.2, the economy of Zimbabwe declined over the period 1999-2008, with the worst decline occurring in 2008. Crop yields were also significantly low during the 2007/08 season contributing to a general shortage of food among households. During the 2008 marketing year (April 2008-March 2009) farmers in the study areas received food handouts from the government and NGOs and this complimented farmers' efforts to survive hunger and malnutrition (Moyo, 2009 - personal communication for Lower Gweru; Bhebhe and Nyathi, 2009 for Lupane). According to these sources, some of the farmers relied on remittances from relatives working in urban areas or in the Diaspora as most young men and women had gone into South Africa to look for jobs. Farmers in the study area mentioned that sale of livestock as an alternative source of income was normally done when droughts and hunger were experienced, but although the farmers were generally experiencing food shortages during the 2008 marketing year, few of the farmers interviewed in January and February 2009, had sold livestock. Kinsey *et al.* (1998) in their study on coping strategies for drought in Zimbabwe, concluded that this coping mechanism is consistently employed in Zimbabwe, contrary to the common belief that smallholder farmers in the country rarely dispose of their cattle but rather keep them for prestige as high cattle numbers are associated with wealth. The observation by Kinsey *et al*. (1998) perhaps illustrates that droughts are quite frequent and severe in Zimbabwe. Inter-cropping and pot-holing strategies were mentioned by only about 5% of the farmers in Lower Gweru. Some farmers perform traditional ceremonies to appease ancestors and ask for rains and Christians also pray for rain. About 30% of the farmers who responded to rainfall-related problems do very little, if anything, about mid-season dry spells and abrupt end of season. They simply have "no plan". However, other farmers respond to abrupt end of season by resorting to growing vegetables in gardens as well as non-farming activities such as basket making and brick moulding. Staggering of planting dates and cropping in gardens are the two main strategies used to reduce the impacts of mid-season dry spells. Farmers resort to gardens where vegetables and occasionally some maize are grown as these are normally located in areas with a high water table or close to water sources or where farmers have dug wells or installed boreholes. This idea matches the findings by Thomas *et al.* (2007) that farmers try to gain access to land that gives good yields during times of drought. According to some farmers in the study area, if bushes are not cleared of bones and trees/bushes struck by lightning, severe mid-season dry spells are experienced and to avoid these dry-spells, they hold cleansing ceremonies where they burn the bones and trees struck by lightning. It appears there is no documented information pertaining to traditional beliefs or myths on causes of poor rains or drought. It would be interesting to establish other beliefs that farmers have on this subject, verify if they are indeed myths or facts and document them.

Under high rainfall conditions farmers use higher fertilizer rates than they normally use, if the fertilizer is available. They also increase the area planted to crops that require high rainfall, for example sweet potatoes. In Lupane, where farmers generally grow more pearl millet and sorghum than maize, some farmers increase the area planted to maize if high rainfall is anticipated.

Although strategies used by farmers in Lower Gweru and Lupane may be similar to those identified by other researchers for other countries, strategies such as off-farm diversification are probably not as intensively practised in the study areas, as they are practised elsewhere, for example in the Offin river basin of Ghana, where most farmers diversify beyond farming (Gyampoh *et al*., 2009). For communities in Lupane it is particularly not easy to find alternative off-farm jobs as Lupane is far away from other urban centres. Shifting away from reliance on agriculture as the main income source and finding alternative sources of food are also important strategies used by farmers in Malawi and Swaziland (Stringer *et al*., 2009). Strategies such as intercropping which is a major coping strategy against variable rainfall in West Africa (Cooper *et al.,* 2008) and agro-forestry which has been identified as one of the strategies farmers use in dealing with climate variability in Ethiopia (Deressa *et al*., 2009) and Ghana (Gyampoh *et al*., (2009). These could be introduced to farmers in the study areas and other semi-arid areas of Zimbabwe. The practices of delayed fertilizer use and re-planting using seed of early maturing varieties or using a different crop identified by Cooper *et al.* (2008) as coping strategies used by farmers in semi-arid West Africa during the season, in the event of any emerging climatic shocks such as occurrence of dry spells can also be recommended to farmers in these study areas. In Zimbabwe it has also been observed that nowadays, some farmers in low agricultural potential areas do not apply basal fertilizer at planting as is often recommended, but rather apply it to the just emerged crop (Shumba, 1989; Mudhara *et al*., 2002; Mutezo, 2013), as a way of reducing the risk of wasting fertilizer in the event that adequate rains are not received and crop emergence is poor. Shumba (1989) also established that smallholder farmers in Mangwende communal area in north-eastern Zimbabwe, apply compound D fertilizer later to reduce labour requirements at planting time, a factor that allows quick establishment of the crop.

4.4. Conclusion and Recommendations

This chapter has established which agronomic practices and crop production constraints are present in the in Lower Gweru and Lupane communal areas of Zimbabwe. The study also found that smallholder farmers in these areas currently use a wide variety of coping and adaptation strategies for climate variability.

4.4.1. Agronomic practices

This study confirmed that conventional tillage, where the animal drawn mouldboard plough is the main tillage implement, is the major tillage system used in both communal areas. Farmers, particularly those in Lupane, also plant crops in planting basins, while some farmers in Lower Gweru practise zero tillage and hand dig some of their fields. The latter three practices are mainly used by farmers with limited access to draft animals and implements, but some farmers with adequate draft power also use planting basins as they conserve moisture and allow precise application of the limited fertilizers. It was established that for farmers who practise conventional tillage, the main method of planting is behind the plough and planting in furrows opened in winter ploughed fields. Other planting methods used by the farmers include hoe planting and planting in basins. Plant populations that farmers achieve when using these commonly used planting methods are maize, 37 000-44 000 plants ha^{-1}; sorghum, 66 000-167 000; pearl millet, 44 000-167 000; groundnut, 222 200-476 000 and cowpeas 150 000-333 300 plants ha^{-1}. These populations do not quite match those recommended by extension so field experiments and economic analyses may need to be carried out to determine if there are any statistical differences in crop yield due to these population differences. Farmers can also be advised on the correct number of furrows to skip before planting the next row, when planting behind the plough, particularly for the legume crops and they should also be encouraged to practice winter ploughing.

It was found that the range of crops grown by farmers in the two communal areas is similar. However, the more drought tolerant crops, pearl millet and sorghum, are more widely grown in Lupane than in Lower Gweru and are the major cereal crops in the former. The sour melon "*amajodo*" is also considered an important crop, especially during dry years, by farmers in Lupane, particularly those in Menyezwa Ward. This study confirmed that maize is grown by all farmers in the two communal areas and is the major cereal crop in Lower Gweru. Farmers in both areas grow the legume crops groundnuts, cowpeas and sugar beans, with more farmers in Lupane growing cowpeas than those in Lower Gweru. Crop varieties are almost similar for the two areas, except for maize where the varieties range from very early to early maturing in Lupane, whereas in Lower Gweru the range extends to medium maturing varieties. It was noted that both hybrid varieties and OPVs of maize are grown by farmers in both communal areas, with more farmers in Lupane using OPVs than in Lower Gweru. However, it was disappointing to find that in both areas, improved OPVs are used by fewer farmers than the traditional/local varieties. It is, however, encouraging to report that use of improved varieties of small grain crops (pearl millet and sorghum) has increased since the 1990s.

The study established that adoption rates for practices such as fertilizer use, crop rotations as well as soil and water conservation techniques are generally low in both communal areas. Most farmers are generally knowledgeable about the importance of these practices, but have limited capacity to adopt mainly due to a poor resource base. In Lupane, however, it was found that some farmers are skeptical about using fertilizer as they believe that it "kills" the soil. It was also noted that crop rotations are not effectively implemented due to limited land size, shortage of legume seed and the allocation of particular fields to particular crops. Due to the general shortage of seed, some farmers in Lupane particularly those in Menyezwa Ward, find it economic to grow different crops on the same field. It was also found that more than 70% of the farmers in both communal areas weed their fields twice, while about 10% weed once and that where planting basins are used, farmers weed three times.

Farmers should be encouraged to practise minimum tillage rather than conventional tillage since minimum tillage promotes sustainable agriculture as there is minimum disturbance of the soil. Minimum tillage also uses less energy and is ideal for resource poor farmers who do not have enough draft animals and implements. The minimum tillage technologies that a few farmers in the study areas are using e.g. planting basins are rather labour intensive and use of appropriate equipment rather than using hand hoes may improve adoption of this technology. Tillage practices such as ripping and direct seeding equipment such as the jab planters can also be introduced to the farmers to promote and ease minimum and zero tillage. Crop yields of smallholder farmers in the study areas and other semi-arid areas of Zimbabwe can be improved if availability of improved grain cereal and legume seed is improved through breeding and seed multiplication programmes. Farmers in these areas who grow OPVs of maize should be encouraged to grow improved OPVs as they yield better than the traditional unimproved OPVs. In marginal areas such as Lupane, farmers may not need to weed twice, but this may need verification through field experiments. There is a need to educate farmers who are skeptical about fertilizer use on effects that fertilizers may have on soil characteristics such as soil pH and how such effects can be corrected, to improve use of fertilizers by such farmers. Some observations made by farmers need verification, examples being the effect of intercropping maize and pearl millet on the yield of maize and the effect of donkey manure on crop growth and yield. Thus there is room to improve smallholder farmer crop productivity in the study areas and other semi-arid areas in Zimbabwe, through both extension and research interventions.

Agronomic practices of smallholder farmers that have been established in this chapter will be used as input data in simulating climate change effects on maize yields in the later chapters. Such input data include maize cultivar names, planting times, plant spacing, plant population and amount of nitrogen to apply as well as when it was applied.

4.4.2. Constraints to crop production

It was found that farmers in the study area face several challenges in crop production. Constraints common to both communal areas include biophysical constraints mainly inherently low soil fertility, variable rainfall patterns and low rainfall amounts. Shortage of production resources namely labour, crop inputs and draft power is also experienced by farmers in both communal areas. It was encouraging to find that farmers try hard to deal with some of these challenges. They employ coping strategies such as working together in each other's fields as groups to deal with labour bottlenecks, believing that they achieve more as a group than as individuals and can encourage one another, using seed retained from previous harvests, hiring draft animals and/or implements and to a lesser extent resorting to minimum tillage. Farmers occasionally receive handouts under various Government Input Schemes meant to assist farmers to recover from impacts of natural disasters such as droughts and floods. Shortage of transport to the market is unique to Lower Gweru due to the need to transport perishable horticultural crops (vegetables and fruits), especially in Nyama Ward where livelihoods are derived largely from these crops, while crop damage by elephants is a major problem in Lupane due to proximity to Hwange National Park Zimbabwe and to the border with Botswana. Although the problem of HIV/AIDS pandemic and its effects on agriculture only surfaced in Nyama Ward of Lower Gweru, it is likely that it is also a problem in the other wards and other communal areas of Zimbabwe.

Strategies currently used by farmers to cope with constraints they face in crop production e.g. social/group approach to solving problems should be supported and promoted. Government support should also put emphasis on capacity building of communities, for example by having community based seed multiplication schemes. Projects such as the "Heifer Project International" (HPI)(HPI, 1999) which aims to build-up the national cattle herd to address the problem of draft power shortage by providing initial heifers to smallholder farmers should also be strengthened and expanded.

4.4.3. Coping and adaptation strategies to climate variability and change

With the exception of farmers in Daluka Ward (Lupane) and women farmers in Nyama Ward, it was found that the problem of low and variable rainfall pattern was considered quite important by farmers in both Lower Gweru and Lupane. Specific climate-related concerns cited by farmers include inadequate and erratic rainfall, late start and early cessation of the rains, high frequency of dry spells, droughts and occasional floods. They also mentioned that effect of high summer temperatures. Farmers, particularly those in Lupane, indicated that there are farming decisions that they make based on climate among other criteria. Such decisions include choice of crops and varieties to grow and timing of operations such as planting, weeding and fertilizer application.

It was also noted that farmers use diverse strategies to cope and adapt to the variable and changing climate. These strategies include use of appropriate soil water management techniques; choice of appropriate crops and varieties; adjusting amounts of inputs used, resorting to growing crops in gardens, where water tables are high such as in wetlands or where boreholes and deep wells have been sunk. They also resort to income generation from off-farm activities such as gold panning and brick moulding. Some farmers also strongly believe that their ancestors, if appeased through traditional ceremonies, can make rains fall. Christians also often have prayers devoted to requesting for rains from God. It was found that some farmers simply have no plan, to deal with the adverse weather conditions such as abrupt end of the season, dry spells and high temperatures. Only about 10% of the farmers in Mdubiwa Ward (Lower Gweru) have plots in the two small holder irrigation schemes in this ward, while there are no irrigation schemes in the other three wards. The degree to which the farmers can cope with climate variability and change is however limited by the various constraints faced by these farmers. The identified current coping and adaptation strategies provide insights into possible adaptation strategies that farmers may use under future climate scenarios, where climate is expected to be even drier and warmer, across Southern Africa. The current coping strategies can be tested for their effectiveness under the envisaged future climatic changes and the knowledge gathered on farmers' constraints need to be taken into account when suggesting adaptation strategies. Strategies that are used by farmers in other semi-arid areas of Africa, to cope with or adapt to climate variability and change e.g. intercropping and agro-forestry particularly with legumes should be introduced to farmers in these study areas as well as other semi-arid areas of Zimbabwe. Irrigation development should also be expanded to cushion farmers in the study areas against effects of low and variable rainfall conditions.

CHAPTER 5

SIMULATION OF CURRENT AND FUTURE CLIMATE EFFECTS ON MAIZE YIELD AND SOIL WATER BALANCE COMPONENTS UNDER DIFFERENT AGRONOMIC SCENARIOS, USING APSIM MODEL

5.1. Introduction

Agriculture is significantly influenced by climate and therefore climate change becomes one of the many environmental changes affecting this sector. On a global scale, approximately 70% of the people in developing countries stay in rural areas where livelihoods are based on agriculture (Easterling *et al*., 2007). For the southern African region which includes Zimbabwe, Louw *et al*. (2007) estimate that 80% of the population rely on agriculture for subsistence, employment and income. The sector also contributes 35 percent to the Gross Domestic Product (GDP), for the region (Louw *et al*., 2007). In Zimbabwe, agriculture has contributed up to about 17% of GDP between 1980 and 2008, in years that were not affected by factors such as drought, introduction of the Economic Structural Adjustment (ESAP), introduction of the Fast Track Land Reform Programme (FTLRP) and the Economic crisis of 2008 (Mapfumo, 2012). Agricultural production in Zimbabwe is largely rain-fed and the rainfall pattern is variable and characterized by occurrence of mid-season dry spells and droughts, particularly in Natural Regions III, IV and V of the country (Vincent and Thomas, 1962), where approximately 90% of communal farming land is located (Chiremba and Masters, 2003; FAO, 2006). The study areas, Lower Gweru and Lupane, lie in Natural Regions III and IV, respectively.

5.1.1. Climate change effects on crop productivity

Studies on climate change effects on crop production have been conducted at global (e.g. Hitz and Smith, 2004; Parry *et al*., 2004; IPCC, 2007; Lobell and Field, 2007; Parry 2007), regional (e.g. Rasmussen, 2003; IPCC, 2007; Ngaira, 2007; Parry, 2007) and country (e.g. Downing, 1992; Makadho, 1996; Southworth *et al*., 2000; Butt *et al*, 2005; Crimp *et al.,* 2008; Dimes *et al*., 2008) levels. Effects of climate change on crop production can be direct or indirect. Direct effects are brought about through physiological effects of changes in specific climatic variables on the crop, for example, the effect of increased carbon dioxide (CO_2) concentration on the rate of photosynthesis and on stomatal conductance; effect of temperature on the rate of crop growth; effect of water availability on growth and development of a given crop, and changes in length of growing season. Temperature increase can also affect crops by changing timing of development events in relation to occurrence of extreme weather such as frost and drought (Saarikko and Carter, 1996; Southworth *et al*., 2000). Thus, critical crop stages such as flowering and grain-filling may coincide with unfavourable weather due to changes in timing of crop development stages. C3 plants such as wheat, rice and soybean, have been found to generally benefit more from an enhanced CO_2 atmosphere compared to C4 species such as maize, sorghum and sugarcane (Easterling *et al*., 2007; Tubiello *et al*., 2007; Leakey, 2004). Both Free Air Chamber Experiments (FACE) and crop model simulations have shown yield increases of 10-25% at 550ppm for C3 crops but only an increase of 0-10% for C4 crops (Easterling *et al*., 2007; Tubiello *et al*., 2007). Mature forests of C3 species on the other hand, were found to have no significant response to increased CO_2, with young forests, giving slight positive responses (Easterling *et al*., 2007). Direct effects of an enhanced CO_2 atmosphere can, however, be modified by temperature and precipitation (Streck, 2005; Easterling *et al*., 2007; Tubiello *et al*., 2007) as these variables are also expected to change under climate change. Indirect effects can be through infestation of crops by insect pests, diseases and weeds, since the prevalence of these biotic factors is influenced by climatic conditions. Climate change is also likely to affect soil fertility through factors such as temperature effects on soil processes such as organic matter decomposition and biological nitrogen fixation. There is variation in regional climate change impacts on agriculture with crop yields likely to decrease in tropical and sub-tropical zones due to a shorter (due to hastened crop development arising from an increase in temperature) and drier growing season (Hitz and Smith, 2004; Schlenker and Roberts, 2006; Easterling *et al*., 2007; Tubiello and Rosenzweig, 2008). In contrast, crop yields in the mid- and high-latitudes are expected to increase due to a longer and warmer growing season. Multiple cropping will become possible in these high latitude areas due to longer seasons (Rosenzweig and Hillel, 1995). Considering the above scenario, more crops could be produced in the higher latitudes to maintain constant global food production, while low latitude areas would have to import food (Parry *et al*., 2004), a situation that will render most developed countries more vulnerable to hunger.

Climate change impacts on crop productivity will obviously depend on the degree to which climatic variables change. Parry *et al*. (2004) established the highest global and regional reductions in crop yield under the A1F1 IPCC - Special Report Emission Scenario (highest CO_2 concentration and temperature). They also found yield differences between developed and developing countries to be highest under the A2 scenario (intermediate CO_2 concentration and temperature) and lowest under the B1 and B2 scenarios (lowest CO_2 concentration and temperature). Crop yields in the African region have been found to generally decline as a result of climate change (Meadows, 2006; IPCC, 2007; Schlenker and Lobell, 2010). For Zimbabwe, Makadho (1996) found that rain-fed maize yield for a short season variety responded variedly to climate change depending on planting date, at two stations (Masvingo in Natural Region IV and Karoi in Natural Region II) out of four consistently showing reduction in yield, particularly for planting dates later than 1 November. Dimes *et al.* (2008) also reported a yield reduction of 25% in maize grain yield for a short season variety due to climate change at Bulawayo (west of Zimbabwe and in Natural Region IV).

5.1.2. Smallholder farmer adaptation strategies to climate change

In the absence of appropriate adaptation strategies, communities which heavily rely on agriculture for their livelihoods are likely to suffer from food and nutrition insecurity as well as increased poverty. However, farming communities across the globe are known to already be coping with climate variability and change, although the pace is slow (IPCC, 2007; Kurukulasuriya *et al*., 2006; Mano and Nhemachena, 2007). Farmers have shown considerable resilience to climate variability and change (Adger *et al*., 2003; Burton and Lim, 2005) and adapting to current climate variability can increase resilience to long-term climate change (Cooper *et al*., 2008; IPCC, 2007). However, since future climate changes are likely to occur at a rate faster than has been previously experienced in history (Burton and Lim, 2005; IPCC, 2007), farmers may not necessarily display the same level of resilience in future. Challinor *et al*. (2007) also noted that, in future, individual or community adaptation abilities may not adequately deal with intensified and increased frequencies of climate extremes such as droughts.

Agronomic coping and adaptation strategies to climate variability and change previously identified include use of crops and varieties tolerant to climate stresses, use of mulch, intercropping crops adapted to different climatic conditions, cost-effective water management practices and use of climate forecasts to reduce climate risk (Challinor *et al*., 2007; Howden *et al*., 2007). In Zimbabwe, some of the adaptation strategies used by smallholder farmers are dry planting and early planting, altering planting dates and introducing irrigation (Mano and Nhemachena, 2007). Mubaya (2010) also noted adaptation strategies used by farmers in Zambia and Zimbabwe (including study areas for this study) to include winter ploughing, pot holing, use of planting basins, embarking on off-farm activities to get income and reliance on remittances from relatives working in towns and abroad.

African communities are the most vulnerable to impacts of climate variability and change (Adger, 2003; Challinor *et al.,* 2007; IPCC 2007; Barrios *et al*., 2008; Mertz *et al*., 2009). Reasons for this scenario include heavy dependence of these communities on agriculture which is greatly influenced by climate and limited capacity to cope and adapt as most are resource poor farmers. The majority of these communities are located in geographical areas where production is already limited by climate, rainfall in particular, a factor that pre-disposes them to climate change effects.

5.1.3 .Rationale for this chapter

The importance of agriculture to national economies and food security coupled with the sensitivity of the sector to climate, require that the effects of climate change on agricultural productivity be quantified in order to guide planning. It is also imperative for vulnerable regions and communities to be prepared for the predicted climatic changes. Rural communities in semi-arid regions of Zimbabwe, which include the study areas Lower Gweru and Lupane, rely on agriculture for their livelihoods and are vulnerable to climate change as they have limited capacity to cope with a changing farming environment, due to poor resource bases. In addition, these communities are mostly situated in areas which are degraded due to high population densities. Their soils are also inherently low in fertility (Grant, 1981; Mashiringwani, 1983; Shumba, 1994; FAO, 2006). Thus research work on potential effects of climate change on crop productivity and testing effectiveness of possible adaptation strategies are essential. The maize crop was selected for the study as it is the staple food crop in Zimbabwe.

5.1.4. Objectives

5.1.4.1 Overall objective

The aim of this chapter is to use the Agricultural Production Systems sIMulator (APSIM) model to evaluate the effects of climate change on maize crop yields and to test selected agronomic adaptation strategies, under current and future climate scenarios for the Lower Gweru area of Zimbabwe.

5.1.4.2. Specific objectives

1. To determine the effect of climate change on grain, biomass and stover yield of maize.
2. To determine the effect of climate change on number of days taken by the maize crop to reach physiological maturity.
3. To determine the effect of climate change on the simulated soil water balance, (available water at sowing, seasonal soil evaporation, seasonal transpiration, seasonal runoff and seasonal drainage), with water reset on 1 November of each year.

5.1.4.3 Hypotheses

1. Future climate scenarios do not make significant changes to maize yield (grain, biomass and stover) compared to the current climate data.
2. There is no significant difference in number of days taken by the maize crop to reach physiological maturity under current and future climate.
3. There are no significant differences in the water balance (available soil water at sowing, seasonal soil evaporation, seasonal transpiration, seasonal runoff and seasonal drainage) under current and future climate.

5.2. Methods and Materials

According to Hertel and Rosch (2010), the most commonly used methods in climate impact studies on agriculture are the statistical, Ricardian and crop growth modelling methods. Statistical approaches have been used by researchers such as Schlenker and Roberts (2006), Lobell and Field (2007) and Schlenker and Lobell (2010), while Seo and Mendelsohn (2008), Seo *et al*. (2009), Kurukulasuriya and Mendelsohn (2008a), Hassan (2010) and Mendelsohn and Dinar (2009) are examples of researchers who used the Ricardian approach. Crop growth models have been used by several researchers including van Ittersum *et al*. (2003), Crimp *et al*. (2008) and Dimes *et al*. (2008). Crop growth models and statistical methods are concerned with climate impacts on crop yields whereas the Ricardian methods focus on impacts on land value. This study uses a crop modelling approach to simulate and compare maize crop yields under different climate and agronomic scenarios. The strength of this approach lies in the fact that it is process based and in that crop growth is simulated by stage (Hertel and Rosch, 2010). The approach also allows researchers to specify crop and soil management practices. Thus, with this approach, crop response to changes in climate can be determined and possible adaptation strategies tested. The major limitation with the approach, however, is that most crop growth models tend to be site specific and may not be appropriate for estimating climate change impacts for large geographical areas (Murthy, 2004; Hertel and Rosch, 2010).

Statistical approaches involve determining the relationship between yield and climate change factors, rainfall and temperature, in particular. Although a statistical model has less data requirements and can be applied to larger geographical areas, compared to most crop growth models (Hertel and Rosch, 2010), this approach could not be used in the current study due to absence of reliable historical records on crop yields. Statistical approaches have a limitation in that they cannot incorporate adaptation (Hertel and Rosch, 2010), as they make use of past climate-yield relationships to predict yields. The need to compare different agronomic practices under current and future climate scenarios and to test selected adaptation strategies, in this study, also influenced the choice of a crop growth model over a statistical model approach.

5.2.1. An overview of APSIM model

The Agricultural Production System sIMulator (APSIM) model (McCown *et al*., 1996; Keating *et al*., 2003) version 7.1 was used to simulate and compare maize crop yields under different climate and agronomic scenarios. The model operates on a daily time step and is based on a modular framework where plant, environment (climate, soil) and management modules can be linked up to simulate agricultural systems (McCown *et al*., 1996; van Ittersum *et al*., 2003; Keating *et al*., 2003). The model has modules for a number of crops including maize, barley, wheat, millet, cotton, groundnuts (peanuts), sorghum, sugarcane, lupin, mucuna, canola, hemp, fababean, navy bean, chickpea, sunflower, soybean, lucerne, cowpea and pigeon pea (Keating *et al*., 2003). Soil modules include soil nitrogen (SOILN) which describes dynamics of both carbon and nitrogen in the soil, soil water (SOILWAT), soil phosphorus (SOILP), surface organic matter, manure and residues modules. The model also has a module that enables users to apply particular management actions and conditions (McCown *et al*., 1996; Keating *et al*, 2003). The "met" module contains the long-term climate records for specific meteorological stations, while the climate change module provides a window for in-putting magnitudes in climate (maximum and minimum temperature, radiation, CO_2 and rainfall) shifts. Details of the various modules of the model are outlined by Keating *et al*. (2003). In addition to its application in crop yield prediction in relation to genotype, soil, climate and management factors, the model is a farming systems model capable of addressing long-term resource management issues such as effects of crop rotations and use of residues (Keating *et al*., 2003). The model is most appropriate for use in areas characterized by extensive soil fertility depletion and/or erosion to the extent of reducing viability of crop production, as well as in areas with low and erratic rainfall (McCown *et al*., 1996). These conditions are characteristic of the study area, Lower Gweru. The model has also been found to be effective in augmenting research on crop management in the semi-arid tropics of Africa and Asia (Carberry, 2005). APSIM data input requirements include management data (e.g. crop input amounts and timing of agronomic practices), site specific climate and soil parameters as well as cultivar parameters. Daily climate data (solar radiation (Rs), maximum (Tmax) and minimum (Tmin) temperatures and precipitation amount) are required, while soil parameters required include organic carbon content, available water at field capacity, bulk density, drainage and soil pH. Model limitations are that the model assumes that there are no pests and diseases and that management is optimum. The model also does not simulate impacts of water-logging on plant growth and development.

5.2.2. Construction of composite climate file for Gweru-Thornhill station

The first step towards simulating maize yields under different climate and agronomic scenarios was to build a composite climate file for the Gweru-Thornhill station (ID number 67867050, latitude 19.45 degrees south, longitude 29.85 degrees east and altitude 1429m). APSIM requires continuous daily time series of maximum and minimum temperatures (^{o}C), solar radiation (MJ s^{-1} m^{-2}) and rainfall (mm). Absence of a continuous record of daily observed data for these variables from the Meteorological Services Department of Zimbabwe for Gweru-Thornhill station, necessitated the construction of a composite met-file. The met-file was build from the existing observed data and other sources namely: NCDC/NOAA (http://www.ncdc.noaa.gov/oa/ncdc.html), NASA (http://earth-www.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi and the Risk Management Project (RMP) - ICRISAT. The climate record is from 01 January, 1970 to 31 October, 2008 and climate data for this period will be used in simulating the different climate scenarios. Data gaps in the observed / measured data for the station were filled-in using data from the web based sources as follows: RMP data were used to fill in data gaps on rainfall; NCDC/NOAA to fill gaps on Tmin, Tmax and rainfall data and NASA data to fill in gaps on Tmin, Tmax and radiation. Whereas NCDC/NOAA and RMP data were used as they were, NASA data were scaled up and down as follows:

Tmax = 0.897x + 1.9333 *equation 5.1*

Tmin = 0.961x - 3.238 *equation 5.2*

Radiation (Rs) as Rs = max(3.0, in(0.8*Ra, 1.088x-2.092)) *equation 5.3*

to set the lower limit at 3 and the high values at a value with 0.8 transmissivity (SIPEAA, 2004). The decision on which data source to use (NCDC/NOAA or NASA) for gap filling was based on how well the data (NCDC or NASA) matched observed data, for those periods when observed data were available. This was done by plotting time series of these data and comparing the pattern and magnitudes of these data with that of observed data. Where the pattern was similar, but magnitudes different, relationship between the two (e.g. NASA data vs. observed) was established by plotting the variables against each and fitting a trendline and obtaining a regression equation. The model developed was then used to calculate values to use for gap filling, provided the R-squared value was at least 0.75. Where there were only one or two consecutive days with missing data, average of the values either side of the missing day(s) was used to infill the gaps. The major source of data used to fill gaps in rainfall data was the RMP. For missing shortwave radiation the first option was to generate values from sunshine hours using *equation 5 (shown in next paragraph)* (Prescott, 1940), whenever these data were available. Day of year (DOY) average sunshine hours were in some cases used to fill in missing values of sunshine hours. The second option was to generate solar radiation from observed Tmax and Tmin data, using the Campbell-Donatelli (CD) method (Donatelli and Campbell, 1998) (*equation 4, shown in next paragraph*), where observed Tmax and Tmin data were available and sunshine hours not available. There were ten major periods that required gap filling (see Table.5.1).

Table 5.1. Major periods that had missing data and methods used to fill in gaps in the Thornhill meteorological climate record used in simulating climate change effects using APSIM model

Period	Sources of data used to fill gaps
01/01/1970 - 11/01/1971	RMP rain, observed Tmax and Tmin, sunshine hour for Rs
12/01/1971 - 30/06/1971	RMP rain, DOY averages for Tmax, Tmin,Rs from DOY averages for sunshine hours
01/07/1971 - 30/06/1989	RMP rain, Mainly observed Tmax and Tmin, mostly sunshine hour Rs
01/07/1989 - 31/03/1990	RMP rain, NCDC Tmax and Tmin , Rs is CD
01/04/1990 - 30/06/1991	RMP rain, mainly observed Tmax and Tmin, mostly sunshine hour Rs
01/07/1991 - 13/11/2000	RMP rain, mainly observed Tmax and Tmin, mostly sunshine hour Rs
14/11/2000 - 31/12/2001	RMP rain, observed Tmax and Tmin, Rs is CD
01/01/2002 - 31/12/2002	NOAA rain, mainly observed Tmax and Tmin, also NCDC Tmax and Tmin, Rs is CD
01/01/2003 - 31/12/2003	NOAA rain, mainly observed Tmax and Tmin, Rs is NASA_scaled
01/01/2004 - 30/06/2008	NOAA rain, NASA scaled Tmax and Tmin, Rs is NASA_scaled

Campbell-Donatelli (CD) formula for calculating solar radiation (Rs): (Donatelli, and Campbell, 1998)

Rs = transmissivity * extraterrestrial radiation (Ra) (day of year, lat).....*equation 5.4*: where:

transmissivity = clearskytransm * (1.0 - exp(-CD_b * fTavg * dt^2 * fTmin))

Tavg = (Tmax + Tmin) * 0.5

fTavg = 0.017 * exp(exp(-0.053*Tavg))

dt = Tmax - (Tmin + Tmin1) * 0.5

Tmin = exp(minT / CD_Tnc)

clearskytransm = 0.8

CD_b = 0.463 CD empirical parameter b (temperature range factor for dt)

CD_Tnc = 85.6 CD empirical parameter Tnc (summer night temperature factor)

Calculation of solar radiation from sunshine hours (Prescott, 1940)

Rs = Ra * (a + b * n/N) *equation 5.5*

where Rs = solar radiation at the earth's surface

a = 0.18, transmissivity with no sunshine

b = 0.62, where a+b is the clear sky transmissivity (0.8)

n = observed sunshine hours

N = daylength

Ra = extra-terrestrial solar radiation (at top of atmosphere).

The coefficients a and b, used were those specified for Irene, South Africa (Lat = -25.92 degrees; Longitude = 28.22deg; Clearsky transmissivity = 0.8; CD_b = 0.463; CD_Tnc = 85.6) in the Radiation Estimate (RadEst) parameter document (SIPEAA, 2004) available at (http://www.sipeaa.it/ASP/ASP2/RadEst_DB/parameters_search.html) and Ra was obtained from the NASA site. Daylength, N was obtained using the following formula (Hargreaves, 2009):

$$N = 24 - \frac{24}{\pi} Acos\left(\frac{sin\left(\frac{0.8333\pi}{180}\right) + sin\left(\frac{L\pi}{180}\right)sinP}{cos\left(\frac{L\pi}{180}\right)cosP}\right)$$ *equation 5 6*

where L is latitude (for Gweru Thornhill station L=-19.45) and

P = Asin(0.39795*cos(0.2163108)+2*Atan(0.9671396*tan(0.0086*(J-186))) and

J = day of year.

A composite met_file from 1 Jan 1970 until 31 Dec 2008 (with daily data put in columns) was thus created and the documentation for this file, in terms of data sources and methods used, was included on the met_file (see Appendix III for the met file-format). Time series for all the variables were then checked for consistency using TAMET software (Wall, 1977).The Tav_Amp.exe. file (Hargreaves, 1999) was then run and applied to the created met_file to calculate and insert values of annual average ambient temperature (TAV) and annual amplitude in mean monthly temperature (AMP), which are used by the APSIM SoilN2 module to calculate daily soil temperature for a site (Hargreaves, 1999).

The resultant solar radiation, temperature, and rainfall patterns and magnitudes for the composite climate are typical of the climate of Zimbabwe for example rainfall peak period of DJF and lowest radiation values during winter months (May, June and July) and highest values around October (Drummond and Vowinckel, 1957; Climate Handbook of

Zimbabwe, 1981) (Fig. 5.1a to 5.1c). The high year to year variability in rainfall characteristic of rainfall pattern in Zimbabwe is also quite evident with typical drought seasons, for example 1981/2; 1991/2 and 2002/3 (Fig. 5.1d). The meteorological year runs from July of one year to June of the following year.

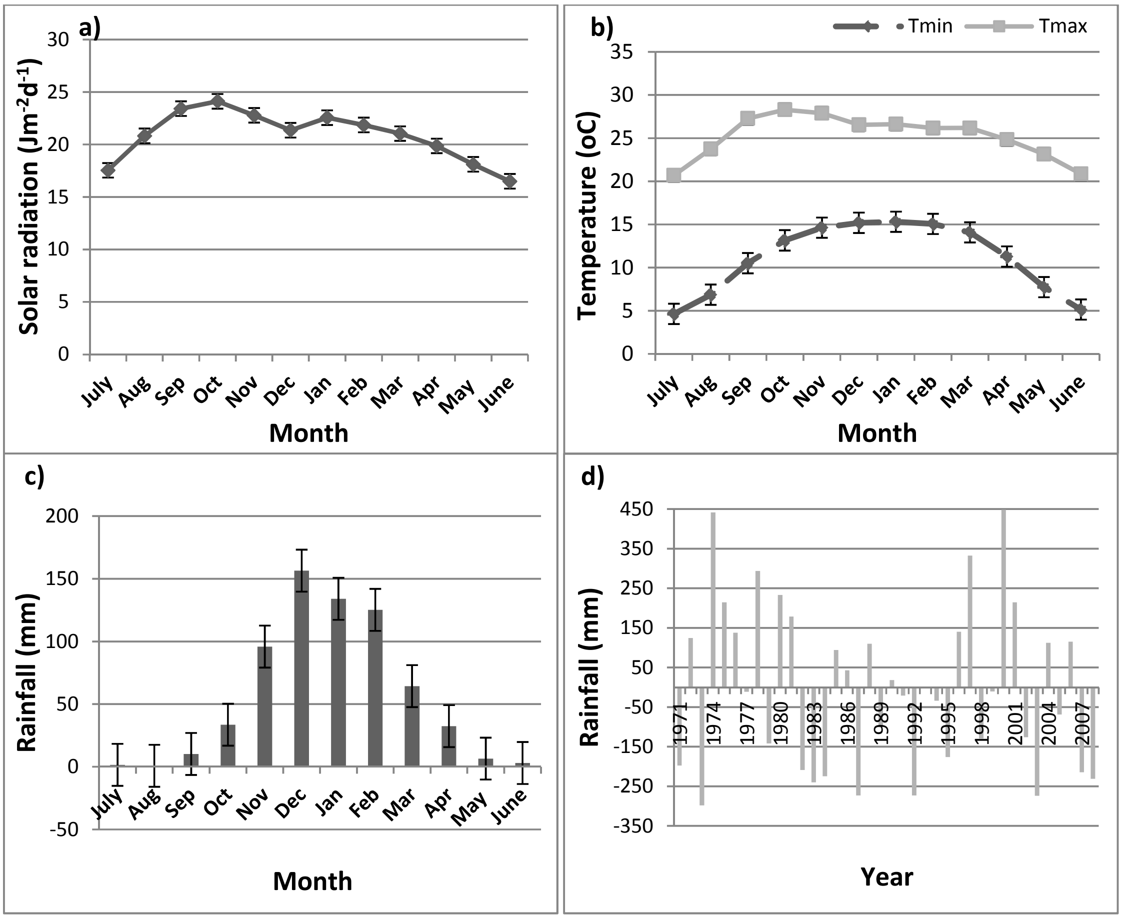


Fig. 5.1 a) Mean daily solar radiation; b) Mean daily temperature; c) Mean monthly rainfall; and d) Annual (July to June) rainfall anomalies for the 1980-2008 composite Gweru_Thornhill climate data

5.2.3. Benchmark simulations

Average maize grain yield (800-1000 kgha^{-1}) for Gweru district (Moyo and Musasanuri, 2009, personal communication; Rukuni, 1994; FAO, 1999; Muzari *et al*, 2012) was benchmarked against its simulated yield, an approach described by Carberry *et al*. (2009) in their farmer participatory use of APSIM model for decision making as a "soft"-evaluation of the model. This was done using the commonly grown varieties SC403, an early maturing variety and SC601, a medium season length variety. A sowing window starting from 15 November and ending 15 January was defined as this is the period during which planting is normally carried out in the study area (Moyo and Musasanuri, 2009 - personal communication). Although varying sowing criteria have been used by different researchers and it seems that there is no standard criterion (Fosu-Mensah, 2012). Dimes *et al*. (2008) point out that 20 mm received in 5 consecutive days is a common sowing criteria and this was the sowing criteria adopted in this study. Thus, sowing was set to occur at the first opportunity when 20 mm were received in 5 days, during the 15 November to 15 January window so that the earliest possible planting date was 15 November and the latest date, 15 January. The amount of initial soil water at the start of the simulation was set at 10% filled from the top. To remove carryover effects, water, nitrogen and surface organic matter (surface OM) were reset on 1 November, which is before the start of each season's sowing window. Sowing density was 3 plants per m^2. Higher yields than expected were initially obtained from the model and the bench mark yields were achieved mostly by adjusting the fraction of organic matter that is inert (F-inert) upwards and organic carbon (OC) content downwards. This was done to reduce the mineralization rate, a factor which was the main reason for over-estimation of maize yield by the model. (Total nitrogen mineralized was one of the outputs that APSIM was set to report on at the end of the harvest). Yields simulated for the two varieties were considered as one data base and quartiles were calculated, noting the yield ranged between the 2nd and 3rd quartiles. The technique removed some extreme outliers and assisted in judging if simulated yields fell within normal range (Hargreaves, 2009 - personal communication). The calibration exercise achieved a situation whereby about 75 of the simulated yields fell between 800-1000 $kgha^{-1}$. The benchmarked set-up provided the base for subsequent simulations for the sensitivity analysis as well as simulations for different climatic and agronomic scenarios.

5.2.4. Climate change scenarios

Use of crop growth models in the study of climate change impacts on crop growth and yield may involve direct or indirect (e.g. post-processing such as weather generators) use of climate model outputs (predicted temperature and/or rainfall changes from current climate) as input to run the crop growth models (Challinor *et al.,* 2009). In some cases, however, the climate model outputs may be used to perturb observed data, thereby creating climate change scenarios (Hewitson, 2003; Challinor *et al*., 2009). In this study, climate change scenarios were created by perturbing the observed long-term climate record for Gweru-Thornhill met station by applying selected temperature and rainfall shifts. This was done using the "climate change" module in APSIM, an approach which has been used in similar studies, for example Crimp *et al.* (2008); Dimes *et al.* (2008) and Hayman *et al*. (2010). The climate control utility allows one to perturb rainfall and temperature by different specified magnitudes. The maize module in APSIM version 7.1 includes carbon-assimilation algorithms that respond to changes in atmospheric CO_2 concentrations. Thus, the level of CO_2 was also specified in the climate change module.

5.2.5. Sensitivity analysis

A sensitivity test was conducted by simulating maize yields under varying temperature and rainfall change magnitudes as well as under varying CO_2 concentrations. The test was done to determine the range of effects of projected climate change scenarios on maize yield in the smallholder farming sector of Zimbabwe. This was done by simulating maize yields for a relatively short season variety SC403 (with an average of 132 days to maturity at an altitude of 1200m (Gwenzi *et al*.,2008)) under different temperature (0; +0.5; +1.5; + 2.5 and 3.5 ^{o}C) and rainfall (0; -5%; -10%; -15%; -20%; and +5%) change magnitudes above or below the current climate. For this sensitivity test, maize yields were simulated under four levels of atmospheric CO_2 concentrations of 370; 490; 580 and 700ppm, for the afore-stated temperature and rainfall shifts. APSIM file generator was used to generate factorial simulations for the various scenario factors (temperature, rainfall and CO_2) with differing levels. The "Analysis2.xls" spreadsheet developed by Neil Huth at CSIRO (*undated*), was then used to import/collect the output results from the model output files into excel, to enable analysis of the APSIM output data.

Simulations were run for Gweru district using the long-term Gweru-Thornhill met_file under nitrogen non-limiting conditions. Soil parameters used to initialize the model are similar to those described in section 5.2.8 (Tables 5.3a and b). A short season maize variety SC403 was used. Sowing conditions and practices were as described for simulations carried out to compare different climate and agronomic scenarios (see section 5.2.7), with water and residues reset on 1 November each year. Conventional land preparation, namely ploughing, was employed**.**

5.2.6. Effect of climate change on smallholder maize productivity

The climate scenarios (temperature, rainfall and CO_2) adopted in the analyses of climate change effects on maize productivity are within the A2 emission scenario projections for Southern Africa for the period 2046-2050 (Christensen *et al*., 2007). They are also in-line with projections for south eastern Africa and Zimbabwe (Hulme *et al*., 2001). The minimum and maximum temperature changes of +3.0^{o}C applied to the crop simulation model are also about the same temperature change (+2.7^{o}C) projected for Gweru-Thornhill meteorological by the Canadian Climate Center (CCC) global climate model (GCM) (Climate Systems Analysis Group (CSAG) at University of Cape Town (UCT) (undated). The projections are available from CSAG (http://data.csag.uct.ac.za/doc/). The CCC model was found to simulate, the "current" temperature for Zimbabwean stations better compared to other GCMs (Unganai, 1996). There are no probabilities attached to the occurrence of the IPCC emission scenarios. The A2 scenario was chosen for the reason that it represents intermediate CO_2 emissions and climate (temperature) sensitivity compared to the B1, B2 and A1 scenarios, which are lower level scenarios and to the A1FI scenario which is the highest level scenario (See appendix I). Unlike, with temperature projections, global and regional models have less agreement in projection of both direction and magnitude of rainfall change (Hulme *et al*., 2001; Tadross *et al.,* 2005; Christensen *et al*., 2007). Rainfall reductions of 10% and 15% by 2050 were considered in the analyses, based on projections of significant reductions of 5-15% in summer rainfall (November-May) for southern Africa by 2050 (IPCC, 2007 WGII Chapter 10) and a similar reduction for the Limpopo river basin (Arnell, 1999). Hulme *et al.* (2001) also projected a significant reduction of 15-25% in mid-summer rainfall over much of southern-eastern Africa, while Tadross *et al*. (2005) projected declining rainfall for the first half of the rainfall season (October to December) and no change for the second half (January to March).

Maize yields and soil water balance components were simulated and compared for the following scenarios, under current agronomic practices (Table 5.2).

Table 5.2. Description of current and future climates used in the climate change impact study

Climate name	Description		
	Temperature change (^oC)	Rainfall change (%)	CO_2 concentration (ppm)
Current climate	0	0	370
Future climate 1	+3	-10	532
Future climate 2	+3	-15	532

5.2.7. Simulation management data for comparing different climate and agronomic scenarios

Simulations were carried out under a "continuous maize system", that is, sole cropping and simulation of planting maize on the same lands each year. Crop parameters of SC401 and SC701 maize varieties, whose descriptions are provided in the APSIM maize crop module, were chosen to describe the varieties SC403 and SC709 respectively, since the parameters are similar to those of SC401 and SC701, respectively. The soil parameters used were those of a soil typical of Mdubiwa Ward, in Lower Gweru (Tables 5.3 & 5.4). Initial water was set at 10% of maximum available water, filling the profile from the top, while initial nitrogen was set at 10kgha^{-1} nitrate (NO_3) and 5kgha^{-1} ammonium (NH_4). Depth of seedbed was set at 150 mm and seedbed preparation done two weeks before sowing. Sowing was set to occur at the first opportunity when 20 mm of rainfall was accumulated in 5 days, within the sowing window of 15 November to 15 January. The crop was sown at a depth of 50 mm, density of 3 plants m^{-2} and inter-row spacing of 0.9 m. Nitrogen, in the form of Ammonium Nitrate (NH_4NO_3), was applied at 84kgha^{-1} (14kg at sowing and 70 kg at 28 days after sowing). Nitrogen, water and residues were reset on 1 November. The parameter *U*, which describes the first stage (constant evaporation rate, when soil water is not limiting) of soil water evaporation was set at 2, while *Cona,* which describes the second stage (falling evaporation rate) was set at 4 in the APSIM soil module.

Table 5.3. Soil water characteristics used in initializing APSIM model, for Mdubiwa site in Lower Gweru

Depth (cm)	BD (g/cc)	DUL (mm/mm)	LL15 (mm/mm)	SAT (mm/mm)	SWCon (0-1)	PAWC (mm)
0-10	1.6	0.13	0.04	0.18	0.7	9.0
10-30	1.5	0.14	0.05	0.20	0.7	18.0
30-60	1.4	0.21	0.14	0.27	0.5	21.0
60-90	1.4	0.22	0.28	0.18	0.5	12.0

BD = Bulk density; DUL = Drained upper limit; SAT = Saturated water content; LL15 = Lower limit of extraction by the crop; SWCon = proportion of water in excess of DUL that drains in one day; PAWC = plant available water capacity

Table 5.4. Soil chemical characteristics used in initializing APSIM model for Mdubiwa site in Lower Gweru

Depth (cm)	pH (water)	F-Biom (0-1)	F-inert (0-1)	OC (%)
0-10	6.0	0.03	0.40	0.667
10-30	6.0	0.02	0.60	0.293
30-60	6.0	0.02	0.75	0.282
60-90	6.2	0.01	0.90	0.126

F-biom = fraction of decomposable soil carbon in the more labile organic matter pool; F-inert = fraction of soil carbon that cannot be decomposed; OC = soil organic carbon as percentage

5.2.8. Data analysis

5.2.8.1. Sensitivity analysis

Anomaly and sigma plots for simulated grain yields were plotted, to detect the effects of varying temperature, rainfall and CO_2 effects on maize yield.

5.2.8.2. Simulation of maize yield and soil water balance components under different climate change and agronomic scenarios

Box and whisker plots were used to establish and compare the general characteristics of simulated output data (e.g. grain and biomass yield, days to maturity and amount of runoff) from different climate and agronomic scenarios. Cumulative distribution functions were used to establish non-exceedance probabilities for particular yield thresholds. Output data were also subjected to the Kolmogorov test for normality, using SPSS version 17 statistical package, to decide on appropriate statistical test for significant differences among treatments (climate and/or agronomic practices). A t-test (parametric test) or Kruskal-Wallis (non-parametric) test for independent samples was then used to determine significant differences among treatments, for normally distributed and non-normally distributed data, respectively. Where the Kruskal-Wallis test (more than two samples test) showed significant differences at $p \leq 0.05$, data were further subjected to the Mann-Whitney test (non-parametric) for two independent samples to test for significant differences between any two treatments.

5.3. Results and Discussion

5.3.1. Sensitivity analysis

5.3.1.1. Single factor effects of temperature, rainfall and CO_2 shifts on maize grain yield effect of change in temperature

Temperature increase in the low range of 0.5-1.5^{o}C above the current climate, increases maize grain yield at higher CO_2 concentrations of 580 and 700ppm (Fig. 5.2). At 700ppm, an increase of even up to 2.5^{o}C (denoted as T2.5 on graphs) slightly increases the yield by about 1%. However, at CO_2 concentration of 420ppm a temperature shift of +0.5^{o}C (T0.5 on graphs) reduces yield, while at 490ppm these temperature increases do not alter yield. For +1.5^{o}C (T1.5 on graphs) and above, yield is reduced at both 420 and 490ppm, while at higher concentrations of 580 and 700ppm yield only starts to decrease at +2.5 ^{o}C and +3.5 ^{o}C (T3.5 on graphs), respectively (Fig. 5.2). Thus, increase in temperature reduces grain yield, with reductions starting to occur at higher temperature thresholds at higher CO_2 concentrations than at lower concentrations. For a given temperature increase, greater reductions also occur at lower CO_2 concentrations than at higher concentrations. Thus, the highest grain yield reduction of 14% occurs at 420ppm and temperature shift of +3.5^{o}C (Fig. 5.2). Increased temperature under climate change exerts its negative effects on crop yield mostly through shortening of the crop growing period (see section 5.4.3). It also increases the amount of evaporation thereby reducing the amount of soil water available to the crop.

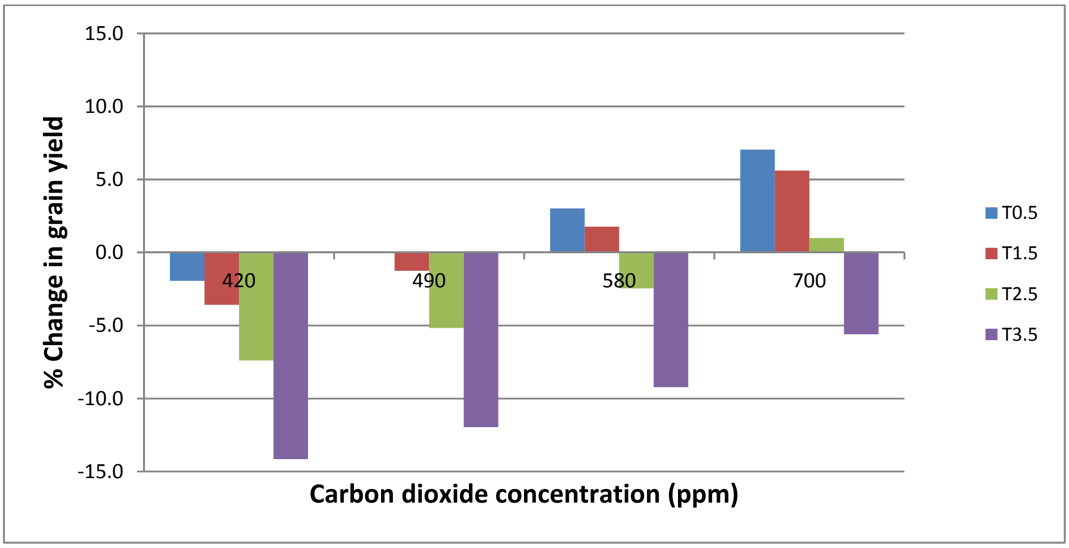


Fig. 5.2. Effect of change in temperature on maize grain yield of variety SC403 simulated under nitrogen non-limiting conditions, for Lower Gweru site, with current rainfall, at four CO_2 levels

Effect of change in rainfall

An increase in rainfall of 5% increases maize grain yield across all CO_2 concentrations, with the highest yield increase of 12% occurring at 700ppm and the lowest of about 5% at 420ppm (Fig. 5.3). Decreases in rainfall amount generally reduce grain yield, with greater reductions occurring at lower CO_2 concentrations and higher negative shifts in rainfall. The greatest yield reduction of about 9%, thus, occurs at 420ppm and -20% rainfall (Fig. 5.3). At 420ppm, grain yield is lower than baseline yield at -5% and higher reductions. However, at 490, 580 and 700ppm, yields are below baseline yield at -10%, -15% and at -20% respectively (Fig. 5.3). The negative effect of reduced rainfall, thus, appears to be off-set by increased CO_2 concentrations up to certain levels, depending on CO_2 concentration, for example, a 5% decrease in rainfall is off-set by a CO_2 increase of up to 490ppm. These results support the view by some authors that crops, particularly C4 crops like maize, will benefit more from a CO_2 enhanced atmosphere, under drought stress conditions than under water stress free environments (e.g. Kimball *et al.*, 2002; Ghannoum *et al.*, 2000 & 2002; Ghannoum, 2009). Water is vital for photosynthesis and other plant biochemical processes and therefore inadequate amounts will impact negatively on crop growth and development. For maize, critical stages for soil water stress are the flowering and grain filling stages and significant yield reductions occur when the crop is stressed during these stages (Ghooshchi *et al.*, 2008; Aslam *et al.*, 2013).

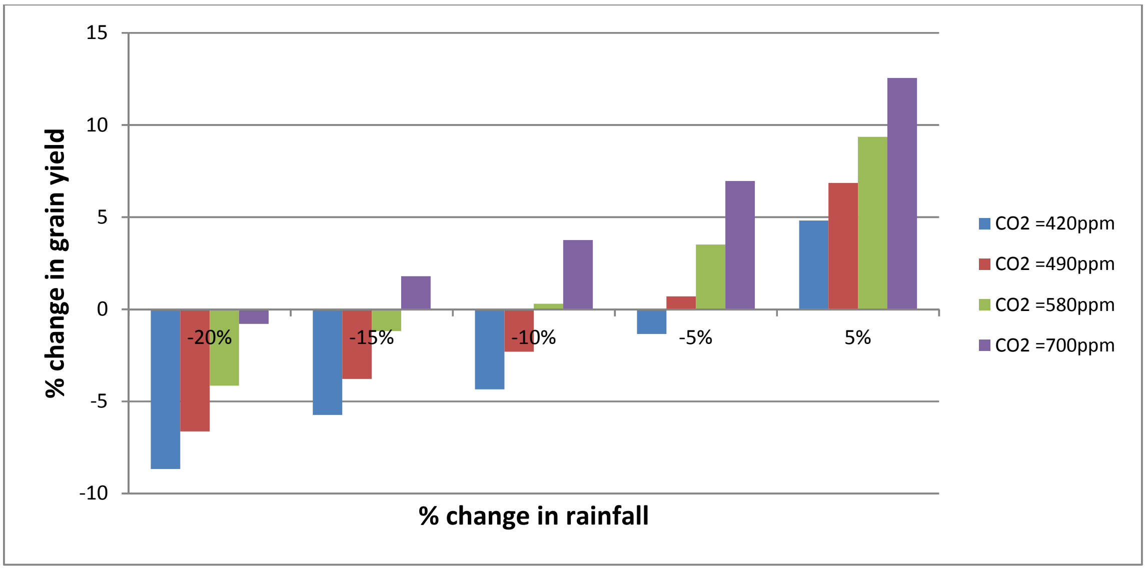


Fig. 5.3. Effect of change in rainfall on maize grain yield of variety SC403 simulated under nitrogen non-limiting conditions for Lower Gweru site, with current temperature, at four CO_2 levels

Effect of change in CO_2 concentration

Increased CO_2 concentration up to 700ppm, in the absence of changes in rainfall and temperature, increases maize grain yield (Fig. 5.4). The highest yield of approximately 10% above the baseline occurs at 700ppm and the lowest of 1.4% at 420ppm (Fig. 5.4). These results are consistent with the widely acknowledged positive effect of CO_2 on crop yield. Increased atmospheric CO_2 concentration increase yield by increasing the rate of photosynthesis (Ghannoum *et al.*, 2000; Kimball *et al.*, 2002; Li *et al.*, 2004; Easterling *et al.*, 2007; Tubiello *et al.*, 2007; Leakey *et al*, 2004; Qiao *et al.*, 2010). At elevated CO_2 stomatal conductance is reduced, leading to reduced transpiration and therefore higher water use efficiency (WUE) (Kimball, 2002; Li *et al.*, 2004; Qiao *et al.*, 2010). WUE has been found to increase more significantly under drought stress (Kimball *et al.*, 2002; Kang *et al.*, 2002; Qiao *et al.*, 2010) and hence increased CO_2 concentration will benefit crops more, under water limiting conditions such as those prevalent in arid and semi-arid regions. The % increase in yield due to increased CO_2 concentration is rather low but this is expected for maize, a C4 crop. C4 species such as maize and sorghum have been found to generally benefit less from an enhanced CO_2 atmosphere compared to C3 species such as wheat, rice and soybean (Easterling *et al*., 2007; Tubiello *et al*., 2007; Leakey, 2004). For example, Easterling *et al*. (2007) and Tubiello *et al*. (2007) report yield increases of 10-25% at 550ppm for C3 and an increase of 0-10% for C4 species.

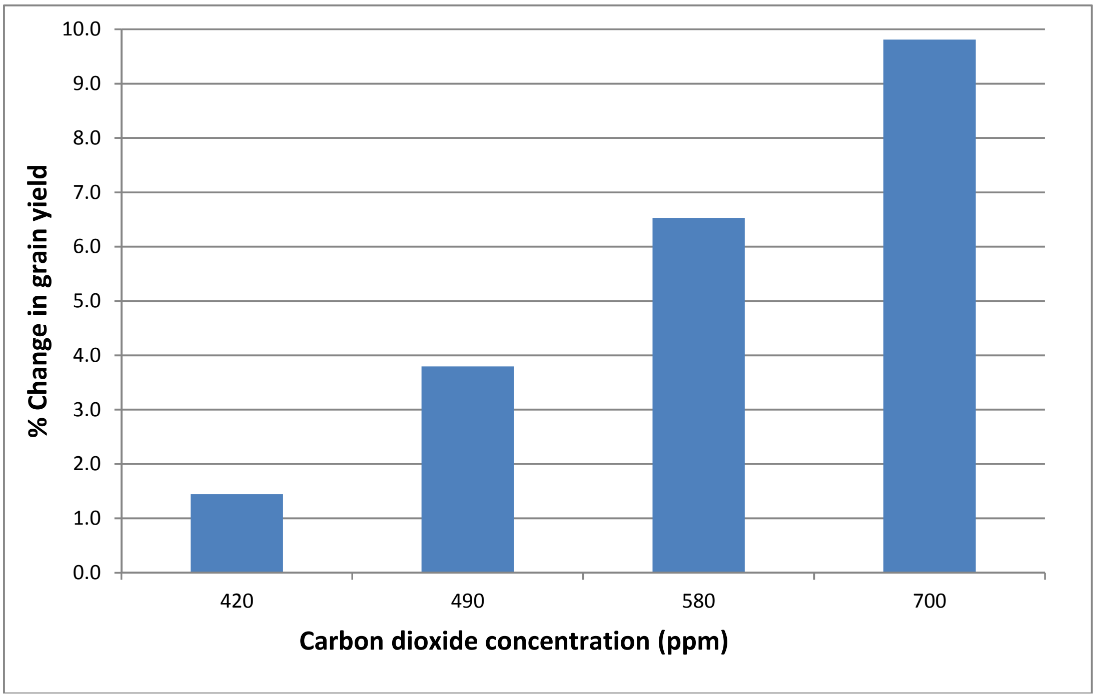


Fig. 5.4. Effect of CO_2 concentration on maize grain yield of variety SC403 simulated under nitrogen non-limiting conditions, for Lower Gweru site, with current temperature and rainfall

5.3.1.2. Combined temperature, rainfall and CO_2 effects

Combined increases in temperature and decreases in rainfall, from current climate, cause greater reduction on maize grain yield than single factor effects (Fig. 5.5a-d). Greater yield reductions occur at lower CO_2 concentrations than at higher concentrations, with combinations of highest temperature and rainfall shifts giving the greatest yield reductions. Thus, the greatest yield reduction of 28% occurs with a temperature increase of 3.5^{o}C and a rainfall decrease of 20% under CO_2 concentration of 420ppm (Fig. 5.5a), whilst the least reduction in yield of 3% occurs with a combination of a temperature increase of 1.5^{o}C and rainfall decrease of 10% under CO_2 concentration of 700ppm (Fig. 5.5d). At the highest CO_2 level an increase in temperature of 0.5^{o}C and a rainfall decrease of 5%, gives grain yield which is 3% higher than the baseline yield, while at 580ppm, yield is not affected (Fig. 5.5c). Decreases in maize yield, particularly at higher temperature increases, greater rainfall decreases and at lower CO_2 levels, confirm the widely adopted fact that, under climate change yield benefits of an enhanced CO_2 atmosphere may be compromised by changes in temperature and precipitation (Ghannoum *et al*., 2000; Streck, 2005; Easterling *et al*., 2007; Tubiello *et al*., 2007).

5.3.1.3. Relative contribution of changes in temperature and rainfall to change in grain yield

Temperature and rainfall shifts due to climate change appear to have equal effect on maize grain yield as depicted by CO_2 level contour maps in Fig. 5.6, where the contour lines are almost at 45 degrees inclination. The contour lines are slightly closer to one another on the top left corner than on the bottom right hand corner, indicating greater yield changes at higher magnitudes of decreases and increases in rainfall and temperature, respectively. Fig 5.6 also indicates that grain yield reduction under, changing temperature and rainfall conditions, varies with CO_2 concentration, with highest yield reductions occurring at 420ppm and lowest reductions at 700ppm. Contrary to the findings, in this study that temperature and rainfall have an almost equal effect on maize crop yield, Dimes *et al*. 2008 (for Bulawayo site, western part of Zimbabwe), concluded that temperature had a greater effect than rainfall, while Akpalu *et al*. (2008) established that rainfall had a greater effect on maize yield than temperature, in the Limpopo river basin of South Africa.

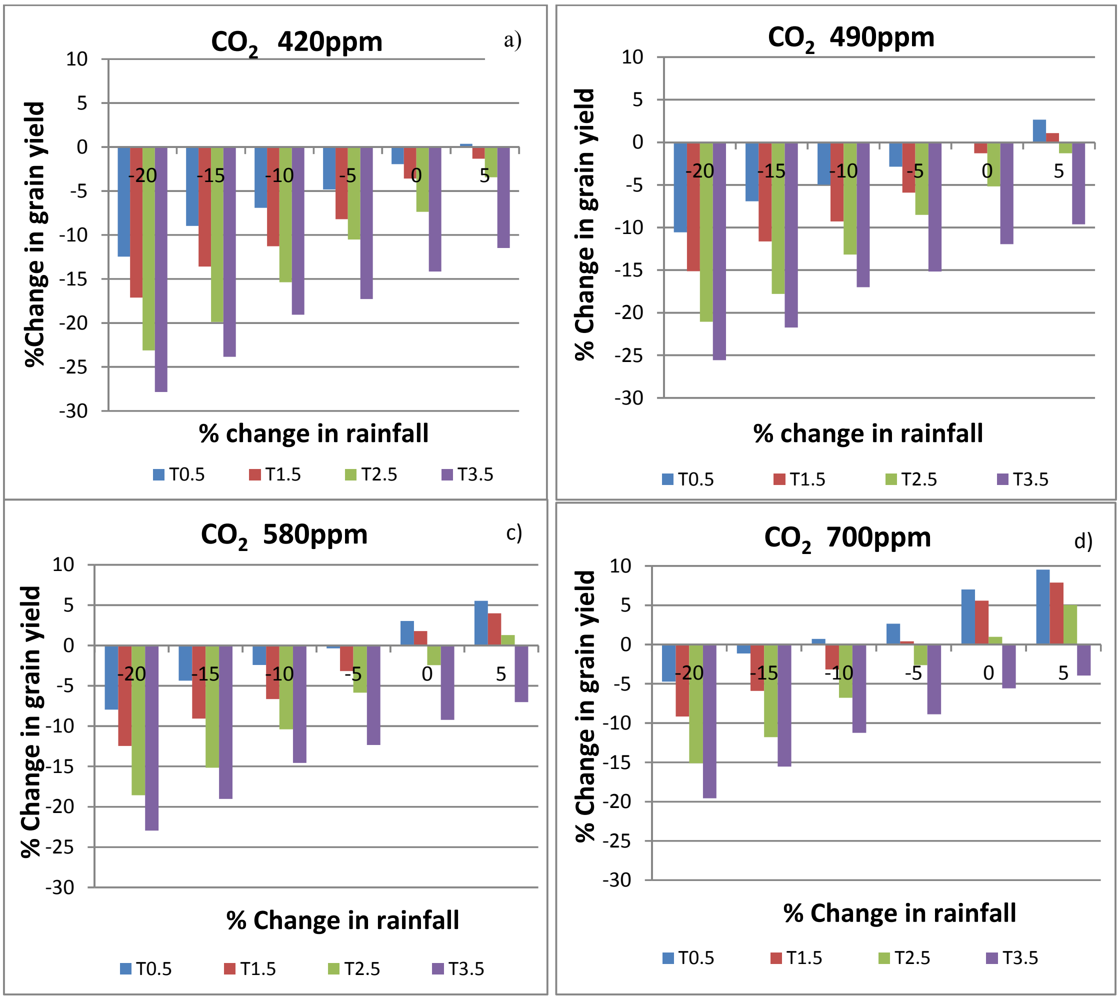


Fig. 5.5. Effect of combined temperature and rainfall change on maize grain yield of variety SC403 for Lower Gweru, (a) at 420ppm CO_2, (b) at 490ppm CO_2, (c) at 580ppm CO_2 and (d) at 700ppm CO_2

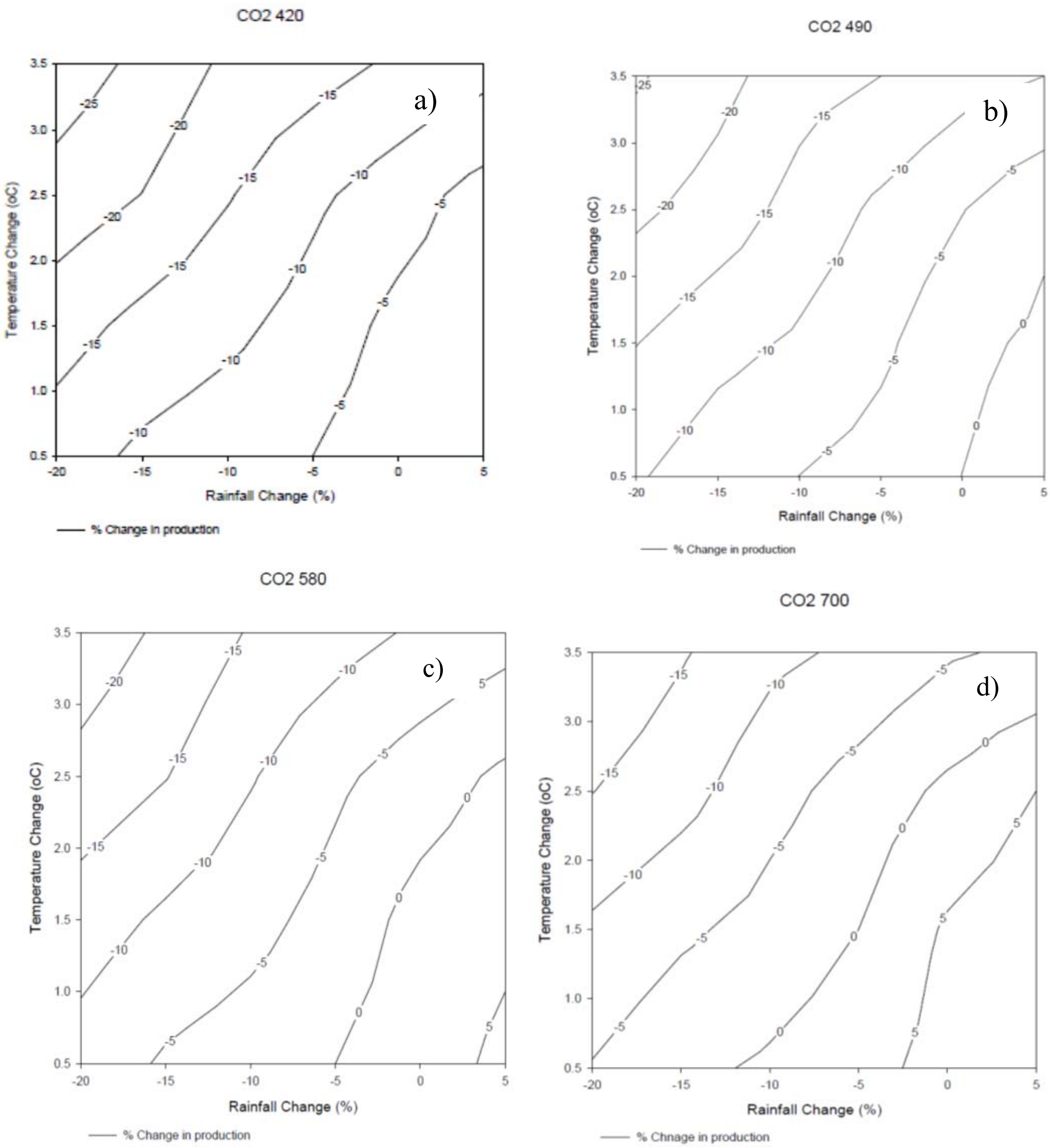


Fig. 5.6. Predicted percentage change in maize grain yield from baseline at Gweru, for a range of temperature and rainfall scenarios at CO_2 concentrations of (a) 420ppm, (b) 490ppm, (c) 580ppm and (d) 700ppm

5.3.2. Effect of climate change on maize grain, biomass and stover yield

Results presented in this section are comparisons of maize yield (grain, biomass or stover) simulated under current climate and two likely climate change scenarios, for Lower Gweru area in Zimbabwe, by 2050. The most likely future climate comprising a temperature increase of $3^{o}C$ and a CO_2 concentration of 532ppm is considered. Future climate 1 and Future climate 2 differ in the magnitude of rainfall reduction, with Future climate 1, having a reduction of 10% and climate 2 a reduction of 15%. Maize yields are compared for a long season variety, SC709, and a short season variety, SC403.

5.3.2.1. Characteristics of maize grain, biomass and stover yield data simulated under current climate and climate change

Maize grain yield

Median yield for SC403 is higher under current climate than under climate change (future climate), with the two future climates having similar yields (Fig. 5.7a). The median yield under current climate is almost equal to the 3rd quartile yield under climate change. Thus, for approximately 3/4 of the years, yields under climate change were lower than the median yield under current climate. Under current climate, yields of this variety are skewed towards the high yield range, but almost symmetrical under climate change (Fig. 5.7a), as depicted by the position of the box between the whiskers. Yields of SC403 are also less variable under climate change than under current climate (Figs. 5.7a and b). For the long season variety, SC709, median yields are slightly higher under climate change than under current climate and median increased in contrast to the lower median for SC403. Inter-quartile yield ranges of this variety, for the two climate change scenarios are similar, depicting similar variability in yield, for the two climates (Fig. 5.7a). Yields for SC709 variety are more variable under current climate (Fig. 5.7b) and are almost symmetrical under both current climate and climate change (Fig. 5.7a). Overall, yields of SC709 are more variable than those of SC403 (Figs. 5.7a) and b) under both current and future climate. However, under climate change scenarios SC709 gave higher median grain yields than SC403, indicating that it would be a better choice under these scenarios which are envisaged by 2050.

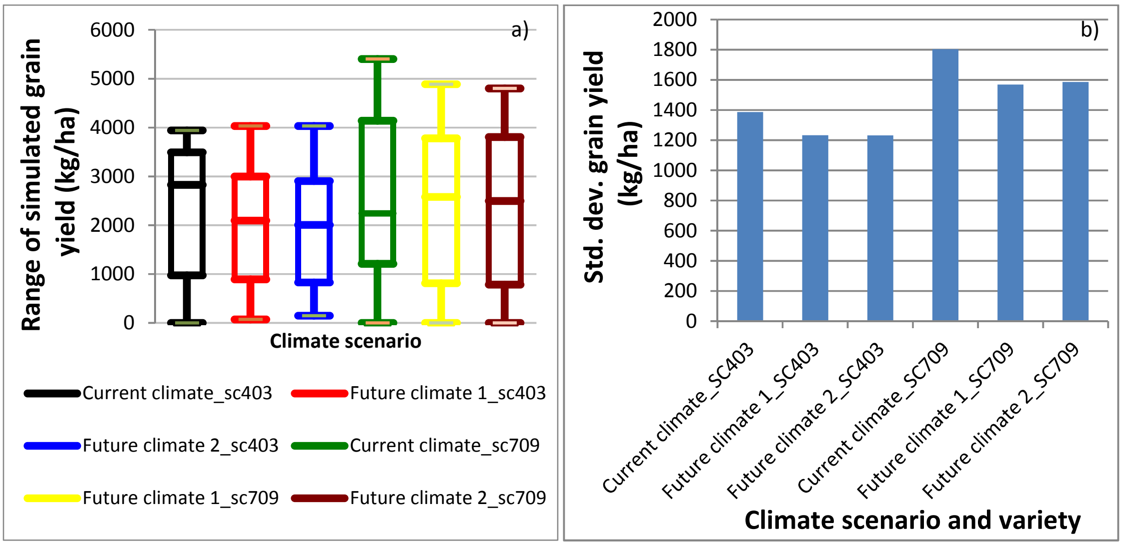


Fig. 5.7. a) Simulated maize grain yield and b) standard deviation of grain yield for SC403 and SC709 varieties, under current and future climate

Maize biomass yield

The median yield for SC403 is higher under current climate than under climate change, with the two future climates exhibiting almost equal median yields (Fig. 5.8a). For this variety, yields show about the same variability under current climate and climate change (Fig. 5.8a and b) and are skewed towards the higher yield range under all three climates (Fig. 5.8a). Median yields for SC709 are about similar under current climate and climate change, with yields being more symmetrical under climate change than under current climate (Fig. 5.8a). For SC709, there is more variability in biomass yield under current climate than under climate change, with yields under the two climate change scenarios showing similar variability (Fig. 5.8b). The biomass accumulated by SC709 under climate change is almost the same as for SC403, thus showing no advantage gained from the longer season variety for total above ground biomass.

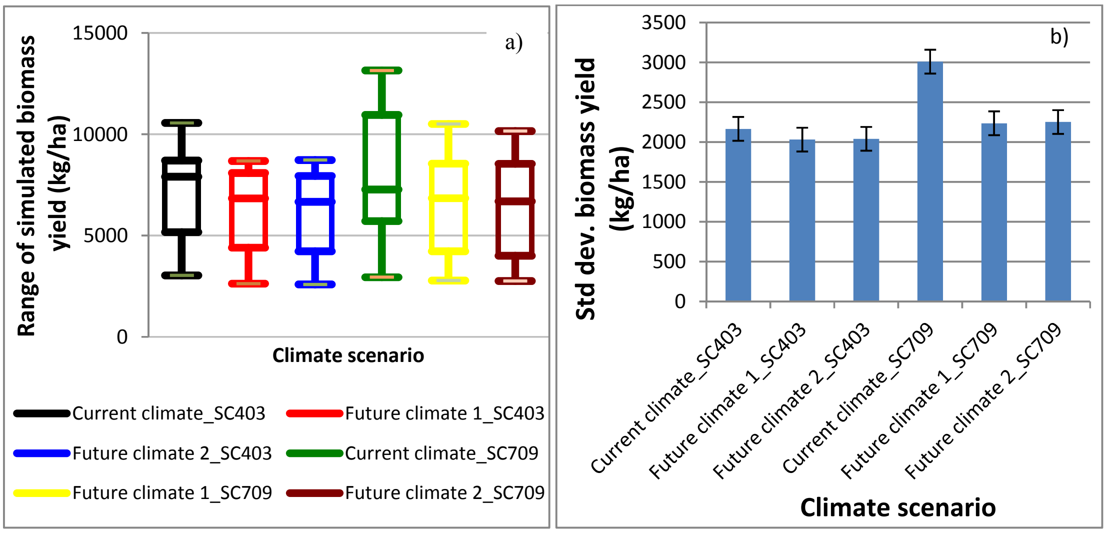


Fig. 5.8. a) Simulated maize biomass yield and b) standard deviation of biomass yield for SC403 and SC709 varieties, under current and future climate

Stover yield

For both maize varieties, median stover yields are higher under current climate than under climate change (Fig. 5.9a), with yield for SC709 under current climate being higher than the 3rd quartile yield under climate change. Thus, for 3/4 of the years, stover yields for SC709 under climate change are lower than the median yield under current climate, thus providing reduced stored fodder for livestock over the dry season. The yield under the two climate change scenarios are almost similar for each variety. Yields are equally variable across all three climates for SC403, while for SC709, stover yields are more variable under current climate than under climate change (Fig. 5.9a and b). Stover yields are symmetrical for SC403 under all three climates and for SC709 under current climate, but skewed towards the higher yield range for SC709 under climate change.

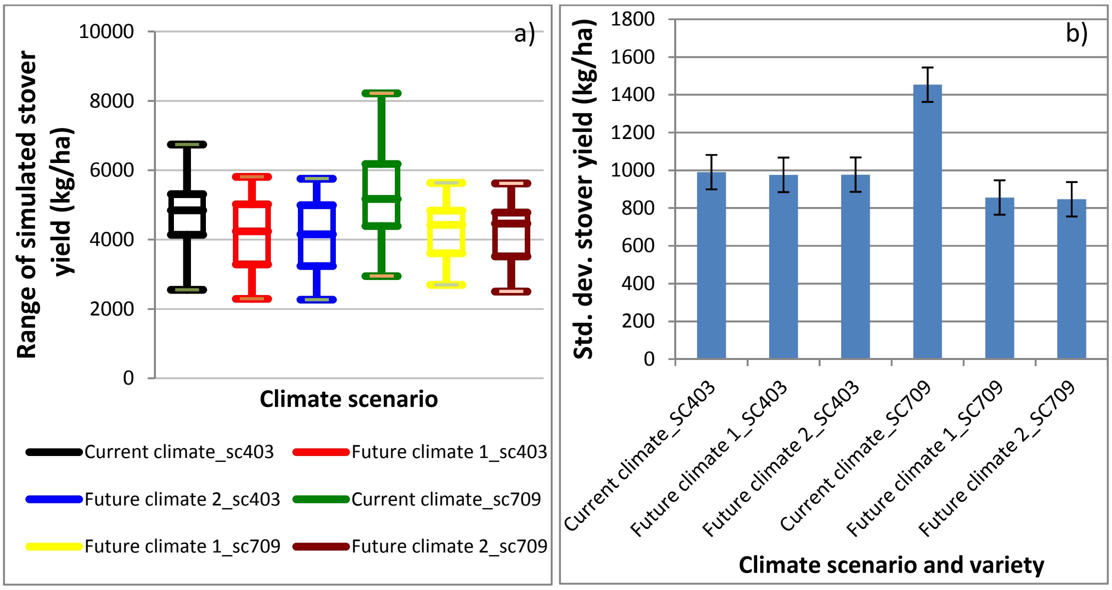


Fig. 5.9. a) Simulated maize stover yield and b) standard deviation of stover yield for SC403 and SC709 varieties grown in Lower Gweru, under current and future climate

5.3.2 2. Probability distribution functions for maize grain, biomass and stover yield under current climate and climate change

Grain yield

For SC403, current climate and climate change appear to give similar yields for the lower grain yield range (up to about 1000 kgha^{-1}, approximately 25% PoNE) and above 4000 kgha^{-1} which represents the extreme yields only obtained in a few years. However, in the range 1200 - 4000 kgha^{-1} maize grain yield under climate change for a particular probability non-exceedance (PoNE), is lower than under current climate (Fig. 5.10a). For example, there is 50% probability that yields of SC403 will not exceed 2000 kgha^{-1}. under climate change, whereas under current climate, a 50% PoNE has a higher yield of about 3000 kgha^{-1}. An almost similar trend is observed for SC709, which also has lower yields for a given PoNE under climate change than under current climate for yield ranges of about 1000-2100 and above 3000 kgha^{-1} (Fig. 5.10b), however, showing smaller differences in yields under future climates until higher than 60% PoNE. Thus, about 50% of the time there would be little difference between grain yield simulated under current climate and climate change conditions.

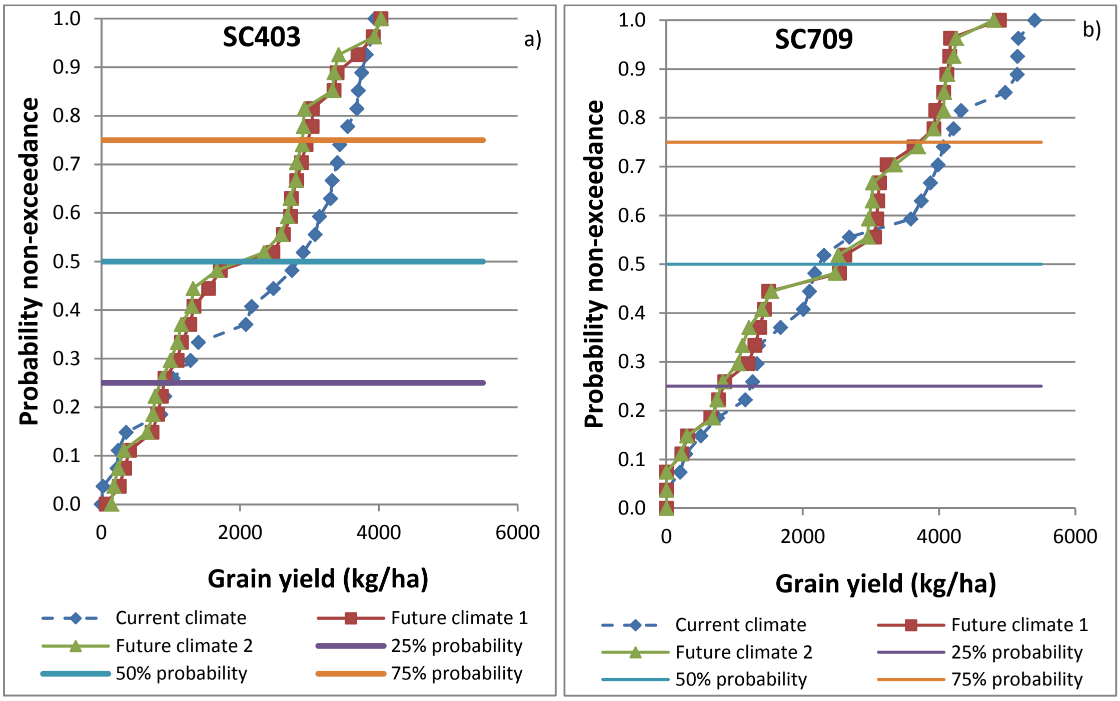


Fig. 5.10. Comparison of probability distribution of maize grain yield for varieties a) SC403 and b) SC709, grown in Lower Gweru, under current and future climate

Biomass yield

Biomass yield for SC403 is consistently lower for a particular PoNE under climate change than under current climate (Fig. 5.11a). For SC709 the same pattern is exhibited for yields below and above about 7500 kgha^{-1}. (Fig. 5.11b), but achieving potentially high values 1 in 4 years of more than 11000 kg ha^{-1} under current climate conditions.

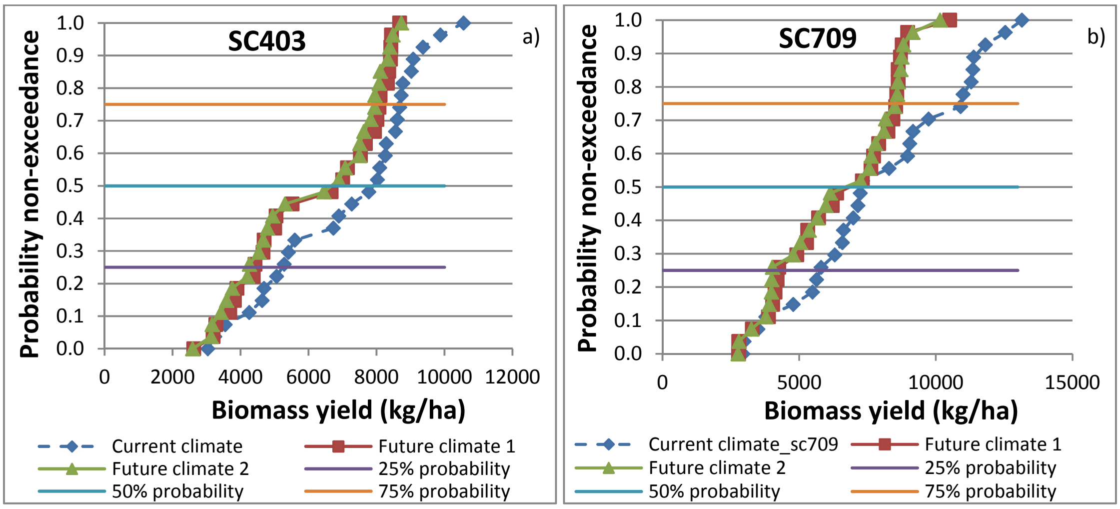


Fig. 5.11. Comparison of probability distribution of maize biomass yield for varieties a) SC403 and b) SC709 under current and future climate

Stover yield

For both varieties stover yield is consistently lower for a particular PoNE, under climate change than under current climate (Figs. 5.12a and b), with a 50% PoNE of 4000 and 4500 kgha^{-1} under climate change and current climate, respectively for SC403. For SC709, there is 50% chance that yields will not exceed 4500 and 5500kgha^{-1} respectively, under climate change and current climate (Fig. 5.12b) and all predictions are higher under current climate. So in all years SC709 will produce less stover under future climates.

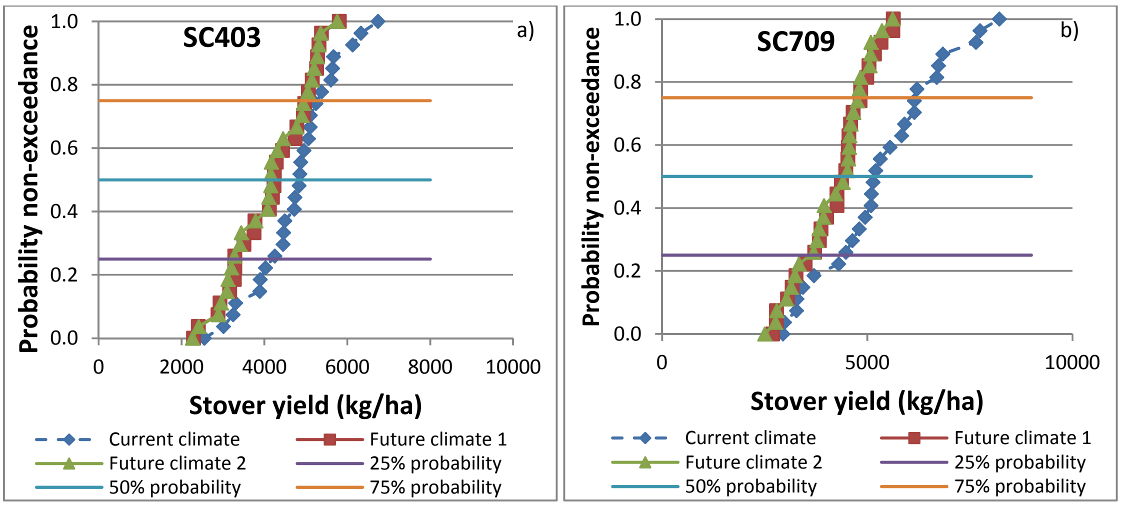


Fig. 5.12. Probability distribution of maize stover yield for varieties a) SC403 and b) SC709 grown in Lower Gweru under current and future climate

For grain, biomass and stover yield, there is more chance that yields do not exceed a given yield under climate change than under current climate. Thus, there is higher probability of getting lower yields under climate change than under current climate. The probability distribution functions also show that yields simulated under the two future climates differ little.

5.3.2.3. Comparison of mean grain, biomass and stover yields of maize grown under current climate and under climate change

Change (from baseline yield) in maize yield due to climate change

Long season variety, SC709, gives higher yields than the early maturing variety SC403 under both current and future climate, with yields of both varieties, being reduced under climate change (Fig. 5.13a-c). Grain and biomass yields of SC403 are reduced by about 13-16% and by 12-14% respectively, while for SC709, grain and biomass yields are reduced by 14-15% and 18-19% respectively. For stover yield, decreases due to climate change are 12-13% and 20-21% for SC403 and SC709, respectively. The small ranges in % change in yield reflect a relatively small yield difference between effects of a 10% and 15% decrease in rainfall represented by Future climate 1 and Future climate 2.

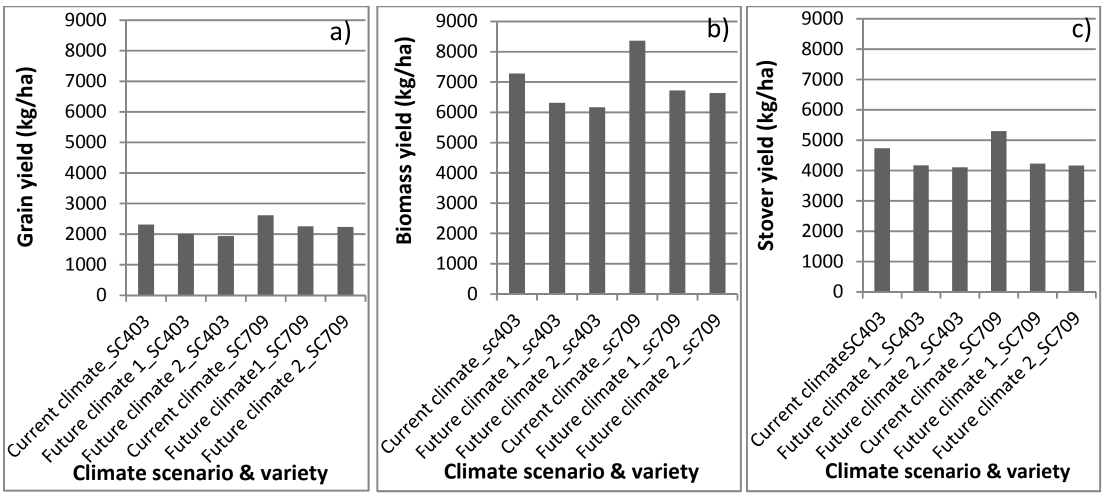


Fig. 5.13. Simulated mean maize a) grain, b) biomass b) and c) stover yields under current and future climate, for SC403 and SC709 varieties grown in Lower Gweru

Statistical comparison of mean yields simulated under current climate and climate change

Simulated yield data are not normally distributed for 13 out of the 18 yield data sets from the different climate and variety scenarios (Table 5.5). Only variety SC403 grain yield data for the current climate and future climate 2 and SC403 biomass yield for all climates are normally distributed (Table 5.5). This outcome of non-normal distribution for most of the yield data is consistent with available literature, as most crop yield data have been reported to be non-normally distributed and to show negative skewness (Hennesy, 2009). Ramirez (1997) and Ramirez *et al.* (2003) concluded that some crop yield distributions are non-normal and show either negative or positive skewness, depending on circumstances. Their conclusions were based on the Corn Belt corn, soybean and cotton yields in the USA. Non-parametric tests, the Kruskal-Wallis and Mann-Whitney tests described in section 5.2 were therefore used to test for significant differences among yields from different climates, as non-parametric tests have no requirement for normally distributed data. Under climate change maize gives lower grain yield ($p=0.420$ for SC403 and $p=0.640$ for SC709) and lower biomass yield ($p=0.077$ for SC403 and $p=0.114$ for SC709) than under current climate (Table.5.6). For stover, yield differences occur at $p=0.066$ and $p=0.010$ for SC403 and SC709 respectively (Table 5.6). Further subjection of mean stover yield data for SC709 to the Mann-Whitney test (test was only done where the Kruskal Wallis test showed significance at $p\leq 0.05$) shows that yield under current climate is significantly higher than yield under the two future climate scenarios (Table 5.7), corresponding p-values being 0.003 for current climate vs Future climate 1, 0.010 for current climate vs Future climate 2 and 0.840 for Future climate 1 vs Future climate 2.

Table 5.5. Kolmogorov_Smirnov test for normality of yield data, for varieties SC403 and SC709, under different climate scenarios

Climate	Kolmogorov-Smirnov		
	Statistic	**Df.**	**Significance**
Grain yield_SC403			
Current climate	0.175	28	0.029*
Future climate 1	0.176	28	0.078
Future climate 2	0.165	28	0.048*
Grain yield_SC709			
Current climate	0.132	28	0.200
Future climate 1	0.158	28	0.072
Future climate 2	0.140	28	0.171
Biomass yield_SC403			
Current climate	0.174	28	0.029*
Future climate 1	0.175	28	0.028*
Future climate 2	0.190	28	0.011*
Biomass yield_SC709			
Current climate	0.125	28	0.200
Future climate 1	0.159	28	0.068
Future climate 2	0.161	28	0.061
Stover yield_SC403			
Current climate	0.102	28	0.200
Future climate 1	0.114	28	0.200
Future climate 2	0.114	28	0.200
Stover yield_SC709			
Current climate	0.079	28	0.200
Future climate 1	0.122	28	0.200
Future climate 2	0.162	28	0.058

*Normally distributed data; $p \leq 0.05$

Table 5.6. Test for significant yield differences among three climate scenarios (Results from Kruskal -Wallis test)

	Grain yield		**Biomass yield**		**Stover yield**	
	SC403	**SC709**	**SC403**	**SC709**	**SC403**	**SC709**
Chi-Square	1.718	0.900	5.132	4.351	5.448	13.007
Df.	2	2	2	2	2	2
Significance	0.424	0.637	0.077	0.114	0.066	0.010*

*Significant difference ($p \leq 0.05$), Grouping variable is climate

Table 5.7. Mean comparison of stover yields for SC709, based on Mann-Whitney test for independent samples

Treatment (climate scenario)	Mean yield ($kgha^{-1}$)
1. Current climate	5 297.4[a]
2. Future climate 1	4 229.2[b]
3. Future climate 2	4 166.7[b]

Means with the same letter are not significantly different from each other at $p \leq 0.05$.

Maize stover is mainly used as livestock feed during the dry season in the smallholder farming sector of Zimbabwe, so is vital to survival of the livestock during the winter period. In recent years farmers in the study area, are being encouraged to use maize stover as mulch, a component of conservation agriculture, which is being promoted throughout the country. Thus reduced stover yield under climate change, will negatively impact on smallholder agricultural productivity and livelihoods.

The decline in maize yield under climate change, found in this study, is consistent with findings from global studies which established that climate change will reduce crop yields in tropical and sub-tropical regions (e.g. Rosenzweig and Liverman, 1992; Hitz and Smith, 2004; Parry *et al*., 2004; Easterling *et al*., 2007; IPCC, 2007; Tubiello and Rosenzweig, 2008). The results are also consistent with a number of research findings on climate change effects on crop yields in Africa (e.g. Meadows, 2006; Turpie *et al.*, 2002; Jones and Thornton, 2003; Schlenker and Lobell, 2010). Schlenker and Lobell (2010), for example, estimate a 22% reduction in maize yield for Africa, due to climate change, while Brown and Crawford (2007) estimate a 6.9% reduction for the same crop, by 2020 for west Africa. In Zimbabwe, Makadho (1996) found somewhat similar result to the current study, that rain-fed maize yields responded variedly to climate change, depending on planting date, with late planting giving lower yields. For two sites (Masvingo in Natural Region IV and Karoi in Natural Region II) out of the four sites they considered, maize yields were consistently higher under current climate than under climate change. Dimes *et al.* (2008) reported a 25% grain yield reduction for a short season variety at Bulawayo site, in western Zimbabwe, due to climate change. The % decrease in maize grain yield established in this study (13-16%) for Lower Gweru is lower than the 25% established for Bulawayo, most probably due to factoring-in of an increased CO_2 level (532ppm) in this study, whereas for Bulawayo, simulations were run for a climate change scenario without CO_2 fertilization. Thus, for this study, increased CO_2 concentration reduced the negative effects of reduced rainfall and increased temperature (Single factor effects examined in this study show that increased CO_2 increases maize yield whereas decline in rainfall and increased temperatures reduce yield). Results from this study thus agree with findings of Dimes *et al*. (2008) in that climate change reduced maize grain yield for the Zimbabwe sites considered, but differ in magnitude of reduction. It should, however, be noted that the p-values at which significant differences in crop yields occur due to climate change are unclear from most of the studies cited herein.

Maize is the staple crop in Zimbabwe and in the study area all farmers grow the crop (see section 4.3.1). The reduction in crop yield due to climate change will thus impact negatively on food and nutrition security. The reduction in stover yield will have an effect on availability of livestock feed, especially during the dry season. Viability of the crop is likely to be reduced in future and farmers may also have to reduce the area grown to the crop. Irrigation development needs to be further expanded and crop varieties that are tolerant to heat stress need to be developed (e.g. Hitz and Smith, 2004; Ortiz *et al.*, 2008).

5.3.3. Effect of climate change on days taken by the maize crop to reach physiological maturity

5.3.3.1. Characteristics of data on simulated number of days to reach maturity under current climate and climate change

Median days to reach physiological maturity are higher under current climate than under climate change for both varieties (Fig. 5.14a). Thus, climate change reduces the number of days taken by the crop to reach physiological maturity due to higher temperatures experienced. The median days under climate change are more than the third quartile for climate change, implying that for 3/4 of the years of analysis (1982-2008), days under climate change are lower than median days under current climate change. Under current climate, the number of days to reach maturity was fairly symmetrical, whereas under climate change, the number of days is slightly skewed towards the lower range (Fig. 5.14a). Number of days taken to reach maturity show more variability under climate change than under current climate (Fig. 5.14b), with the drier future climate (future climate 2) showing slightly more variability than the less dry future climate (future climate 1). For both varieties and for all three climate scenarios, there are days to maturity values that fall well outside the upper range of the other values (outliers) (Fig. 5.14a).

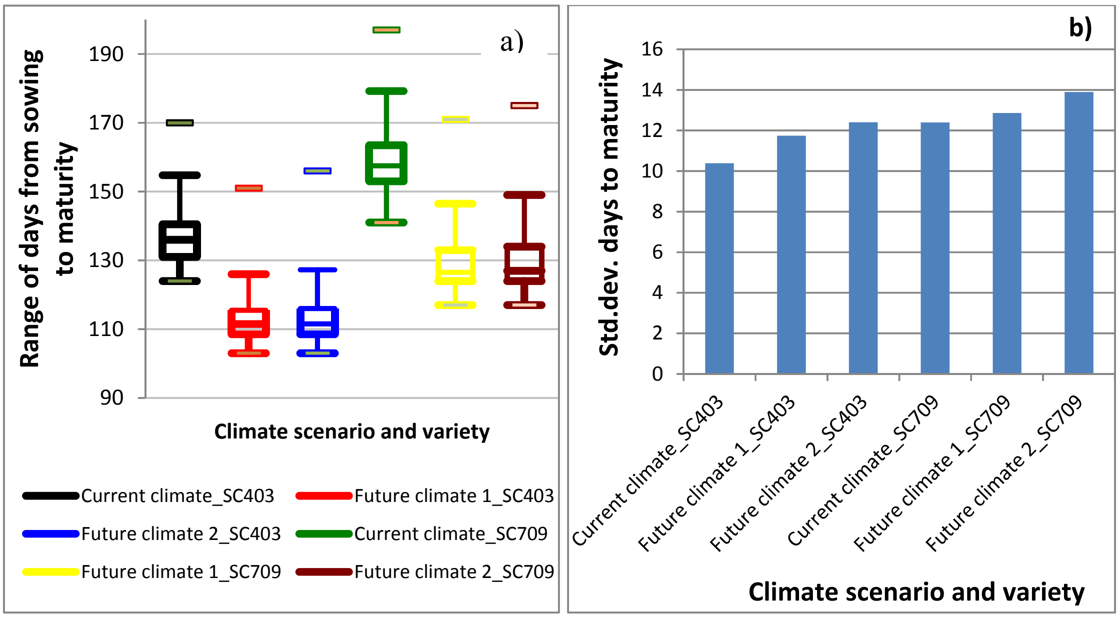


Fig. 5.14. a) Simulated number days to physiological maturity and b) standard deviation for simulated days to physiological maturity for maize varieties SC403 and SC709 grown in Lower Gweru, under current climate and climate change scenarios

5.3.3.2. Mean comparison of days to physiological maturity under current and future climate

Under current climate the number of days taken by the short season variety, SC403, to reach physiological maturity is 138. However, under climate change, the number of days is reduced by 23 to 115 for both future climate scenarios (Fig. 5.15). The number of days to reach maturity for SC709 is reduced by 29 days from 160 to 131 under both future climate 1 and 2. Thus, under climate change the number of days to reach maturity for the long season variety approaches that of the short season variety, under current climate.

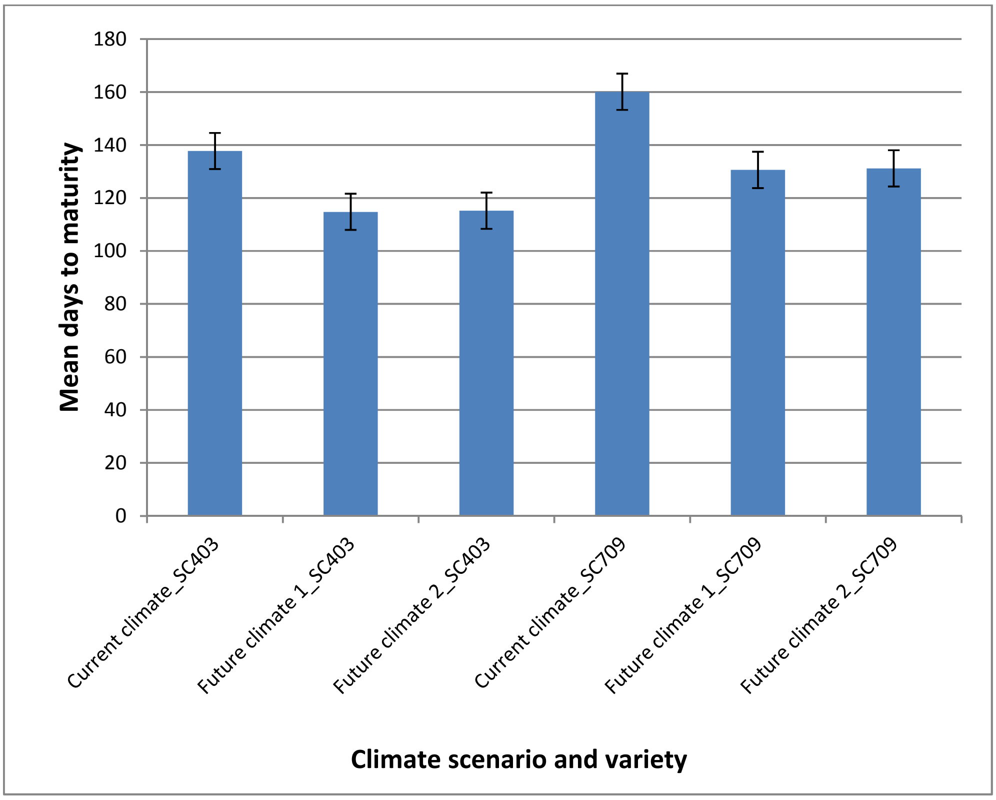


Fig. 5.15. Simulated mean days taken by maize varieties SC403 and SC709 grown in Lower Gweru, to reach physiological maturity under current and future climate scenarios

Statistical analysis

Data on number of days taken to reach physiological maturity for both varieties are normally distributed (Table 5.8). A t-test for independent samples was performed to compare mean days taken by the maize crop to reach maturity, under the different climate scenarios. There is a significant difference ($p<0.05$) in days to reach maturity under current climate and climate change for both varieties (Table 5.9), with the varieties taking significantly more days to mature under current climate than under climate change (Table 5.10). However, for both varieties, there is no significant difference ($p=0.895$ for SC403 and $p=0.874$ for SC709) in number of days, between Future climate 1 and 2, which have the same temperature increase of $3^{o}C$ and rainfall reductions of 10% and 15%, respectively (Tables 5.9 and 5.10). This result is expected since it is temperature that drives phenological development of a crop, with increased temperature hastening growth and development and hence reducing the duration from sowing to physiological maturity.

Table 5.8. Test for normality of data for number of days to reach physiological maturity for varieties SC403 and SC709

Climate	Kolmogorov-Smirnov Statistic	Df	Significance
SC403_days after sowing			
Current climate	0.164	28	0.051*
Future climate 1	0.277	28	0.000*
Future climate 2	0.257	28	0.000*
SC709_days after sowing			
Current climate	0.189	28	0.011*
Future climate 1	0.233	28	0.000*
Future climate 2	0.248	28	0.000*

***** Significant (p≤0.05)

Table 5.9. Test statistics for comparison of mean number of days to maturity under current and future climates

	T-test of means of number of days for maize to reach maturity							
	Variety	t	df	Sig. 2-tailed	Mean difference	s.e difference	95% confidence interval Lower	95% confidence interval Upper
Under current climate vs. future climate 1	SC403	7.753	54	0.000*	22.96	2.96	17.02	28.90
	SC709	8.737	54	0.000*	29.50	3.38	22.73	36.27
	T-test of means of number of days for maize to reach maturity							
	Variety	t	df	Sig. 2-tailed	Mean difference	s.e difference	95% confidence interval Lower	95% confidence interval Upper
Under current climate vs. future climate 2	SC403	7.372	54	0.001*	22.54	3.06	16.40	28.17
	SC709	8.218	54	0.000*	28.93	3.52	21.87	35.99
	T-test of means of number of days for maize to reach maturity							
	Variety	t	df	Sig. 2-tailed	Mean difference	s.e difference	95% confidence interval Lower	95% confidence interval Upper
Under future climate 1 vs. future climate 2	SC403	-0.133	54	0.895	-0.43	3.23	-6.90	6.04
	SC709	-0.160	54	0.874	-0.57	3.58	-7.75	6.61

*significant difference

Table 5.10. Mean comparison of days to maturity for SC403 and SC709 under current climate and climate change

Climate	Mean number of days taken to reach maturity for SC403	Mean number of days taken to reach maturity for SC709
Current climate	137.75^{a}	160.11^{c}
Future climate 1	114.79^{b}	130.61^{d}
Future climate 2	115.21^{b}	131.18^{d}

1. Comparisons are within variety. 2. Means with the same letter within variety, are not significantly different from each other (p>0.05)

The reduction in number of days to physiological maturity, under climate change exhibited by both the short and long season varieties is consistent with trends established by other researchers (e.g. Tao *et al.,* 2006; Challinor and Wheeler, 2008; Dimes *et al*., 2008; Shively, 2008; Gordo and Sanz, 2010; Ma *et al*., 2012; Wang *et al*., 2011). Shively (2008) for example, estimated that the number of days to reach physiological maturity for maize would be reduced by 5-10 days by 2050 for Indiana (U.S.A). The reduction in number of days to maturity for maize, of 17 and 18% (corresponding to a reduction of 23 and 29 days for the short and long season variety respectively) obtained in this study, is consistent with the estimated reduction in days to maturity for a short season maize variety grown at Bulawayo (south west of Zimbabwe) by 2050 (Dimes *et al*., 2008). Both future climates considered in this study have the same temperature change magnitude (+3.0 ^{o}C), hence one expected the same number of days to maturity (about 115 and 131 days for the short and long season varieties, respectively) for each variety under the two climate change scenarios.

The main reason for reduced days to maturity under climate change is increased temperature which hastens growth and development of the crop. Increased temperature advances the onset and reduces duration of phenological stages such as unfolding of leaves, flowering and fruiting stages (Gordo and Sanz, 2010), thereby shortening the crop growing season (Rosenzweig and Liverman, 1992; Wang *et al*., 2011). The resultant effect is less time available for CO_2 assimilation resulting in less total CO_2 assimilated during the growing season and reduced dry matter accumulation. A rise in mean daily temperature was found to reduce maize yield by 16% in central U.S.A (Brown and Rosenberg, 1997), while yield of wheat decreased by 10% for every a 1^{o}C rise in mean seasonal temperature (Mitchel *et al*., 1993 cited in Da Matta, *et al*., 2010). The greatest temperature effect on grain crop yield is during the flowering (when the number of grains per ear, in the case of cereal crops is determined) and grain filling (when the weight of the grain is determined) stages (Challinor and Wheeler, 2008; Da Matta *et al*., 2010). In addition to causing a reduction in crop yield, hastened crop maturity due to increased temperature is also often associated with reduced quality of crop products, for example decreased protein and mineral content (Da Matta *et al*., 2010). Thus, for human populations that rely on crop products for their diets, health may be compromised by climate change, through malnutrition. However, early maturity may have some benefits for example, it could enable production of more than one crop in one season, where soil water is not limiting e.g. under irrigation. It also allows early availability of food, before farming households run out of food stocks from previous season's harvest. Effects of shortened crop growth cycle due to increased temperature may be reduced by breeding for varieties that are tolerant to high temperatures. For farmers in the study area, shifting from the currently grown short season maize varieties to long season varieties may improve yields, under climate change conditions (as shown in Fig. 5.7a).

5.3.4. Effect of climate change on soil water balance components

Simulated soil water balance components were considered under production of the currently grown maize variety, SC403. The soil water balance components considered were available soil water at sowing, seasonal soil evaporation, transpiration, seasonal runoff and seasonal drainage.

5.3.4.1 Available soil water at sowing (extractable soil water at sowing - sow_esw)

Characteristics of simulated available soil water at sowing (sow_esw)

Although the same sowing criterion of 20mm of rainfall received in 5 consecutive days, was used for all climate scenarios, average extractable soil water at sowing (sow_esw) (for whole soil profile) was tracked to establish the exact amount of soil water accumulated at sowing under the different climates. Median sow_esw for current climate is higher than that for climate change, with the two future climates showing slightly different medians (Fig. 5.16). For all three climate scenarios, there are extractable soil water amounts that fall outside the upper normal range of values (outliers) (Fig. 5.16). The inter-quartile ranges for current climate and future climate 1 are almost equal implying similar variability in sow_esw under these climates (Fig. 5.16). The standard deviation for sow_esw also shows that variability in sow_esw is about the same under current climate and climate change (Future climate 1 and Future climate 2) (Fig. 5.17). Data for all three climates are skewed towards the lower range values of available soil water at sowing.

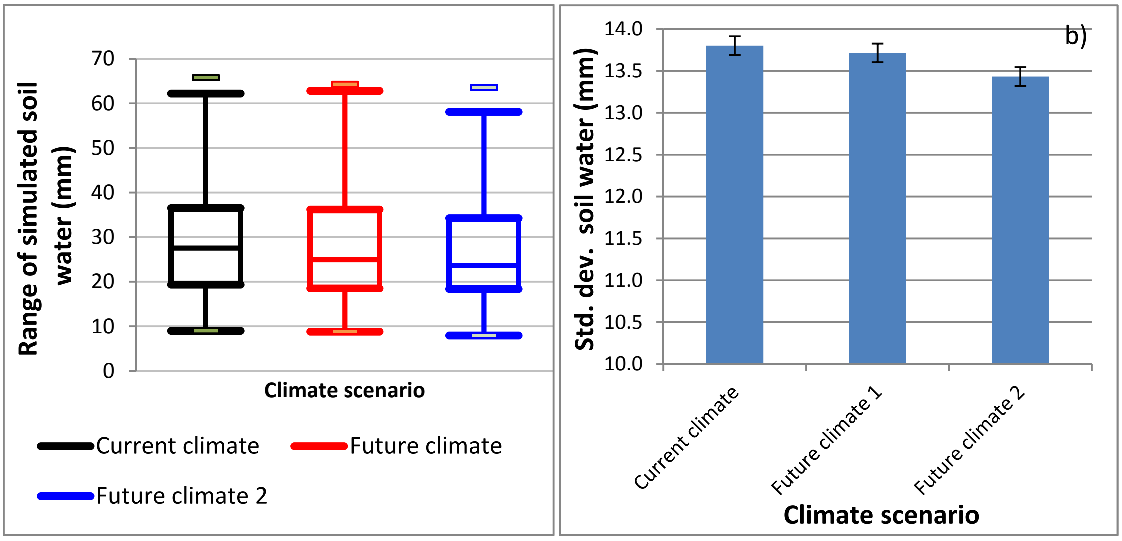


Fig. 5.16 a) Simulated total available soil water and b) standard deviation for soil water available at sowing for SC403 grown at Lower Gweru under current and future climate change

Mean comparison of available soil water at planting (sow_esw) under current climate and climate change

Although the criteria for sowing was the same for all three climate scenarios (at least 20mm accumulated in 5 days), the actual amount of extractable soil water (sow_esw) at sowing was 29.7 mm, 27.3mm and 26.4 mm under current climate, Future climate 1 and Future climate 2, respectively (Fig. 5.17). Thus, climate change slightly reduced sow_esw with greater reduction (11%) occurring under a drier climate (Future climate 2) than under a less dry one (Future climate 1) which results in 8% reduction.

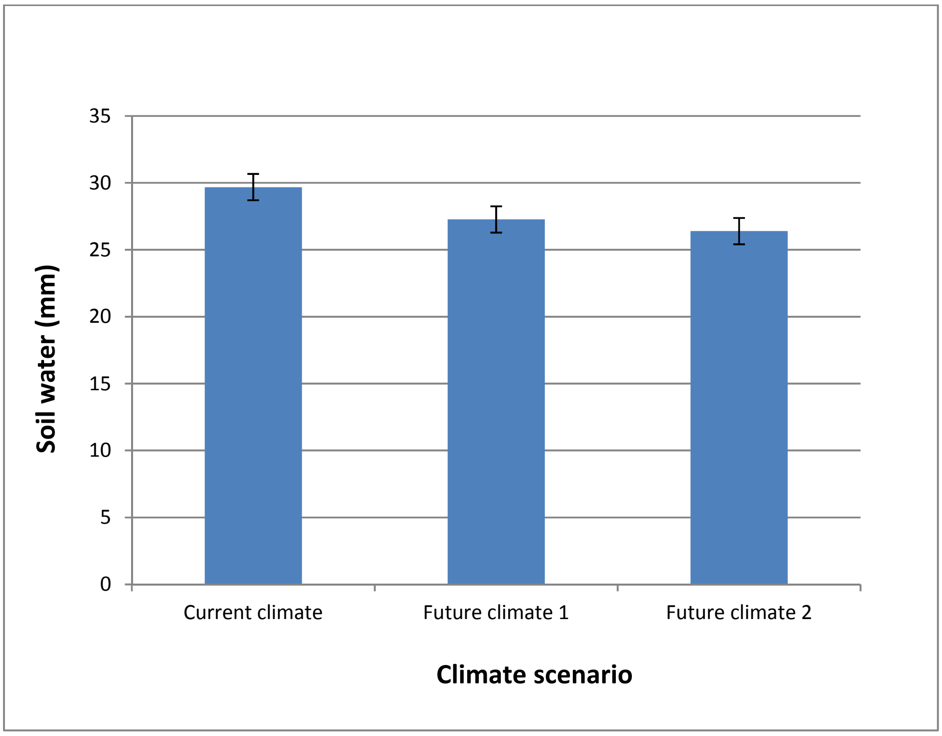


Fig. 5.17. Simulated average soil water available at sowing under current climate and climate change for SC 403 grown in Lower Gweru

Data on available soil water at sowing (sow_esw) are normally distributed for Future climate 1 ($p<0.05$), but not normally distributed for current climate and Future climate 2 ($p>0.05$) (Table 5.11). The non-parametric test, Kruskal-Wallis test was used to test for significant differences in sow_esw, among the different climates. There are slight differences in soil water available at sowing, between current climate and climate change ($p=0.502$) (Table 5.12).

Table 5.11. Test for normality of data for available soil water at planting under different climate scenarios

Climate	Kolmogorov-Smirnov		
	Statistic	df	Significance
Current climate	0.156	28	0.079
Future climate 1	0.165	28	0.048*
Future climate 2	0.163	28	0.054*

* Significant ($p< 0.05$)

Table 5.12. Test statistics for testing significant differences in sow_esw between current climate and climate change (Kruskal-Wallis test)

Chi- Square	1.379
Df	2
Significance	0.502

Grouping variable is climate

Lack of significant differences among the three climates is expected, since planting was set to occur at the first opportunity when at least 20 mm of water accumulated in the soil in 5 days, with the earliest planting set to occur on 15 November and the latest on 15 January. Thus, the amount of available soil water at sowing should be more or less similar irrespective of climate scenario. Predicted sowing dates were similar for the three climate scenarios, with approximately 75% of the simulated sowing dates falling within the period mid to end of November, while 25% of the sowing dates fell during the first and third dekads of December (data not shown). These results suggest that by 2050, climate change may not alter timing of the start of the season. Contrary to these results about 67% of farmers in the study area (Lower Gweru) claimed that they had observed late start to the season in the past 5-10 years, during a survey conducted during 2008 (Mubaya, 2010), However, farmers' perception of delayed start to the season are not consistent with trends in historical records, as no significant change was noted in start of the growing season (Murewi *et al*, 2012).

5.3.4.2. Simulated seasonal soil evaporation, transpiration and evapotranspiration

Characteristics of simulated seasonal evaporation and transpiration data

The median values for both simulated soil evaporation and transpiration are higher under current climate than under climate change (Fig. 5.18a). The median soil evaporation values for the two future climates are almost similar, being 169.5 and 167.8 mm for the less dry climate (Future climate 1) and for the drier climate (Future climate 2), respectively (Fig. 5.18a) compared to that of the current climate which stands at 186.5 mm/season. Median transpiration rates show a similar pattern to that of soil evaporation with current climate, Future climate 1 and Future climate 2 having values of 107, 100 and 98 mm/season respectively (Fig. 5.18a). Thus both soil evaporation and transpiration decline for a sandy soil and short season variety SC403 in Lower Gweru, under climate change. There is greater year to year variability under current climate than under climate change, for both soil evaporation and transpiration as indicated by the standard deviations for these simulated parameters (Fig. 5.18b). The standard deviations under current climate are 34.4 and 27.2 mm/season for evaporation and transpiration, respectively, while the lowest deviations are those for Future climate 2 which are 30.9 and 26.0 mm/season respectively. The differences in standard deviation between Future climate 1 and 2 are minimal for both parameters being 0.3 and 0.2 mm for evaporation and transpiration, respectively. Thus generally, under climate change, rates of soil evaporation and transpiration can be predicted more accurately than under current climate.

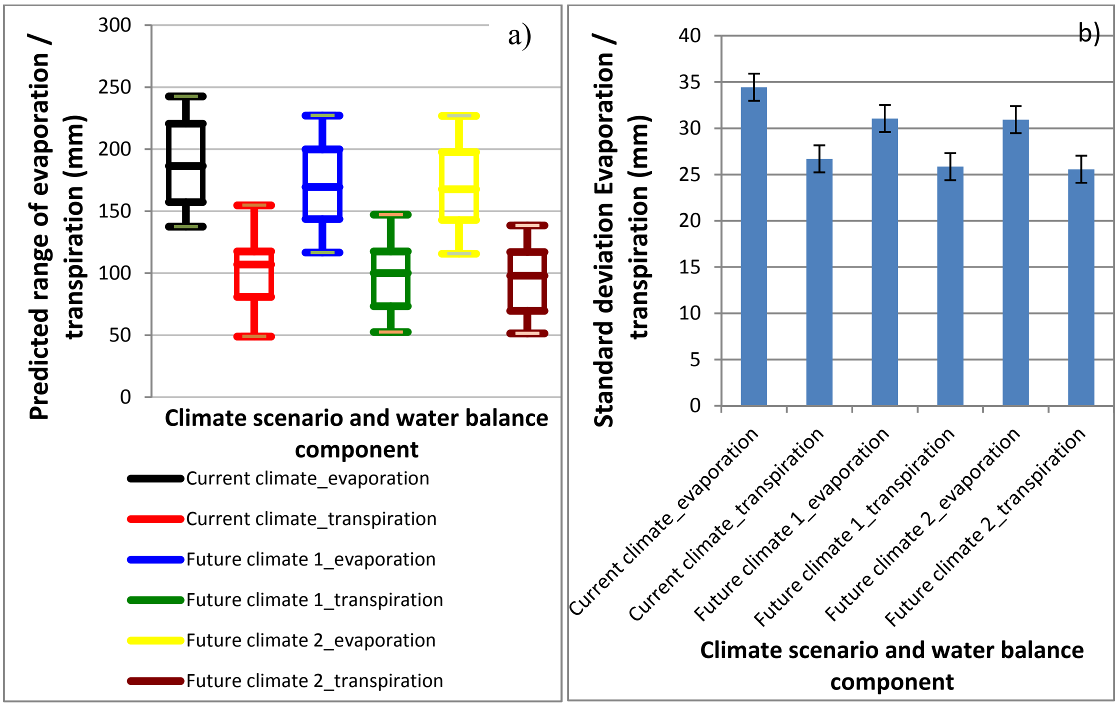


Fig. 5.18 a) Simulated seasonal evaporation and transpiration and b) standard deviation for simulated evaporation and transpiration for maize variety SC403 grown on a sandy soil in Lower Gweru

Mean comparison of simulated seasonal soil evaporation and transpiration under current climate and climate change

The amount of seasonal evaporation from a sandy soil planted to the early maturing maize variety SC403 is about 10% higher under current climate than under climate change (Fig. 5.19). The mean seasonal transpiration for maize variety SC403 was highest under current climate (Fig. 5.19), being about 102.3 mm. Under climate change, the amount of water transpired by the crop is reduced by 5% and 8% under the less dry (Future climate 1) and more dry (Future climate 2) climate change scenarios, respectively (Fig. 5.19).

Except for evaporation simulated under current climate all other simulated evaporation and transpiration data for the three climate scenarios are not normally distributed (p>0.05) (Table 5.12). A non-parametric test (Kruskal Wallis test) was thus, used to test for significant differences among simulated seasonal evaporation and seasonal transpiration under the three climates. Results of the test show significant differences in mean evaporation and in transpiration simulated under the different climate scenarios at p=0.08 and p=0.656, respectively for soil evaporation and transpiration (Table 5.13).

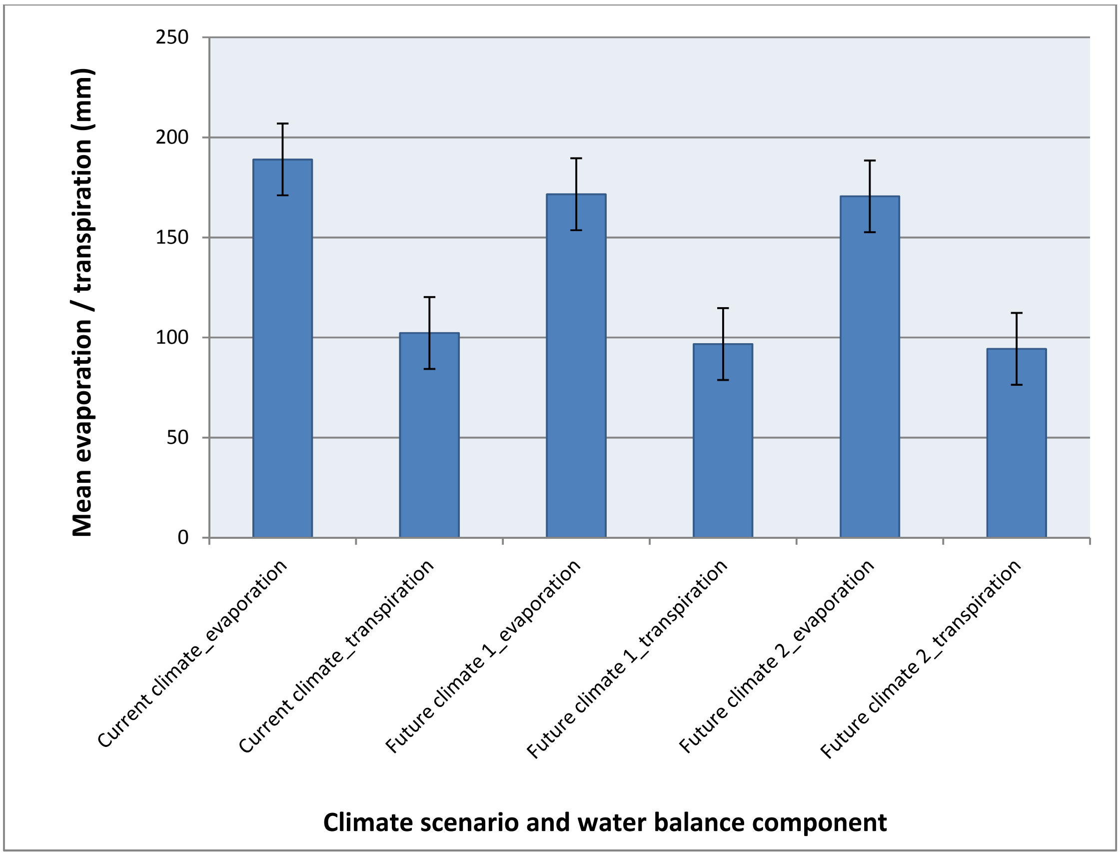


Fig. 5.19. APSIM simulated mean seasonal evaporation and seasonal transpiration from SC403 maize variety grown on a sandy soil in Lower Gweru, under current climate and climate change conditions

Mean comparison simulated seasonal evapotranspiration, under current climate and climate change

APSIM simulates seasonal soil evaporation and crop transpiration. In this study the amount of seasonal evapotranspiration (ET) was obtained by summing up amounts of soil evaporation and transpiration per season. Both soil evaporation and transpiration are higher under current climate than under climate change (Fig. 5.19) and correspondingly, ET which comprises approximately 35% water loss through transpiration and 65% through evaporation from the soil, is higher under current climate than under climate change (Fig. 5.20). Climate change reduces ET by 8 and 9%, respectively for the less dry climate and drier climate change scenarios (Fig. 5.20). Simulated ET data are normally distributed for Future climate 2 ($p=0.041$), but are not normally distributed for current climate and Future climate 1 ($p>0.05$) (Table 5.13), hence the non-parametric test, Kruskal Wallis test for independent samples was used to test for differences among ET means under the three climate scenarios. Significant difference in simulated ET among the three climates occur at $p=0.108$) (Table 5.14).

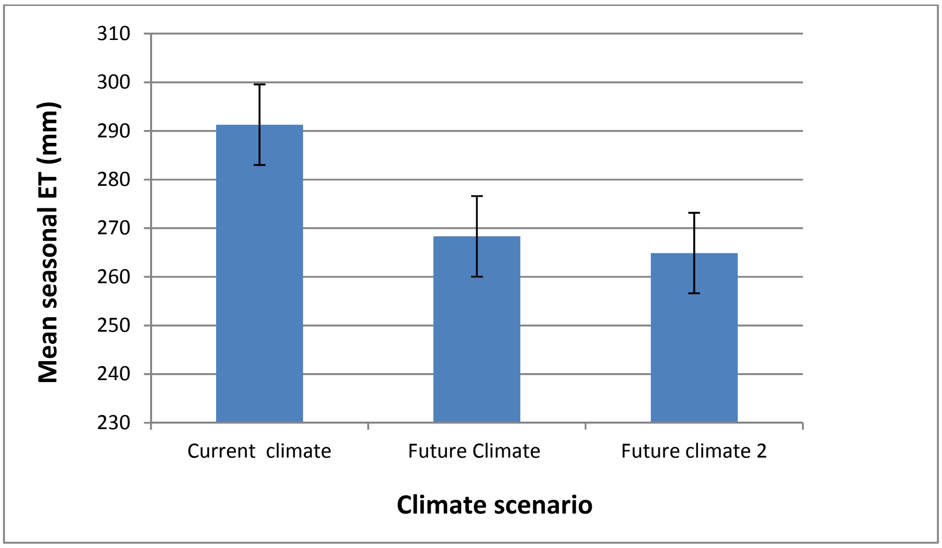


Fig. 5. 20. Simulated evapotranspiration under current climate and climate change for a sandy soil and maize variety, SC403 grown at Lower Gweru

Table 5.13. Kolmogorov_Smirnov test for normality of simulated evaporation, transpiration and evapotranspiration data

Climate	Kolmogorov-Smirnov		
	Statistic	**df**	**Significance**
Seasonal evaporation			
Current climate	0.166	28	0.046*
Future climate 1	0.138	28	0.181
Future climate 2	0.129	28	0.200
Seasonal transpiration			
Current climate	0.098	28	0.200
Future climate 1	0.131	28	0.200
Future climate 2	0.149	28	0.115
Seasonal evapotranspiration			
Current climate	0.163	28	0.055
Future climate 1	0.154	28	0.088
Future climate 2	0.168	28	0.041*

*Normally distributed data ($p<0.05$)

Table 5.14. Test statistics for significant differences in simulated seasonal evaporation, transpiration and evapotranspiration under current climate and climate change (Kruskal-Wallis test)

	Seasonal evaporation	Seasonal transpiration	Seasonal evapotranspiration
Chi- Square	5.045	0.845	4.453
Degree of freedom	2	2	2
Significance.	0.080	0.656	0.108

Grouping variable is climate

The projected temperature increase of 3^{o}C by 2050, used in this study to simulate water balance components under climate change, provides possibility for increased soil evaporation, transpiration and therefore ET. However, simulated mean values for these water balance components show a decline from the current climate, although the % reductions are not statistically significant at $p\leq0.05$. The reduction in soil evaporation under climate change could be constrained by limited amount of water in the soil under climate change conditions compared to the current climate, since climate change scenarios used in this study comprised a reduction in rainfall of 10% (Future climate 1) and 15% (Future climate 2). Soil evaporation was also simulated under a sandy soil and this reduces the amount of water available for evaporation due to the low water holding capacity of the soil. These explanations (effect of reduced rainfall and low water holding capacity soils) are backed by, for example, Wegehenkel and Kersebaum (2009)'s findings that the regions in the Ucker catchment in north east Germany which showed a decline ET under climate change, were those which had a higher reduction in precipitation and soils with lower water storage capacity. The effect of soil water availability on actual rate of evaporation from land surfaces is also highlighted by Allen *et al*. 1998; IPCC, 2007a; Harmsen *et al*., 2009; Centre for Ecology and Hydrology, Natural Environment Research Council (CEH) (undated).

The potential increase in evaporation due to increased temperature, under climate change could also have been offset by other climatic variables for example, wind speed, amount of water in the atmosphere and radiation (Wang *et al*., 2006; IPCC, 2007a; Badawy, 2009; Moratiel *et al*., 2010; Snyder *et al*., 2011). However, in dry regions, such as the study area, humidity may have a limited influence on rate of evaporation (IPCC, 2007a; Badawy, 2009). The amount of soil evaporation from a cropped area also depends on the crop characteristics, particularly with regards to the amount of radiation that crop canopy allows to get through to the soil (Allen, *et al*., 1998). Centre for Ecology and Hydrology, Natural Environment Council (undated) also points out that large plant surfaces may intercept rainfall before it gets to the soil underneath, thereby reducing the amount of soil water and therefore amount of soil evaporation. Climate elements namely temperature, wind and relative humidity which control evaporation are also affected by climate change, thereby making it difficult to predict the effect of climate change on evaporation. In modelling the effect of climate change on the water balance, in this study, effect of wind and relative humidity were not factored in.

Similar to soil evaporation, there is a potential for increased transpiration due to an increase in temperature, under climate change. However, results from this study show a decrease (though not statistically significant) of 5-7% in transpiration rate from the short season maize variety SC403 grown on a sandy soil at a density of 30 000 plants/ha, under climate change. The most probable reason for the reduction in transpiration under climate change is the shorter crop duration under this climate scenario compared to under the current climate. It was established in section 5.3.3.2 of this thesis that the number of days taken by maize to reach physiological maturity under climate change decreased by 23-29 days depending on variety. The decrease in amount of transpiration could also emanate from increased stomatal resistance to water loss, due an increased CO_2 concentration under climate change. In this study the two climate change scenarios used comprise a CO_2 level of 532ppm compared to 370ppm used for baseline simulations. Several authors including IPCC (2007a), Ge *et al*. (2013) and Snyder *et al*. (2011) have reported decreases in ET rates under climate change and attributed this to reduction in stomatal conductance due to increased CO_2 concentration. Studies on effect of elevated CO_2 on growth of agricultural crops (e.g. Kimball, 2002; Li *et al*., 2004; Qiao *et al*., 2010) have also established that stomatal conductance is reduced, under elevated CO_2 concentration leading to reduced transpiration. Similar to soil evaporation, climatic factors such as wind speed, amount of radiation and humidity can modify the effect of temperature on rate of transpiration. Whereas in this study, climatic factors such as wind speed may have off-set temperature effects of increasing evaporation, transpiration and therefore ET, these factors may lead to overestimation of temperature effects in other situations (Badawy, 2009). The influence of these climatic factors varies with geographical location and time of the year (IPCC, 2007a; Badawy, 2009).

A decrease in ET reduces crop water requirements per unit of dry matter produced by the crop, thus increasing the water use efficiency of the crop. WUE has been found to increase under elevated CO_2 concentrations and water stressed environments (e.g. Kimball, 2002; Li *et al*., 2004; Ghannoum, 2009; Qiao *et al*., 2010).

Due to wide variation in methods that have been used to estimate effects of climate change on ET or evaporation from land and/or water surfaces by different researchers for different geographical locations comparing results from this study with specific results from other research work is difficult.

5.3.4.3. Simulated seasonal runoff

Characteristics of simulated seasonal runoff data

Median seasonal rainfall under current climate is higher than that under climate change, with the drier climate (Future climate 2) having a lower median than the less dry climate (Future climate 1) (Fig. 5.21a), suggesting the possibility of reduced runoff under climate change. Inter-quartile ranges (Fig. 5.21a) and standard deviations (Fig. 5.21b) indicate that there is more variability in seasonal runoff under current climate than under climate change. Thus, under climate change, amount of seasonal runoff can be predicted with greater certainty than under current climate. Seasonal runoff prediction for all three climates is skewed towards the lower runoff range.

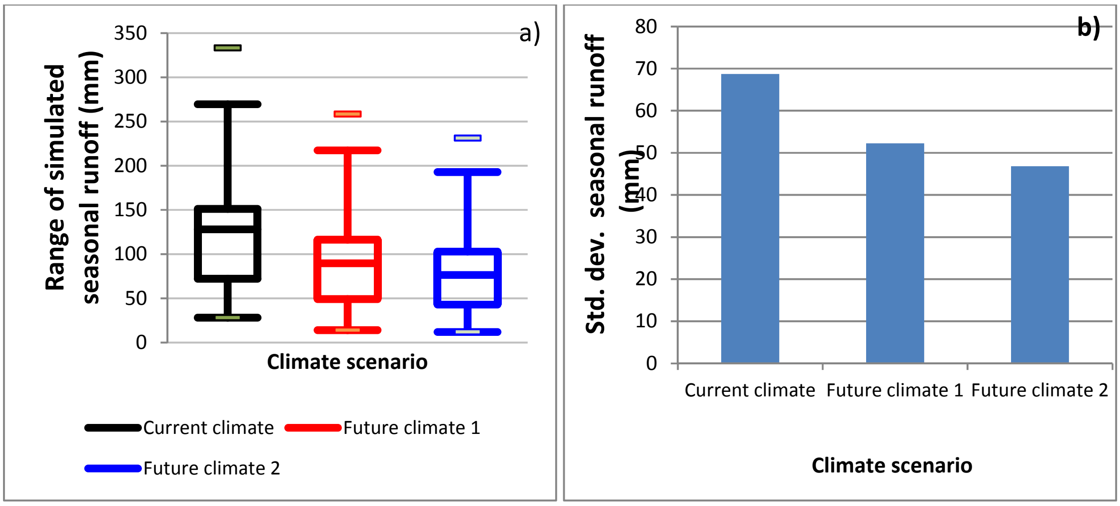


Fig. 5.21. a) Box and whisker plot and b) standard deviation for seasonal runoff under current climate and climate change, predicted under maize cultivation with APSIM

Mean comparison of seasonal runoff under current climate and climate change

Seasonal runoff is reduced by 28% from 132 mm under current climate to 94.7 mm under the less dry climate change scenario (Fig. 5.22). A greater reduction of 38% in seasonal runoff occurs under the drier climate change scenario (Future climate 2) (Fig. 5.22). Seasonal runoff data are not normally distributed ($p>0.05$) (Table 5.15), hence use of a non-parametric test to test for significant differences in runoff among the different climates. Test statistics from Kruskal-Wallis test show that there are significant differences in amount of runoff among the different climates ($p=0.010$) (Tables 5.16). Seasonal runoff under current climate is significantly greater than runoff under both future climates ($p<0.05$) (Table 5.17 & 5.18). The difference in amount of seasonal runoff between the two future climates is significant at p=0.258 (Table 5.17) The null hypothesis that there is no significant difference in seasonal runoff under current climate and climate change can therefore be rejected. Reduction in amount of runoff under climate change is most likely due to reduced rainfall amount under these climate scenarios.

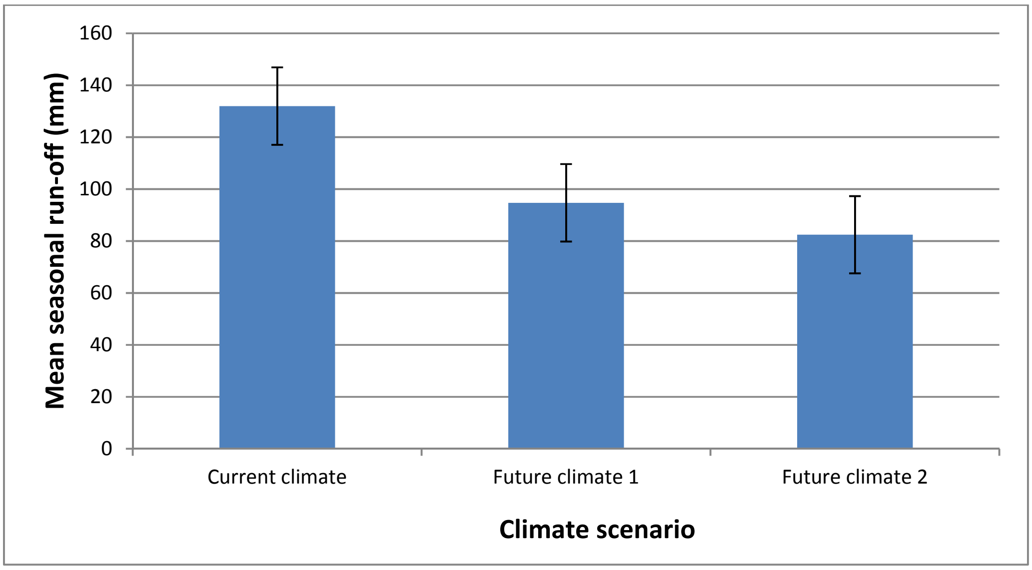


Fig. 5.22. APSIM **s**imulated mean seasonal runoff under current climate and climate change for a sandy soil cropped to maize in Lower Gweru

Table 5.15. Kolmogorov-Smirnov test for normality of data for simulated seasonal runoff

Climate	Kolmogorov-Smirnov		
	Statistic	df	Significance
Current climate	0.121	28	0.200
Future climate 1	0.132	28	0.200
Future climate 2	0.129	28	0.200

Table 5.16. Test statistics for significant differences in seasonal runoff between current climate and climate change (Kruskal-Wallis test)

Chi- Square	9.163
Df	2
Significance.	0.010*

Grouping variable is climate

Table 5.17. Test statistics for significant differences in seasonal runoff between different pairs of climates (Mann-Whitney test)

Compared climates	Statistic	Z	Asymptotic sig.(2-tailed)
Current climate vs. Future climate 1	261.00	-2.147	0.032*
Current climate vs. Future climate 2	221.00	-2.802	0.005*
Future climate 1 vs. Future climate 2	323.00	-1.131	0.258

* Significant difference

Table 5.18. Mean comparison of simulated seasonal runoff under current climate and climate change

Climate Scenario	Mean seasonal runoff (mm)
Current climate	132.00[a]
Future climate 1	94.73[b]
Future climate 2	82.43[b]

Means with the same letter are not significantly different from each other ($p>0.05$).

Many studies have shown that runoff is positively related to rainfall (e.g. Arnell, 1999; Desanker and Magadza, 2001; Wilk and Hughes, 2002; Arnell *et al*., 2003; Boko *et al*, 2007; Love, *et al.,* 2010; Chiew *et al.,* 2009; Mango *et al*., 2011; Teng *et al.,* 2012) and that the relationship is non-linear (Arnell *et al*., 2003; Mango *et al*., 2011). Global responses of runoff to changes in rainfall, under climate change vary depending on whether rainfall amount and intensity are expected to increase or decrease. In temperate regions, the degree of melting of glaciers due to increased temperatures under climate change will also determine the amount of runoff. According to IPCC (2007b) runoff will increase under climate change in high latitude areas and in equatorial Africa and Asia as well as in south east Asia, while in mid-latitude areas and most subtropical regions, runoff will decline. Barrios *et al*. (2008) highlight the high sensitivity of runoff to changes in rainfall amount in arid and semi-arid regions. The 28-38% reduction in runoff under a drier future climate (10-15% reduction in rainfall amount) obtained in this study is consistent with the pattern in runoff established from other studies in most parts of Africa, including Southern Africa and Zimbabwe. Examples include a reduction in runoff of about 50% predicted with a rainfall reduction of 10% across southern Africa (Reibsame, 1989 cited in Barrios *et al*., 2008) and a reduction of 26-40% from a decline in rainfall of 10-25% for the Zambezi river basin (Arnell, 1999). For Zimbabwe, national annual runoff is projected to decrease by 50% by 2075 when rainfall is projected to decrease by 15-19% and potential evapotranspiration to increase by 7.5-13.0 % (Ministry of Mines, Environment and Tourism in Zimbabwe, 1998b). For the upper Limpopo basin in Zimbabwe, Love *et al*. (2010) found a good correlation between rainfall and runoff for some discharge stations in the western part of the river basin. Results in that study as well as those from other studies, show that percentage change in runoff is much more than the associated percentage change in rainfall and as suggested by Arnell *et al.* (2003), this scenario implies that the cause for reduction in runoff is not reduced rainfall alone.

Differences in magnitude of the changes in runoff between findings in this study and other studies are likely to be due to the scale of investigation. While results from this study are based on a relatively small grid block representing one meteorological station, results for the other studies are based on river basins, national and regional scales, where data for several meteorological stations are considered. Differences could also be due to differences in climate change scenarios used in projecting runoff and the absolute amounts of rainfall involved. Magnitude of runoff will also depend on factors such as soil type, land characteristics e.g. slope and land use.

Amount of runoff has implications on water availability in water resources storage facilities such as dams and rivers, with reduced runoff leading to lower availability. River flows are sensitive to changes in rainfall (Desanker and Magadza, 2001) and reduced runoff may lead to cessation of seasonal streamflows as noted for Zimbabwe by Magadza (2000). Thus, under climate change, increased water shortages for various uses, including agriculture (irrigation, livestock and fisheries) and human consumption are expected in the study area. Similar effects are expected in other areas of Zimbabwe and in other parts of Africa where climate change is characterized by, among other changes in climatic variables, a significant reduction in rainfall. Quality of water is likely to deteriorate under reduced runoff conditions due to low dilution of pollutants by low water flow (Jacobs *et al*., 2000). Poor water quality may have implications on productivity of irrigated crops as well as on livestock and human health.

Effects of reduced runoff are largely negative, particularly with respect to availability of surface water, which is the main source of water, accounting for 90% of the water used in

Zimbabwe (Brown *et al*., 2012). However, reduced runoff will reduce soil erosion, although as suggested by Varallyay (2010), this may increase wind erosion. Reduced soil erosion reduces amount of nutrient losses that may occur from crop fields, while general land degradation and siltation of water sources such as rivers and dams will be minimized.

Results from this study show that climate change will worsen the water scarcity situation in the study area. Therefore, there is need for judicious use of this scarce resource, for example use of efficient irrigation technologies (e.g. as suggested by Karrou and Oweis, 2010), use of crops with low water requirements and recycling of water (e.g. Durham *et al*., 2005; Heinz *et al*., 2011). Reduced water availability also calls for adoption of water harvesting technologies at both macro (large catchment) and micro (e.g. crop field) levels (e.g. Mupangwa *et al*., 2006; Oweis and Hachum, 2006; Ibraimo and Munguambe, 2007; Ibraimo, 2009; Ali *et al.*, 2010; Karrou and Oweis, 2010; Bunclark and Lankford, 2011; Tesfuhuney, 2012; Tesfuhuney *et al*., 2013). Issues of the likely reduced water quality, under climate change will also need to be addressed.

5.3.4.4. Simulated seasonal drainage

Characteristics of simulated seasonal drainage

The median drainage under climate change (Future climate 1 and 2) is lower than that under current climate (Fig. 5.23a) suggesting less drainage under climate change than under current climate. Under both current climate and climate change drainage can get to zero in certain seasons (Fig. 5.23a). The inter-quartile range (Fig. 5.23a) and the standard deviation (Fig. 5.23b) is higher under current climate than under climate change implying less variability in drainage under climate change. The variability is less under the drier (Future climate 2) climate change scenario than the less dry one (Future climate 1). Less variability under climate change implies that drainage could possibly be predicted with greater certainty under this climate scenario than under current climate.

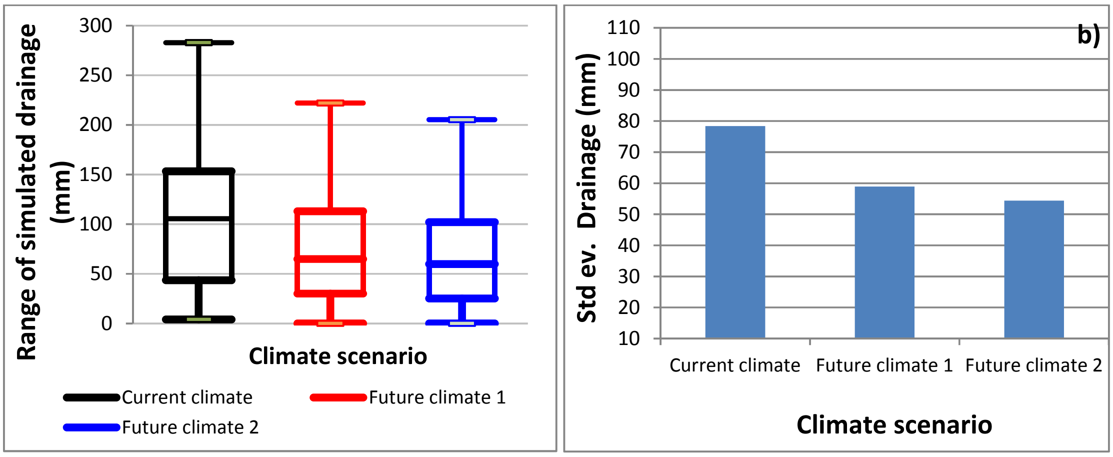


Fig. 5.23 a) APSIM simulated seasonal drainage and b) standard deviation for simulated seasonal drainage under current climate and climate change for a sand soil in cropped to maize in Lower Gweru

Mean comparison of seasonal drainage under current climate and climate change

Seasonal drainage is reduced by 28% and 36% from 109.4mm, respectively, under the less dry climate change scenario(Future climate1) and the drier scenario (Future climate 2) (Fig. 5.24). Seasonal drainage data are not normally distributed (p>0.05) (Table 5.19). Results from the Kruskal-Wallis test used to test for differences among drainage means from the different climate scenarios, show that significant differences in drainage among the three climate scenarios occur at p=0.112 (Table 5.20).

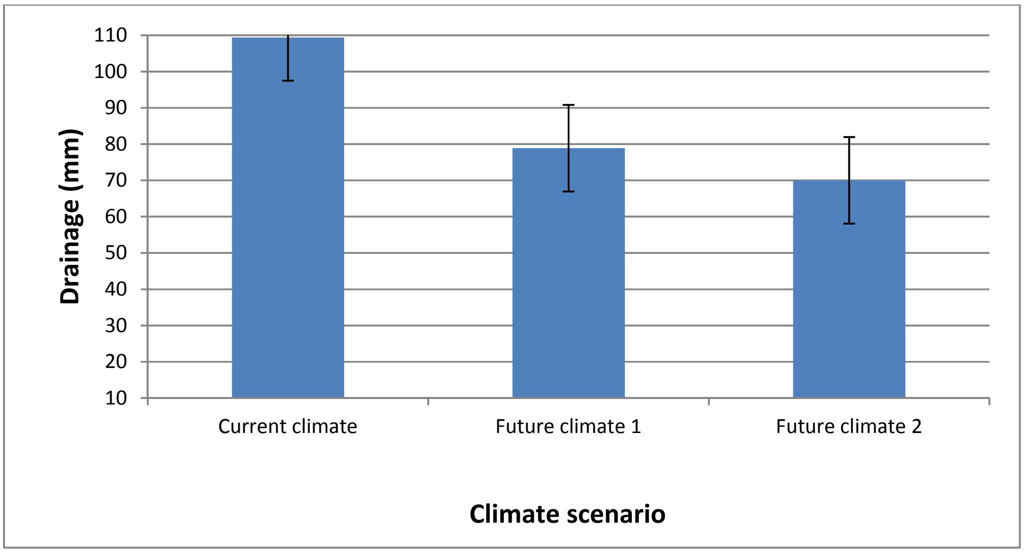


Fig. 5.24. Simulated mean seasonal drainage under current climate and climate change for a sandy soil in Lower Gweru

Table 5.19. Kolmogorov-Smirnov test for normality of data for simulated seasonal drainage under different climate scenarios

Climate	Kolmogorov-Smirnov		
	Statistic	df	Significance
Current climate	0.145	28	0.137
Future climate 1	0.114	28	0.200
Future climate 2	0.099	28	0.200

Table 5.20. Test statistics for significant differences in simulated drainage between current climate and climate change (Kruskal-Wallis test)

Chi- Square	4.378
df	2
Significance.	0.112

Grouping variable is climate

The reduction in seasonal drainage under climate is most probably due to reduction in rainfall amount. Similar to rainfall-runoff relationships, past research work has shown that drainage and rainfall are positively correlated (e.g. Verburg and Bond, 2003; Watson *et al*., 2004; Conway, 2009). The study area receives about 650mm of annual rainfall on average and the 28% and 36% reduction in drainage due to a reduction of 10% and 15% in rainfall (65 mm and 100 mm reduction) respectively, obtained in this study is consistent with the estimated reduction in drainage for the 400-1000 mm annual rainfall zone of Africa. For this zone, which covers Zimbabwe and therefore the study area, a reduction from 500 mm to 450 mm (10 mm or 10% reduction) is estimated to reduce drainage by 50%, whereas a reduction from 600 mm to 550 mm (10 mm or 8% reduction) results in a 25% reduction in drainage (Conway, 2009). Thus for the same reduction in rainfall amount, a greater reduction in drainage occurs in an area which receives lower rainfall than in one which receives higher rainfall. Amount of drainage will also depend on the water holding capacity of the soil and for sandy soils, which are characteristic of soils in the study area, higher drainage is expected than for heavier soils.

A decline in drainage water may lead to accumulation of salts in the crop root zone (Ayers and Westcot, 1985; McCauley and Jones, 2005) due to inadequate water to leach off salts from this zone (McClauley and Jones, 2005; Timms *et al*., 2012). This is, however, likely to be the case in areas where water tables are shallow. Under saline conditions there is reduced water uptake by crops as more energy would be needed to extract water compared to non-saline conditions (Ayers and Westcot, 1985; Brady and Weil, 2002; McClauley and Jones, 2005). The net effect of saline soil conditions is poor crop growth, wilting or even death of crops (Balba, 1995; Brady and Weil, 2002; McCauley and Jones, 2005). In future farmers cropping fields with shallow water tables may have to grow crops and /or varieties that are less sensitive to saline conditions for example sorghum (Hanson *et al.,* 2006) which is already being grown in the drier parts of the country, including parts of the study area. A reduction in drainage water reduces groundwater recharge (Watson *et al*., 2004; Timms *et al*., 2012) and results in lower riverflows (Conway, 2009). Thus reduced drainage reduces amount of water available for agricultural purposes as well as other uses such as human consumption. Low recharge of groundwater keeps the water table low, making it expensive to draw up water for irrigation and other purposes. However, reduced drainage may be beneficial, due to reduced possibility of nutrient leaching from crop root zone. Other factors, remaining unchanged, reduced drainage will result in more water being available in the root zone of crops.

5.4. Conclusion and Recommendations

5.4.1. Sensitivity analysis

Small temperature increases of 0.5-1.5^{o}C from the current temperature have positive effects on grain yield of the maize crop at high CO_2 concentrations, but reduce yield at lower CO_2 concentrations. Thus temperature effects on grain yield may be off-set by increased atmospheric CO_2 concentration. The highest yield reduction of 14% occurs at the lowest CO_2 concentration of 420ppm (an increment of 50ppm, from the current concentration) and at the highest temperature shift of +3.5^{o}C from current temperature.
An increase in rainfall amount of 5% from the current climate increases maize grain yield at all CO_2 concentrations, with greatest yield benefit of 12% being obtained at the highest CO_2 level of 700ppm. A reduction in rainfall amount generally reduces grain yield, with reductions starting to occur at greater rainfall reduction for higher CO_2 concentrations and at lower reductions for lower CO_2 concentrations. For example, yield drops below baseline level at -5% rainfall for CO_2 concentration of 420ppm, whereas for 700ppm,

yield only drops below baseline yield at -20% rainfall. Thus, under drought stress conditions, higher yields can be obtained at higher CO_2 concentrations than at lower CO_2 concentration. This supports the findings by several researchers that an enhanced CO_2 atmosphere will benefit plants more under water stress conditions. The yield benefits that accrue from an enhanced CO_2 atmosphere are clearly demonstrated by the yield increases from baseline, obtained in the absence of changes in rainfall and temperature. The relatively low yield increases of 1.4 -10%, from baseline, obtained at 420 -700ppm are comparable with yield increases for C4 crops cited in literature. Higher yield increases due to CO_2 fertilization have been reported for C3 crops instead. Combined temperature and rainfall effects on maize yield show that for a combination of high temperature increases (2.5-3.5^{o}C) and high percentage reduction (10-20%) in rainfall amount, positive effects of CO_2 on yield are offset, particularly at lower CO_2 concentrations. It appears that increase in temperature and decrease in rainfall, under climate change will have an almost similar effect on maize grain yield.

5.4.2. Climate change effect on maize yield

Climate change reduces all maize yield components (grain, stover and biomass) for both short season (about 140 days from sowing to maturity) and long season (about 160 days to maturity). Grain yield is reduced by 13-16% for both maize maturity groups, while stover yield is reduced by 13 and 21% and biomass accumulation by 13 and 19% for short and long season varieties, respectively. The probability of yield not exceeding a given value is always higher under climate change than under current climate, indicating less risk of getting lower yields under current climate than under future climate. However, except for stover yield of the long season variety, the decline in yield due to climate change is not statistically significant at $p \leq 0.05$. The decline in yields could, however, have significant economic implications. Beyond, 2050 reductions in grain and biomass yields are likely to become significant since future climate is expected to get drier and hotter, for the southern African region, which includes Zimbabwe. Although maize yields decline under climate change, they are less variable compared to what they are currently and thus they can be predicted with more certainty in future.

Reduced crop yields due to climate change will reduce food and nutrition security of smallholder farmers in Lower Gweru and other parts of Zimbabwe. Maize stover, which is an important livestock feed during the dry season will also be less available in future due to climate change. Farmers may cope and/or adapt to the reduced crop yields by reducing the area planted to maize or the currently grown varieties. Expansion of irrigation schemes and breeding of crop varieties that are tolerant to drought and heat stress will also cushion farmers from effects of climate change. Since cropping is more sensitive to a dry and hot climate, than livestock production, farmers may also invest more in livestock, particularly small stock production, in future. Instead of relying largely on agriculture, as they currently do, smallholder farmers need to exploit and/or strengthen other forms of livelihoods.

In this chapter effects of change in the long-term mean climate conditions on smallholder maize crop productivity were established. However, under climate change, the frequency and intensity of extreme weather events such as drought and floods are expected to increase. Thus farmers in the study area and other parts of the country will likely experience the severe negative impacts of these weather events which include damage and /or destruction of crops and livestock as well as infrastructure, more frequently in future than they are experiencing currently. Thus strategies to deal with these extreme climate events need to be strengthened.

5.4.3. Climate change effect on days to physiological maturity

The number of days from sowing to physiological maturity for maize is reduced by 17% for both short and long season varieties and this reduction is statistically significant ($p \leq 0.05$) There is also greater variability in number of days to maturity under climate change than under the current climate. A decreasing trend in days to maturity, which is mainly caused by hastened crop growth and development due to increased temperature, is consistent with findings by various researchers. Reduction in the number of days to maturity is one major reason for reduced crop yields under climate change and hence, breeding for maize varieties that are tolerant to high temperatures will help reduce crop yield losses due to climate change. Days to maturity for the long season variety are reduced by 29 days to 131 days which is about the number of days (138) taken by the currently grown short season variety to mature, under the current climate. This suggests that growing long season varieties in future may reduce maize yield losses due to climate change. Although mean yields of the long season maize variety are higher under both current and future climate, smallholder farmers in the study area currently grow short season varieties as they show lower inter-seasonal yield variability than late maturing varieties.

5.4.4. Climate change effect on water balance components

Available soil water at sowing showed similar variability under the current climate and climate change, implying similar predictability of this soil water component under the two climates. There is no significant difference in amount of soil water at sowing between current climate and climate change. Most of simulated planting dates (about 75%) are between mid-end November for both current climate and future climate, showing that climate change may not change the start of the growing season at least by 2050.

Soil evaporation and transpiration are reduced by about 9% and 6% respectively, under climate change. The resultant ET is about 8.5% lower under climate change than under current climate change. The decreases in these variables are, however, not significant. Thus, there is no evidence that the demand for water by the maize crop for the study area and other locations with similar soil characteristics and experiencing similar climatic conditions, will change due to climate change, by 2050.

Climate change reduces both runoff and drainage, with greater reductions occurring under the drier (-15% rainfall) climate change scenario than the less dry (-10% rainfall) scenario. This trend, which is largely due to reduced rainfall amount, under climate change, is consistent with findings from a number of regional and country studies. Runoff is reduced by 28-38%, while drainage is reduced by 28-36%. The reduction in runoff due to climate change is statistically significant, but there is no significant difference in runoff between the two climate change scenarios (-10% and -15% rainfall). The reduction in drainage under climate change is not significant although beyond 2050, the reduction is likely to become significant as the climate is likely to get drier. A decline in both runoff and drainage leads to reduced recharge of surface and ground water sources, thereby reducing water availability for agriculture and other uses. Reduced runoff may also reduce quality of water, threatening human and livestock health, while reduced drainage may result in accumulation of salts which can reduce crop growth or even damage crops, depending on level of concentration. Cost of drawing water from deep water tables, resulting from reduced recharge of ground water is likely to be higher in future, than at present. Low availability of water from both surface and ground water resources will require efficient use of water, for example through use of efficient irrigation technologies, use of water harvesting techniques and recycling of water. Measures to address poor water quality, will be required. Salinization problems may be addressed by growing crops that are tolerant to salt concentration such as sorghum and soybean. Breeding for salt tolerant maize varieties will, in future, allow maize to maintain its status as the major cereal crop in Zimbabwe and other arid and semi-arid parts of Africa. Irrigation water may also be used to leach out salts from the root zone of crops, but this may not be readily adopted by smallholder farmers, due to financial constraints.

CHAPTER 6

SIMULATING EFFECTS OF TILLAGE PRACTICE ON SOIL WATER BALANCE AND MAIZE YIELD OF SC403 VARIETY GROWN IN LOWER GWERU ON A SANDY SOIL, USING APSIM

6.1. Introduction

The objective of this chapter is to generate and present data and information on tillage effects on soil water balance and maize yield. These data and information are required to facilitate discussions with farmers in Chapter 7 where the likelihood that farmers may adopt mulch or planting basins as possible strategies against climate change will be assessed. The generated information from simulations done in this chapter will also contribute to literature on effect of mulch and planting basins on soil water balance and maize crop yield. The chapter contents are limited to a brief outline of the method used to simulate tillage effects (as most of the simulation management has been described in Chapter 5). Simulated soil water balance components and maize yield outputs will be presented in this chapter while discussions of the results will be integrated into Chapter 7 as most important outcomes of the simulations were discussed with farmers at a level the researchers believed farmers would understand.

6.2. Materials and Methods

Simulated soil water balance components (extractable soil water at sowing, soil evaporation, seasonal runoff and drainage) and maize yield (grain, stover and biomass) were compared among conventional tillage treatments (conventional ploughing using animal drawn plough, CP), CP + mulch and use of planting basins). Two mulch levels, 3 and 10 tha^{-1} were considered. The comparisons were done under current climate, using SC403 maize variety, grown on a sandy soil in Mdubiwa Ward of Lower Gweru. The soil characteristics are described in section 5.2.7. Simulations were performed as described in section 5.2.8. For mulch treatments, the source of mulch used was maize residues, with a carbon to nitrogen ratio (CNR) of 80 and a carbon to phosphorus ratio (CPR) of 50. The residues were applied on the soil surface at sowing at 3 and 10 tha^{-1}. For the basin treatment, tillage date was 15 October and the reduction in curve number due to tillage effects was set at 20% and amount of accumulated rainfall to dissipate tillage effects was set at 300 mm (Dimes, 2011 - personal communication). For conventional ploughing, curve number reduction was set at 10% and amount of rainfall to dissipate tillage effects at 50mm. With the exception of cumulative rainfall required to dissipate planting basin tillage effects, the curve numbers and amounts of rainfall sufficient to dissipate tillage effects are comparable to those used by Mupangwa (2008). A lower amount of cumulative rainfall of 250mm was considered enough to dissipate planting basin tillage effects in Mupangwa (2008). For both mulch and basin treatments nitrogen, water and residues were reset on 1 November of each season as with previous model runs.

Significant differences among the different tillage treatment means were tested using the T-test for independent variables for normally distributed data and the non-parametric tests Kruskal Wallis and Mann-Whitney tests for non-normally distributed data. The tests were performed using SPSS version 17 statistical package.

6.3. Results

6.3.1. Effect of tillage practice on the soil water balance (available water at sowing, seasonal soil evaporation, runoff and drainage) under current climate

Simulated extractable soil water at sowing (sow_esw)

Although sowing criteria (at least 20 mm accumulated in 5 days) was the same for all treatments, actual amount of available water at sowing (sow_esw) was lowest under CP being 29.70 mm and highest under 10 tha^{-1} mulch and basin, being about 32.75mm (Fig. 66.1a). Thus 10 tha^{-1} mulch and basin increased sow_esw by 10% while 3 tha^{-1} mulch increased sow_esw by 5% (Fig. 6.1a). Standard deviations for all four treatments fall within a narrow range of 14.02-17.62 mm, with basin having the highest standard deviation and CP, the least (Fig. 6.1b). The 3 tha^{-1} mulch treatment has standard deviation almost equal to that of CP, being 14.89 mm, while 10 tha^{-1} mulch treatment has standard deviation of 16.50 mm.

Simulated sow_esw data are normally distributed for all four tillage treatments ($p \leq 0.05$) (Table 6.1), hence a parametric test, t-test for independent samples was employed to test for significant differences among treatment means. The p-values for differences in sow_esw among CP, CP + mulch and basin treatments ranged between 0.440 and 0.970 (Table 6.2).

Simulated soil evaporation

Planting basins had a negligible effect on soil evaporation (Fig. 6.1a). Mulch reduced the amount of evaporation from the soil, with 3 tha^{-1} and 10 tha^{-1} resulting in 2% and 10% reduction, respectively (Fig. 6.1a). The standard deviation for soil evaporation is highest and similar for CP and basin being about 80 mm/season. Mulch treatments have relatively low standard deviations, with 10t mulch having the lower value of 66 mm/season and 3t mulch, about 78 mm (Fig. 6.1b).

Simulated seasonal evaporation data are normally distributed for CP treatment only (p=0.05), while data for both mulch and basin treatments are not normally distributed (p>0.05) (Table. 6.1). Thus, the non-parametric Kruskal-Wallis test for independent samples was used to test for significant differences among the four tillage treatments. There were significant differences in soil evaporation among the tillage treatments (p=0.045) (Table 6.3). The 10 tha^{-1} mulch treatment had significantly lower evaporation rates than CP (p=0.017), 3 tha^{-1} mulch (p=0.043) and basin (p=0.019) treatments (Tables 6.4 and 6.5), while p-values for differences in evaporation among CP, 3 tha^{-1} mulch and basin treatments were all greater than 0.50 (Table 6.4).

Simulated seasonal runoff

Compared to CP, both mulch and basin treatments had lower runoff. Basin treatment had the greatest reduction in runoff of about 36%, followed by 10 tha^{-1} mulch with 20% and then 3 tha^{-1} mulch with 5% reduction (Fig. 6.1a). CP had the highest standard deviation of 68.7 mm/season while the lowest standard deviation of 59.7 mm/season was associated with 10 tha^{-1} mulch (Fig. 6.1b). The 3tha^{-1} mulch and basin treatments had 66.2 and 62.0 mm/season standard deviation, respectively (Fig. 6.1b). With the exception of basin treatment which had the lowest runoff, but relatively high standard deviation, generally the greater the amount of runoff, the greater the year to year variability in seasonal runoff.

None of the simulated runoff data are normally distributed ($p>0.05$) (Table 6.1), thus the non-parametric Kruskal-Wallis test was used to detect treatment differences. Results of this test show that tillage practice had a significant effect on mean seasonal simulated runoff ($p=0.015$) (Table 6.3). Further testing (Mann-Whitney test) to identify which specific treatments showed mean differences in seasonal runoff indicated that basin treatment had significantly lower runoff than 3 tha^{-1} mulch and CP ($p<0.05$) (Table 6.4). The amount of runoff was, however, not significantly different between basin and 10 tha^{-1} mulch treatments, neither did it differ among 3 tha^{-1} mulch, 10 tha^{-1} mulch and CP treatments ($p>0.05$) (Tables 6.4 and 6.5).

Simulated seasonal drainage

Use of mulch and planting basins increased seasonal drainage, with basin treatment having the highest increase of 42%, followed by 10 tha^{-1} mulch treatment with 30% and 3 tha^{-1} mulch with 7% increase (Fig 6.1a). CP had the least year to year variability in seasonal drainage corresponding to a standard deviation of 78.2 mm, while 10 tha^{-1} mulch had the highest standard deviation of 91.4 mm/season (Fig. 6.1b). Basin and 3 tha^{-1} mulch had standard deviations of approximately 87.3 and 81.1 mm respectively (Fig. 6.1b). Thus, drainage can be predicted with greatest certainty under conventional ploughing and with least certainty under 10 tha^{-1} mulch system.

Similar to simulated runoff data, simulated seasonal drainage data for all tillage practices are not normally distributed ($p>0.05$) (Table 6.1), hence a non-parametric Kruskal-Wallis test was used to test for significant differences among treatment means. The amount of seasonal drainage did not differ significantly ($p>0.05$) among CP, mulch and basin treatments (Tables 6.3 and 6.5). Thus the null hypothesis that tillage system does not significantly affect the amount of drainage cannot be rejected.

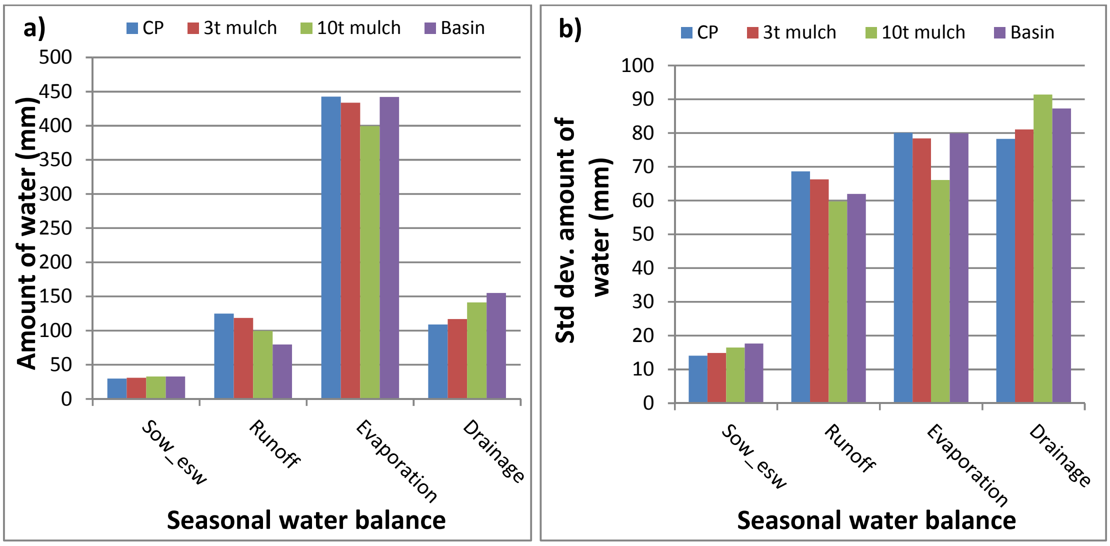


Fig. 6.1. Simulated a) mean and b) standard deviation for soil water balance components, under different tillage practices in the production of maize variety SC403 grown on a sandy soil in Lower Gweru, under current climate changed

Table 6.1. Kolmogorov-Smirnov test for normality of water balance data simulated for a sandy soil planted to SC403 maize variety under different tillage practices in Lower Gweru, under current climate

Water balance component	**Tillage practice**	**Statistic**	**df**	**Significance**
Available soil water at planting (sow_esw)	Conventional ploughing (CP)	0.163	28	0.054*
	3 tha^{-1} Mulch	0.166	28	0.047*
	Basin	0.184	28	0.016*
	10 tha^{-1} Mulch	0.187	28	0.014*
Seasonal evaporation	Conventional ploughing (CP)	0.164	28	0.053*
	3 tha^{-1} Mulch	0.146	28	0.128
	Basin	0.163	28	0.055
	10 tha^{-1} Mulch	0.151	28	0.100
Seasonal runoff	Conventional ploughing (CP)	0.122	28	0.200
	3 tha^{-1} Mulch	0.143	28	0.149
	Basin	0.121	28	0.200
	10 tha^{-1} Mulch	0.134	28	0.200
Seasonal drainage	Conventional ploughing (CP)	0.142	28	0.156
	3 tha^{-1} Mulch	0.152	28	0.098
	Basin	0.106	28	0.200
	10 tha^{-1} Mulch	0.153	28	0.092

* Significant ($p \leq 0.05$)

Table 6.2. Mean comparison of available soil water at sowing for different tillage practices under current climate, for SC403 maize variety grown on a sandy soil in Lower Gweru (t-test)

Compared tillage practices	T-test of means					95% confidence interval difference	
	t	df	Sig. 2-tailed	Mean difference	s.e difference	Lower	Upper
CP vs. 3t mulch	-0.297	54	0.768	-1.143	3.853	-8.867	6.582
CP vs. 10t mulch	-0.771	54	0.444	-3.143	4.076	-11.319	5.033
CP vs. Basin	-0.700	54	0.487	-2.965	4.234	-11.462	5.533
3t vs. 10t mulch	-0.477	54	0.635	-2.000	4.189	-10.400	6.400
3t mulch vs. Basin	-0.419	54	0.677	-1.821	4.341	-10.533	6.890
10 t mulch vs. Basin	-0.039	54	0.969	-0.179	4.542	-9.285	8.928

Table 6.3. Test statistics for significant differences in soil water balance among the different tillage practices, under current climate (Kruskal-Wallis test)

	Seasonal evaporation	Seasonal runoff	Seasonal drainage
Chi-Square	8.064	10.326	5.422
Df	3	3	3
Significance	0.045*	0.016*	0.143

Grouping variable is tillage practice. * Significant difference ($p<0.05$)

Table 6.4. Test statistics for significant differences in soil water balance among different pairs of tillage practices (Mann-Whitney test)

Water balance component	Compared practices	Statistic	Z	Asymptotic sig.(2-tailed)
Seasonal evaporation	CP vs. 3t mulch	353.0	-0.639	0.523
	CP vs. basin	389.0	-0.049	0.961
	CP vs. 10t mulch	247.0	-2.376	0.017*
	3t mulch vs. basin	354.0	-0.623	0.533
	3t mulch vs. 10t mulch	268.5	-2.024	0.043*
	basin vs. 10t mulch	249.0	-2.343	0.019*
Seasonal runoff	CP vs. 3t mulch	361.5	-0.500	0.617
	CP vs. basin	223.5	-2.762	0.006*
	CP vs. 10t mulch	291.5	-1.647	0.100
	3t mulch vs. basin	242.5	-2.450	0.014*
	3t mulch vs. 10t mulch	311.5	-1.319	0.187
	basin vs. 10t mulch	301.0	-1.492	0.136

*Significant difference ($p<0.05$)

Table 6.5. Mean comparison of water balance components simulated for a sandy soil on which maize is grown in Lower Gweru, under different tillage practices and current climate

Tillage practice	Extractable soil water at sowing (mm)	Mean potential evaporation (mm)	Mean seasonal runoff (mm)	Mean seasonal drainage (mm)
Conventional ploughing (CP)	29.7	442.5^{a}	124.9^{a}	109.2
3 tha^{-1} mulch	30.9	433.6^{a}	118.7^{a}	117.1
10 tha^{-1} mulch	32.8	399.4^{b}	99.7^{ac}	141.5
Basin	32.7	442.2^{a}	79.7^{c}	155.0

Means with the same letter within a given column are not significantly different from each other ($p>0.05$)

6.3.2. Effect of tillage practice on SC403 maize yield (grain, biomass and stover) under current climate

Mulch and basin treatments had negligible effects on three yield parameters (grain, biomass and stover) of maize variety SC403 grown on sandy soil in Lower Gweru (Fig. 6.2a). Mean grain yield was slightly reduced by 1%, 2% and 5% due to 3 tha^{-1} mulch, basin and 10 tha^{-1} mulch treatments, respectively. Basin treatment did not affect either biomass or stover yield, while 10 tha^{-1} mulch slightly increased both biomass and stover yield by 1.5%. The 3 tha^{-1} mulch treatment reduced biomass and stover yield by about 4% (Fig. 6.2a). Grain yield shows greater variability under conventional ploughing and under 3 tha^{-1} mulch treatment, which have standard deviations of about 1387 and 1348 $kgha^{-1}$, respectively (Fig. 6.2b). The standard deviation is lowest for 10 tha^{-1} mulch being 1190 $kgha^{-1}$, while that of the basin treatment is about 1325 $kgha^{-1}$. Thus, there is higher grain yield stability under 10 tha^{-1} mulch compared to the other three treatments. However, for both biomass and stover, 10 tha^{-1} mulch has the highest standard deviation of 2170 and 996 $kgha^{-1}$ respectively, while 3 tha^{-1} has the lowest standard deviation of 1803 and 891 $kgha^{-1}$ for biomass and stover, respectively (Fig. 6.2b). Biomass and stover yields for CP and basin show about the same year to year variability, with standard deviations of about 2 000 $kgha^{-1}$ for biomass and 945 $kgha^{-1}$ for stover (Fig. 6.2b).

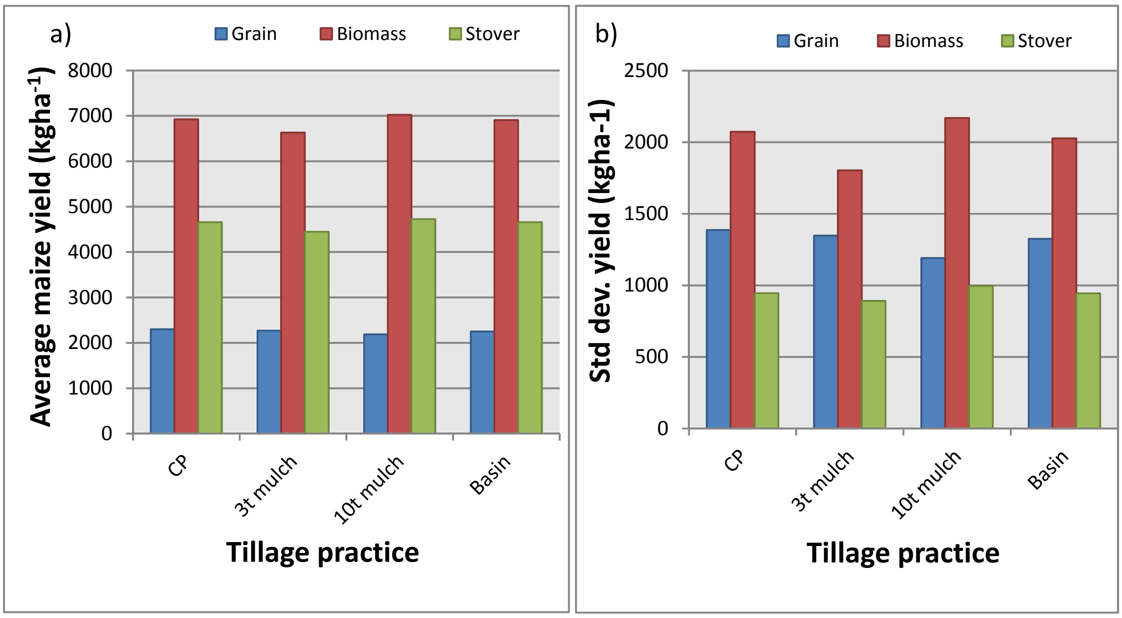


Fig. 6.2. Simulated a) mean and b) standard deviation for maize yield of SC403 variety grown on a sandy soil in Lower Gweru under different tillage practices, under current climate change

All simulated grain and biomass yield data are normally distributed ($p<0.05$) (Table.6.6). A parametric, t-test for independent samples was thus used to test for significant differences in mean grain and biomass yields under different tillage practices. However, not all simulated stover yield data are normally distributed ($p>0.05$) (Table 6.6), hence the non-parametric Kruskal-Wallis test was used to detect any significant differences in stover yield among the different tillage treatments. There were no significant differences in maize grain, biomass and stover yield among the four tillage practices ($p>0.05$) (Tables 6.7; 68 and 6.9).

Table 6.6. Kolmogorov-Smirnov test for normality of simulated maize yield data for variety SC403 grown on a sandy soil under different tillage practices in Lower Gweru, under current climate

Yield component	Tillage practice	Statistic	df	Significance
Grain yield	Conventional ploughing (CP)	0.179	28	0.022*
	3 tha^{-1} Mulch	0.176	28	0.027*
	Basin	0.172	28	0.034*
	10 tha^{-1} Mulch	0.182	28	0.018*
Biomass yield	Conventional ploughing (CP)	0.174	28	0.029*
	3 tha^{-1} Mulch	0.176	28	0.026*
	Basin	0.170	28	0.037*
	10 tha^{-1} Mulch	0.179	28	0.022*
Stover yield	Conventional ploughing (CP)	0.100	28	0.200
	3 tha^{-1} Mulch	0.117	28	0.200
	Basin	0.120	28	0.200
	10 tha^{-1} Mulch	0.159	28	0.069

* Normally distributed data ($p\leq0.05$)

Table. 6.7. Test statistics for mean comparison of grain yield of SC403 maize variety grown on a sandy soil in Lower Gweru, under different tillage practices, under current climate (t-test)

Compared tillage practices	T-test of means						
						95% confidence interval difference	
	t	df	Sig. 2-tailed	Mean difference	s.e difference	Lower	Upper
CP vs. 3t mulch	0.180	54	0.858	102.100	567.123	-1034.968	1239.168
CP vs. 10t mulch	0.326	54	0.746	112.634	345.570	-580.553	805.825
CP vs. Basin	0.135	54	0.893	48.818	362.553	-678.092	775.726
3t vs. 10t mulch	0.238	54	0.813	80.975	339.970	-600.860	762.810
3t mulch vs. Basin	0.048	54	0.962	17.157	357.219	-699.029	733.343
10 t mulch vs. Basin	0.190	54	0.850	63.818	336.722	-611.442	739.078

Table 6.8. Test statistics for mean comparison of biomass yield of SC403 maize variety grown on a sandy soil in Lower Gweru, under different tillage practices, under current climate (t-test)

Compared tillage practices	T-test of means						
						95% confidence interval difference	
	t	df	Sig. 2-tailed	Mean difference	s.e difference	Lower	Upper
CP vs. 3t mulch	0.087	54	0.931	31.661	365.571	-701.230	764.601
CP vs. 10t mulch	0.733	54	0.467	391.036	533.247	-678.880	1460.952
CP vs. Basin	0.210	54	0.834	118.071	561.165	-1007.116	1243.259
3t mulch vs. 10t mulch	0.556	54	0.580	288.936	519.265	-752.585	1330.456
3t mulch vs. Basin	0.029	54	0.977	15.971	547.896	-1082.506	1114.449
10 t mulch vs. Basin	0.532	54	0.597	272.964	512.751	-755.358	1301.286

Table 6.9. Test statistics for significant differences in maize stover yield among the different tillage practices, under current climate (Kruskal-Wallis test)

Chi-Square	1.466
Df	3
Significance.	0.690

Grouping variable is tillage practice

CHAPTER 7

OPINIONS OF SMALLHOLDER FARMERS IN LOWER GWERU COMMUNAL AREA ON PROJECTED FUTURE CLIMATE AND POSSIBLE ADAPTATION STRATEGIES

7.1. Introduction

The majority of the people in Zimbabwe and the southern African region as a whole derive their livelihoods from rain fed agriculture. Rosegrant *et al*. (2002) estimate that 90% of cereal production in sub-Saharan Africa is from rain-fed agriculture, while according to Ngigi (2009) only 6% of African agricultural land is under irrigation. In these regions, agricultural productivity is compromised by low and variable rainfall. Agriculture has been identified as the sector most vulnerable to climate variability and change (IPCC, 2007; Kurukulasuriya and Mendelson, 2008a; Mendelsohn, 2009), with dry-land (rain-fed) African farms, being more sensitive to climate especially temperature, than irrigation farms (Kurukulasuriya and Mendelson, 2008a). African communities, in particular those in the sub-Saharan region, are thought to be the most vulnerable (Adger, 2003; Barrios *et al.*, 2008; IPCC, 2007; Mertz *et al*., 2009; Gandure *et al.,* 2013) because of multiple stressors and limited adaptive capacity.

Research work has established effects of climate change on agricultural productivity (e.g. Jones and Thornton, 2003; IPCC, 2007; Thorntorn *et al*., 2007; Nhemachena *et al*., 2010; Schlenker and Lobell, 2010) and on the well-being of farming communities in Africa (e.g. Adger, 2003; Slater *et al*., 2007; Barrios *et al*., 2008). To reduce impacts of climate change on agricultural productivity, appropriate adaptation strategies have to be put in place. Maddison (2007) reckons that perception is a prerequisite for adaptation to climate variability and change. Farmers are reported to have perceived changes in climatic variables over time. Several authors have established perceptions of some communities in Africa, on climate variability and change. Examples are from communities in southern Africa (in South Africa - Maddison, 2007, Nhemachena and Hassan, 2007 & Gandure *et al*., 2013; in Zambia - Nhemachena and Hassan, 2007; Mubaya, 2010 & Mubaya *et al*., 2012; in Zimbabwe - Nhemachena and Hassan, 2007, Mubaya, 2010 & Mubaya *et al*., 2012); in west Africa (in Burkina Faso, Ghana and Niger - Maddison, 2007 & Akponikpe *et al.,* 2010; in Senegal - Maddison, 2007 & Mertz, 2009; in Benin and Togo - Akponikpe *et al.,* 2010); in east Africa (in Ethiopia - Maddison, 2007); in north Africa (in Egypt - Maddison, 2007) and in central Africa (in Cameron - Maddison, 2007). According to Mubaya (2010) and Mubaya *et al*. (2012), farmers in the study area's perceptions of climate variability and change include increased lengths of dry spells, increased number of seasons with inadequate rainfall, a rise in temperature, increased frequency of droughts as well as late start and early end of the rainy season. However, not all farmers perceive such changes and not all perceptions are true or match climate records. Thus, it is essential to inform stakeholders such as farmers of the envisaged changes in climate, to enhance adaptation of possible strategies, in the face of climate variability and change. In their analysis of factors that determine adoption of adaptation strategies to climate change, at farm level in Southern Africa, Nhemachena and Hassan (2007) concluded that lack of information on long-term climate change and short-term climate variations was a major determinant of adoption of adaptation strategies. Eichberger and Guerdjikova (2012) also highlight lack of information on climate change as a major barrier to adoption of alternative agricultural technologies in the light of climate change. In this study, smallholder farmers were informed about the envisaged future climate of southern Africa, by 2050 (see details in section 6.2.2). This was done after giving farmers feedback on the results of a survey that was conducted during 2008 in the study area, to establish farmer perceptions of climate variability and change (Mubaya, 2010; Mugabe *et al*., 2010; Mubaya *et al*., 2012).

Crop and water management strategies to address climatic change have been suggested by various researchers including Challinor *et al. (*2007), Howden *et al.* (2007), IPCC (2007), Ngigi (2009), Tubiello *et al.* (2002) and Rosenzweig and Tubiello (2007). Some of these strategies involve appropriate crop choice, use of inter-cropping systems or cultivars adapted to different conditions, water management practices to either conserve soil water (for example using mulch and rain water harvesting technologies) or to address effects of excessive soil water such as water logging and nutrient leaching, development of smallholder irrigation schemes, employing diversified farming activities including both crops and livestock and making use of climate forecasts to make appropriate farming decisions. Some of these strategies are already being employed by farmers in the study area and elsewhere in Africa to address effects of current climate variability (e.g. Cooper *et al*., 2008; Mubaya, 2010, Chapter 4 of this thesis).

The first objective of this chapter is to establish and document opinions of farmers in Lower Gweru area of Zimbabwe about the expected future climate of Zimbabwe by 2050. Specific objectives are to establish farmers' envisaged effects of climate change on agricultural productivity and how they could possibly counteract some of the predicted negative effects or maximize on positive effects. The chapter also seeks to find farmers' opinions concerning the likelihood of adopting selected adaptation strategies against a changing climate. The agronomic strategies considered for this objective are shifting from growing early maturing maize varieties to late maturing ones and using either mulchor planting basins. Soil water balance and maize yield simulated under different tillage practices in Chapter 6 and different climate scenarios in Chapter 5 will be presented to farmers. This would facilitate discussions with farmers, on their likelihood of adopting late maturing season maize varieties, mulch and planting basins.

7.2. Materials and Methods

7.2.1. Study area and selection of farmers

Focus Group Discussions (FGDs) were conducted on 22 and 23 October, 2011 with a total of 36 farmers (13 women and 23 men) in Lower Gweru communal area, to establish farmer opinions on projected climate and to assess the likelihood whether these farmers could adopt selected adaptation strategies to climate variability and change. The farmers were drawn from a total of six villages, three villages in Mdubiwa Ward and another three from Nyama Ward (Fig 6.1 and Table 6.1).

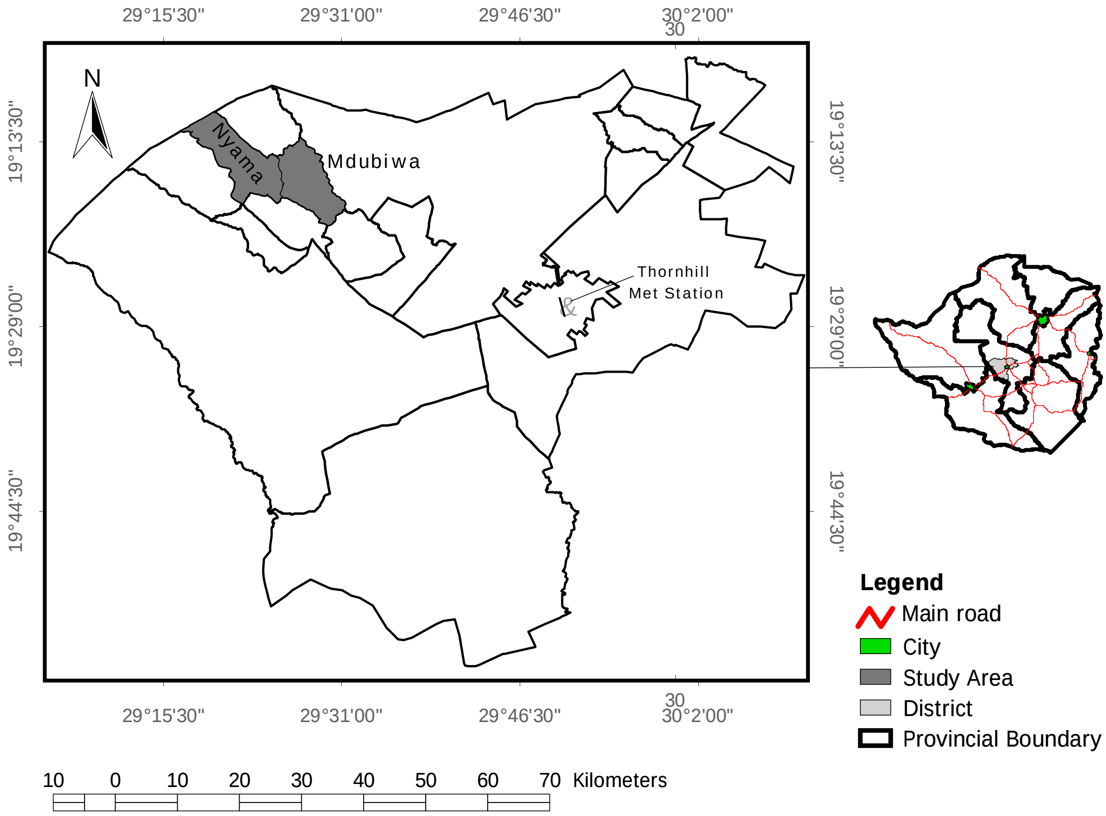


Fig. 7.1. Wards in Gweru District, from which farmers were selected for the focus group discussions

Table 7.1. List of wards and villages in Lower Gweru, from which farmers were selected for the focus group discussions

Ward	Villages
Mdubiwa	1. Mxotshwa 2. Nsukunengi 3. Madinga
Nyama	4. Matonsi, 5. Guduza 6. Siyabalandela

Six farmers were selected from each village using systematic random sampling from household lists that were obtained from the village heads (the same lists were also available from the Department of Agricultural Research and Extension Services, AGRITEX). Each village list had a total of 100 households. Farmers were grouped into three wealth groups as it was hypothesized that farmers' responses to climate change issues would vary depending on their economic and social status. Wealth ranking is a tool widely used in Participatory Rural Appraisal (PRA) (Jules *et al*., 1992; Mearns *et al*., 1992; Chambers, 1994; Loader and Amartya, 1999; Davis, 2001; Swathi Lekshmi *et al*., 2008) and it provides a way of obtaining information pertaining to the economic status of households (Reddy, 1997). The method considers a number of issues that contribute to the well-being of households and communities (Loader and Amartya, 1999) for example the physical assets that households possess. The objective of grouping was explained to the farmers after which they were asked to spell out the criteria they considered to classify one as "rich", "intermediate" or "poor". The major criteria that farmers agreed to use in categorizing themselves into the three wealth groups were livestock ownership (cattle ownership in particular), the type of homestead one possessed, farm implement ownership and access to labour (Table 6.2). These criteria have also been used in wealth ranking by other farming communities (e.g. Kalisa and Nshmyumukiza, 2007 in southern Rwanda; Swathi Lekshmi *et al*., 2008 in Namakkal district of Tamil Nadu, India; Ncube et al., 2009 in Tsholothslo, western Zimbabwe). After agreeing on the criteria, farmers were then asked to self-categorize themselves at village level. Farmers belonging to the same category were then grouped together and the resultant groups were named group A (for the rich), group B (for the intermediate) and group C (for the poor). The number of "rich" and "intermediate" farmers was almost the same, while the "poor" constituted the largest group of 15 (Fig. 6.2). Out of the 11 rich farmers, three were women, while two and eight women fell into the "intermediate" and "poor" categories which had totals of 10 and15 farmers respectively. Thus, 60% of the women farmers were classified as poor, whereas men were distributed evenly across the three wealth categories (8 rich, 8 intermediate and 7 poor).

Table 7.2. Criteria used by farmers in Mdubiwa and Nyama Wards to categorize themselves into wealth classes

Criteria	Rich	Intermediate	Poor
1. Number of cattle owned	More than 5 cattle	2-5 cattle	0-1 cattle
2. Possession of farm implements.	Normally have a plough & cart plus other implements e.g. harrow & cultivator.	Have at least a plough. May need to team up with others to prepare land for planting.	No farming implements except the hoe. Rely on others for land preparation or dig their fields using hoes.
3. Type of homestead.	Nicely built & clean homestead. Brick under asbestos or iron sheets houses. Have toilet & protected well or borehole.	Decent homestead. May have toilet & a protected well.	Homestead with one (in most cases a hut) or two small buildings used by whole family. No toilet nor protected well.
4. Access to labour.	Labour not a major constraint. Normally hire labour.	Normally use family labour, but sometimes hire labour.	Work in "rich" farmers' fields & in return rich farmers plough their fields.

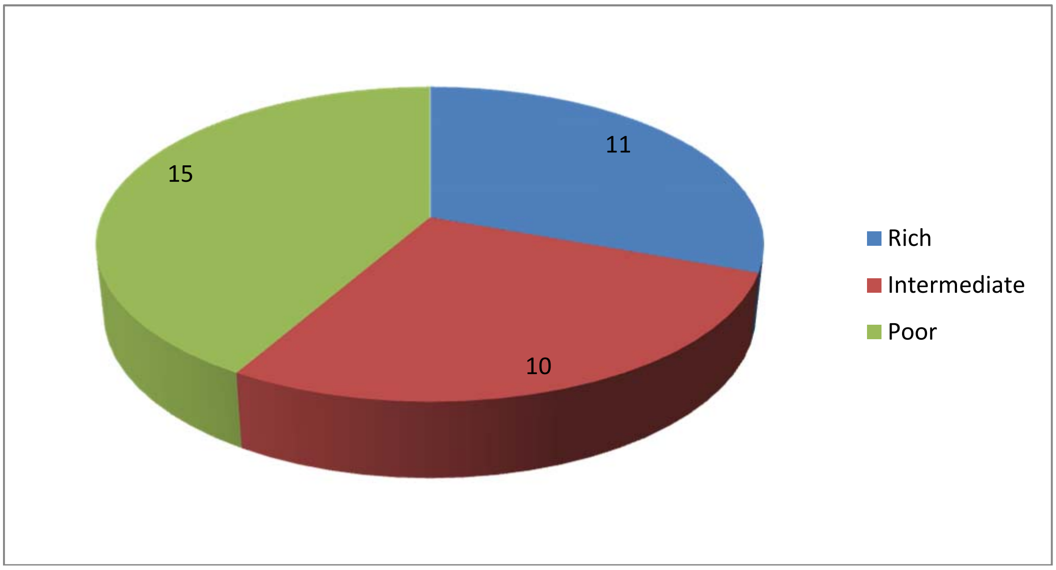


Fig. 7.2. Number of farmers in each wealth category (rich, intermediate and poor) who participated in FGDs in Lower Gweru

Due to a combination of lack of draft animals and implements the poor farmers often planted their crops late while the rich planted early and the intermediate farmers usually planted fairly early (Moyo and Musasanuri, 2010 - personal communication). This scenario led to relatively low yields being attained by the poor farmers. According to Moyo and Musasanuri, 2010 - personal communication) poor access to other production resources such as improved seed and fertilizers (organic and inorganic), further compromised crop productivity of the poor farmers in Lower Gweru.

7.2.2. Presentation of future climate scenarios to farmers and seeking their reactions

The starting point for providing information on climate change to the farmers was telling and/or reminding them of the International Development Research Centre/Climate Change and Adaptation in Africa (IDRC/CCAA) project on climate variability and change had activities that were conducted in their villages during the period 2008 to 2010. Those activities included a baseline survey to establish farmer perceptions on climate variability and change as well as mother-baby agronomic trials conducted in response to national seasonal rainfall forecasts for the 2007/08 and 2008/09 seasons (Masere, 2012; Chagonda, 2013). It was noted that, out of the 36 farmers who participated in this current FGDs, three had participated in the 2008 baseline survey, while four had participated in the mother-baby trials. A summary of Lower Gweru farmers' previously collected perceptions (Mubaya, 2010; Mubaya *et al*., 2012) (Table 7.3 and Fig. 7.3), was presented to the farmers who were then asked whether they agreed or disagreed with those perceptions. This was done to give them a chance to think about the climate of their area and any changes that they had noticed over the years and to enhance their participation in subsequent discussions. The exercise was then followed by presentation of the climate projections and some comments (by researchers) on farmer perceptions.

Table 7.3. Lower Gweru farmers' perceptions on climate change and variability, based on survey carried out in 2008 (Adapted from Mubaya, 2010)

Perception	**Percentage of farmers concurring with perception (n= 180 farmers)**
Increased seasons without enough rainfall	68
Increased occurrence of excessive rains	43
Rains start late and end early	67
Rain comes earlier	20
Increased lengths of dry spells	42
Extremes in temperatures	38

Projected temperatures and rainfall shifts for Zimbabwe by 2050 were presented to the farmers. The presented projections, based on the A2 CO_2 emission scenario, were an increase in temperature of 2.3 to 4.5 ^{o}C (IPCC, 2007) and a decrease in rainfall of about 10-15% (projections according to the ECHAM5 and GFDL models; Ministry of Mines, Environment and Tourism in Zimbabwe, 1998b). Farmers were then asked to give their opinion as to what they thought would be the impact of such changes on agricultural productivity. They were also asked to suggest how they could reduce any possible negative impacts or maximize on any positive impacts. Farmers wrote responses to these questions on manila charts and presented their findings to the whole group (Fig. 7.4).

Fig. 7.3. Facilitator John Dimes presenting Lower Gweru farmer perceptions on climate change and variability to farmers who participated in November 2010 FGDs in the same area

Fig. 7.4. Farmer, Linnet Tshange entertaining questions after her presentation on behalf of group C

7.2.3. Presentation of simulated climate change effects on maize yield to farmers and the effect of using selected adaptation strategies

Farmers were informed that a crop model could be used to establish the possible impacts of climate change on crop productivity in their area. To this effect, the concept of a crop model was explained to the farmers and their understanding of a model is reflected on what they said about a crop model (Box 7.1).

Box. 7.1
Lower Gweru farmers' excerpts to illustrate their understanding of use of a crop model

- "A model can help us in preparing for the season, that is, the inputs we can use and the area we can plant."
- "It helps to make budgets and to save money."
- "A model can be very close to what we do in our fields and the results can be close to those obtained in the model."
- "As farmers, where can we get these computers to enable us to use these models?"

Following discussions with farmers on the concept of a crop model, researchers then presented maize grain and stover yields simulated for a crop grown on a sandy soil in Lower Gweru under current climate and climate change for 2050 (Fig. 7.5 a & b). This was done despite the seemingly lack of significant difference in simulated mean yields between current climate and climate change (from chapter 5), to stimulate discussion with farmers. Emphasis was put on the overall percentage decrease in yield as well as on the number of individual years that had either lower or higher yields , under current climate or climate change. Simulated number of days taken to reach physiological maturity by the maize crop (Fig. 7.7) were also presented to the farmers. The yields and number of days to maturity were those simulated using APSIM, in Chapter 5. Presentation of these outputs from APSIM was an objective way of informing farmers about how climate change could affect maize yield and growing season duration at their locality, by 2050. The message given to the farmers was that higher grain yields were obtained under current climate than under climate change for 17 out of the total 28 years that were considered in the analysis and in 6 out of the past 10years (1999 to 2008) (Fig. 7.5a). They were also informed that on average climate change decreased maize grain yield by about 16% and stover yield by 13%. Out of the 28 years considered in the simulations, 21 years had higher stover yields under current climate while for the past 10 years (1999-2008) 7 out the 10 years had higher yield under current climate than climate change (Fig. 7.5b). Thus, under climate change the risk of getting lower yields was higher than under the current climate. Climate change significantly reduced ($p<0.05$) the number of days taken by a relatively short season maize variety SC403 to reach physiological maturity by approximately 23 days (see 5 section 5.4.3) (Fig. 7.6).

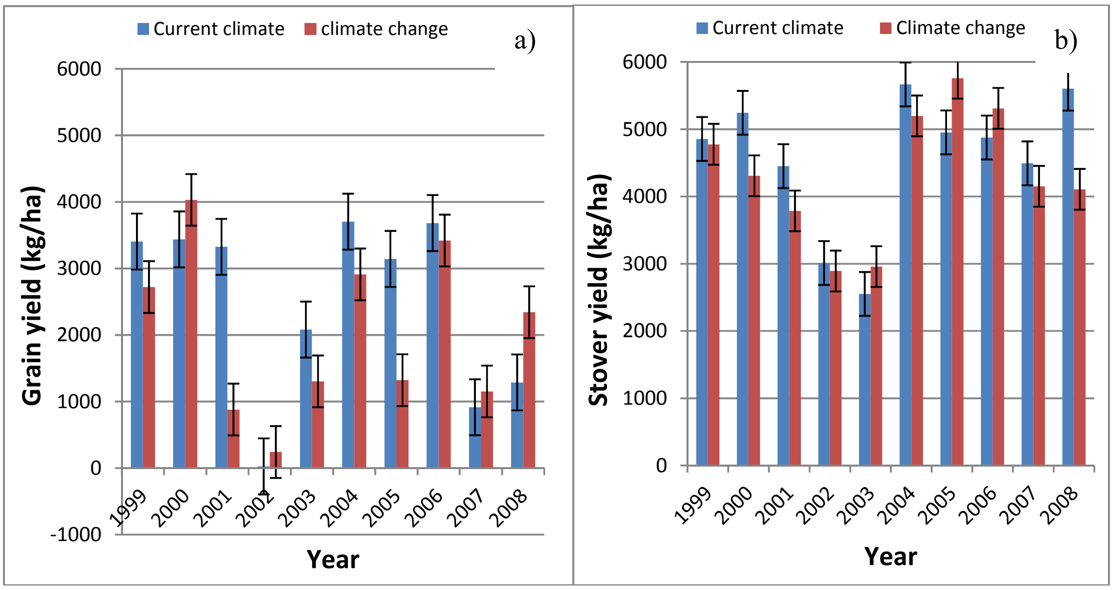


Fig. 7.5. Effect of climate change on a) grain yield and b) stover yield of SC403 maize variety grown on a sandy soil at Lower Gweru

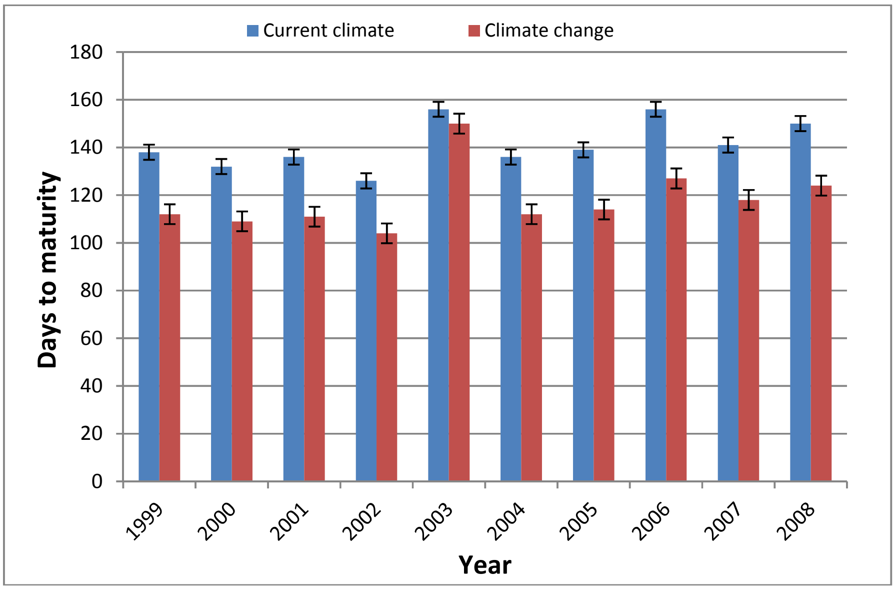


Fig. 7.6. Effect of climate change on days to physiological maturity SC403 maize variety grown on a sandy soil at Lower Gweru

7.2.4. Assessing the likelihood that farmers would adopt selected adaptation strategies to climate variability and change

The acceptability or possibility of adoption of three selected strategies for adaptation to climate change, by the farmers, was assessed. This was done by asking farmers to provide reasons for readiness or non-readiness to adopt the strategies. The selected strategies were use of mulch, use of planting basins and growing of long season maize varieties. The first two were selected as these were important components of conservation agriculture (CA), which was being promoted by the Department of Agricultural Technical and Extension Services (AGRITEX) in the study area at the time of this study. CA was also being promoted and practised in other parts of Zimbabwe and Southern Africa (Rockström, 2001; Mupangwa *et al.,* 2007; Siziba, 2008; Twomlow *et al.,* 2008b; Mazvimavi, 2011). Farmers in this study had also mentioned CA as a possible strategy to reduce impacts of climate change, while Mubaya (2010) and Chapter 4 of this thesis, also established that farmers in the study areas (Lower Gweru and Lupane) already used planting basins and to a lesser extent mulch as coping strategies against climate variability and change. Selection of growing long season maize varieties as a strategy was based on the findings in Chapter 5 of this thesis that under climate change the reduction in maize grain yield was less when a long season variety was grown, compared to when a short season variety was grown. To enhance farmer responses to adoption of the three strategies, soil water balance components namely, available soil water at sowing, seasonal soil evaporation, seasonal runoff and seasonal drainage under mulch, basins and conventional ploughing (conventional ploughing + no mulch) were simulated as described in section 6.2 and presented to the farmers. Simulated maize yields under the different agronomic practices were also presented. Comparison of simulated number of days to reach physiological maturity as well as simulated maize grain yield (generated from Chapter 5) were also shown comparing short and long season maize varieties under climate change. Discussions on the model outputs were carried out with the farmers, after which they were asked to indicate any possible barriers to the adoption of the three strategies.

Facilitators had the opportunity to inform and/or explain to farmers some technical / agronomic aspects pertaining to climatic change as well as the use of mulch. Researchers also learnt about how farmers performed most of their cropping activities and the limitations to the attainment of high crop yields.

7.3. Results and Discussion

7.3.1. Farmers' reactions to the 2008 survey results on perceptions of climate variability and change by Lower Gweru farmers

To a large extent, farmers agreed with results of the 2008 survey (Table 7.4) conducted in their area (Lower Gweru), to establish farmer perceptions on climate variability and change. With the exception of *"increased duration of dry spells"*, a greater proportion of the farmers (100% of them in most cases) concurred with perceptions of at least 50% of the farmers interviewed during the 2008 baseline survey (Table 7.4). The main purpose of the exercise was, however, to facilitate a smooth discussion of the subject on climate variability and change, rather than to generate information, since not all farmers were aware that a survey of this nature had been carried out in their villages let alone participated in the 2008 survey. The exercise provided feedback to a community which had contributed valuable information on climate variability and change. Nearly all farmers agreed with the perceptions probably because they wanted to agree with the "official" position and not necessarily because they had the same perceptions. The exercise did not also allow for independent thinking. It was only for the additional climate variability dimension of "*increased frequency of dry spells*" that there was variance in farmers' views (Table 7.4).

Table 7.4. Responses to Lower Gweru farmers' perceptions of climate change and variability by farmers at the FGDs held in November, 2010

Perception	No. of farmers who agreed (Out of 36)	No. of farmers who disagreed (Out of 36)	No. of farmers who agreed with perception during the 2008 survey (Out of 180)
Increased seasons without enough rainfall	36 (100%)	0 (0%)	122 (68%)
Increased occurrence of excessive rains	0 (0%)	36 (100%)	77 (43%)
Rains start late Rains start early	36 (100%) 0 (0%)	0 (0%) 36 (100%)	- 36 (20%)
Rains end early **Rains end late*	34 (94.5%) 2 (5.5%)	2(5.5%) 34 (94.5%)	- -
Rains start late and end early	-	-	120 (67%)
Increased lengths of dry spells	36 (100%)	0 (0%)	75 (42%)
Temperature extremes more often	5 (15%)	31 (85%)	68 (38%)
**Increased frequency of dry spells*	10 (28%)	26 (72%)	-

*These were additional rainfall pattern parameters to those used in the 2008 survey

Researchers emphasized to the farmers, the need by researchers, to verify their perceptions on climate variability and change by analysing historical records for trends on temperature and rainfall pattern. Farmers showed much keenness in getting feedback from researchers on whether their perceptions matched researchers' findings.

7.3.2. Farmer reactions to climate projections

7.3.2.1. Farmer perceptions of possible effects of future climate on agricultural productivity

Farmers' responses to possible effects of climate showed that they were concerned about crop and livestock productivity as well as availability of water resources, food and nutrition security and about their general well-being (Box. 7.2). The farmers' envisaged effects were all negative and there were no marked differences in the nature of responses across the three categories of farmers. However, it appears the rich farmers showed greater concern for livestock than the other groups by mentioning effects on livestock first and by elaborating on the nature of livestock losses. This response was expected, given that this group of farmers owned more cattle (at least five head of cattle) than members of other groups. The more elaborate response on effects on livestock by this group could also be because more than half of farmers in this group were younger (between 45 and 60 years) whereas for the medium group more than half the group were old people (more than 70 years) while the resource poor farmer group had a wide range of age groups with about a third of them being in the range 25-35 and about two-thirds being between 45 and 70 years. It appears that the predicted increases in temperatures were taken by farmers to be dramatic as they envisaged burning of crops to occur (resource rich and resource poor farmers). This was probably due to a misconception of the intensity of heat associated with the projected temperature increase by 2050 or limited knowledge of crop response to such a change, on the part of farmers. However, the medium group suggested that burning would occur if fertilizers were applied to the crop. Farmers also mentioned that climate change would reduce crop yields (medium and resource poor groups) and cause seed losses (medium farmers). According to the medium group farmers planting seed was generally expensive and not readily available. Thus, if low yields are obtained due to climate change effects, when a farmer has invested much in planting seed, then this would mean a great financial loss. Farmers envisaged a reduction in availability of water resources, a factor that would negatively affect both livestock and human beings due to shortage of drinking water. According to the farmers, climate change would impact negatively on their well-being through increased poverty, hunger and starvation, increased prevalence of diseases and malnutrition as well as increased cases of school drop outs. Farmers in Lower Gweru expect these impacts since their livelihoods are based on agriculture (Mubaya, 2010; Moyo, 2010 - personal communication) which is the main source of food and income. However, the medium category farmers did not indicate concern on number of school drop outs. This is probably because most of them no longer had children of school going age. Similar to communities elsewhere in the world, and Africa in particularly, responses by farmers in Lower Gweru show that these farmers know that they are vulnerable to climate change.

Box. 7.2
Farmers' perceived climate change effects on agricultural productivity

Resource rich farmers (Group A)

- "We will lose livestock due to poor conception rates and death of some animals."
- "Crops will be burnt."
- "There will be hunger and starvation."
- "Drinking water will be inadequate for both livestock and human beings."
- "Diseases and malnutrition will be prevalent."

Medium resource farmers (Group B)

- "There will be waste of seed and yield."
- "If we apply fertilizers, crops will be burnt."
- "Availability of water for livestock and human consumption will be reduced."

Resource poor farmers (Group C):

- "Crops will be burnt."
- "Crop yields will be reduced."
- "Availability of water for livestock and human consumption will be reduced."
- "There will be increased cases of school drop outs."
- "Climate change will increase poverty and thieving will be more rampant."

Although farmers could not quantify the degree to which agricultural productivity, water resources and their well-being would be affected by climate change, their perceptions of climate change effects are consistent with established climate change effects for southern

Africa (e.g. effect on crop productivity - IPCC, 2007a, Dimes *et al*., 2008, Rosenzweig and Tubiello, 2007, Schlenker and Lobell, 2010; Chapter 5 of this thesis; effect on water resources - Arnell, 1999, IPCC, 2007a, Eriksen *et al.*, 2008; effect on livestock - Topp and Doyle, 1996, Baker and Viglizzo 1998, Morgan *et al*., 2007, Thornton *et al*., 2007; Ziervogel *et al*., 2008; socio-economic effects and poverty - Adger, 2003, IPCC, 2007a; Slater *et al*., 2007; effect on health and food security - Case, 2006, IPCC, 2007a, Schimidhuber and Tubiello, 2007; Nhemachena *et al*., *undated*.).

7.3.2.2. Farmers' suggested strategies to deal with future climate

The medium wealth group, which had more than half of its members above 70 years of age provided the least number of ideas for adaptations. This is contrary to the expectation that, since these elderly people have lived through many years of varied climatic conditions they should have a large wealth of experience to draw from, with suggestions for possible alternative farming interventions. It is, however, possible that these farmers were not free to share information on adaptations when other farmers within and outside their own group were around.

The strategies that were suggested by the farmers were largely concerned with cropping and tended to address water shortages. The strategies hinged on soil water conservation, crop choice, fertiliser use, irrigation and soil water conservation (Box. 7.3). Their skewed focus on cropping strategies was probably because they considered crop productivity to be more sensitive to climate variability and change, compared to livestock productivity. The suggested strategies are similar to those that the farmers in this study area use to deal with current rainfall variability (Mubaya, 2010, Mubaya *et al*., 2012; Chapter 4 of this thesis). However these strategies (to deal with current rainfall variability) are in limited use for example, only about 10% of the farmers in Mdubiwa ward, benefit from the two existing irrigation schemes, in the ward (see chapter 4). According to findings in Chapter 4 of this thesis, adoption rates for soil water conservation techniques in the area are also low, for example, only about 5% of the farmers in Lower Gweru practise pot holing (a practice where small holes are dug in-between the growing crop usually using a hoe, to harvest and conserve water (University of Zimbabwe, 2006) or ridging. Chuma *et al.* (2001), Mutekwa and Kusangaya (2006), Marongwe *et al*. (2012) and Nyamadzawo *et al*.

(2013) also reported low adoption rates for soil water conservation techniques by smallholder farmers in different parts of Zimbabwe.

Contrary to farmers' thinking, that the use of early maturing varieties would help reduce impact of climate change on yield, simulated maize yields show a greater yield reduction for early maturing varieties than late maturing varieties, under climate change (Dimes *et al*., 2008; Chapter 5 of this thesis). Thus under climate change, smallholder farmers in the study area and other semi-arid areas could improve crop productivity, particularly where irrigation is employed, by shifting to the current late maturing varieties. Although simulation results show that mean yields of SC709 are also higher current climate, than for SC403, the higher year to year variability in grain yield associated with growing the late maturing variety (SC709), makes SC403 a more suitable variety under the current climate.

Resource-rich farmers proposed supplementing natural grazing with animal feed – this being the only strategy to deal with the likely reduction in livestock productivity, that the farmers suggested. Supplementary feeding with stock feed has its own challenges since the current source of feed is mostly grain from crop production, an enterprise which is also negatively affected by climate change. It, thus, appears that the farmers did not quite integrate livestock and cropping systems in their thinking. Other strategies that farmers could employ include increasing numbers of small livestock (e.g. goats and sheep) and reducing those of cattle as small livestock could be better suited to a warming and drying climate (Nhemachena *et al.,* 2010; Nhemachena *et al*., *undated*). They could also shift towards keeping more browsers (e.g. goats) than grazers since climate change favours growth and development of browse tree species, in semi-arid rangelands (Morgan *et al*., 2007). Farmers could also resort to keeping indigenous animal breeds (e.g. *Mashona* and *Nguni* cattle breeds) rather than exotic breeds (e.g. *Brahman*) or cross breeds of indigenous and exotic breeds, since indigenous breeds are more tolerant to higher temperatures expected under climate change conditions (Thornton *et al*., 2007). Most farmers in the study area and other semi-arid communities in Southern Africa practise mixed crop-livestock systems and these systems are more suitable under climate change compared to specialized systems based on cropping or livestock production alone

(Nhemachena *et al*., *undated*). Thus, farmers can intensify their current crop-livestock systems, while those few practising only crop or livestock production can shift to mixed crop-livestock systems.

With the exception of irrigation development, all the strategies suggested by farmers are self-directed showing that farmers have the will power to deal with climate change themselves. However, there is need for capacity building, for example, through educating farmers on climate services that address climate variability and change, strengthening of existing strategies. Some integration of the available weather forecasting products to address some of the current issues in their farming systems together with the introduction of new and suitable strategies.

Box. 7.3
Lower Gweru farmers' suggestions on how to reduce or capitalize on possible impacts of climate change

Resource rich farmers (Group A)

- ✓ "Practise conservation agriculture."
- ✓ "Grow small grains."
- ✓ "Supplement grazing with animal feed."
- ✓ "Apply low levels of fertilizer."
- ✓ "Practise winter ploughing and deep ploughing to conserve moisture."
- ✓ "Government should embark more on irrigation development."

Medium resource farmers (Group B)

- ✓ "Practise water conservation by ridging and pot-holing."
- ✓ "Grow drought tolerant crops such as sorghum, pearl millet, cowpeas and maize variety SC403 which matures early."

Resource poor farmers (Group C)

- ✓ "Grow early maturing varieties."
- ✓ "Grow drought tolerant crops."
- ✓ "Practise conservation farming."
- ✓ "Apply minimal fertilizer."

7.3.3. Summary of discussions held with farmers on simulated soil water balance components and maize grain yield under different agronomic and climate scenarios

APSIM model outputs presented in section 6.A.3 (effect of mulch and basin on yield and water balance) and those simulated in chapter 5 (climate change effects on maize yield and days to maturity) were based on 28 years of climate data (1981-2008). Thus, the simulated maize yield and soil water balance parameters correspond to the 1980/81-2007/08 cropping seasons. To allow better and easier comprehension of the subject of discussion by farmers, results of the simulations were presented year by year only for a shorter period of 10 years. Graphs shown to farmers were drawn from model output data for "the past ten years" (1998/99 -2007/08 seasons) (Figs. 7.7-7.9) as it was hypothesized that farmers would perhaps recall the past 10 years with regards to rainfall pattern and agricultural productivity. This would, presumably, facilitate discussions with the farmers. Discussions were also limited soil water balance and to grain yield, although in Chapters 5 & 6 biomass and stover yield were also simulated.

7.3.3.1. Effect of mulch on soil water balance and maize grain yield

The benefits of using mulch on water retention in the soil profile as shown by the soil water balance were evident (Fig. 7.7). On average (28 years considered) 3 tha^{-1} of mulch reduced runoff and soil evaporation by 5% and 2%, respectively and increased available soil water at planting by 4%. Application of 10 tha^{-1} reduced runoff and soil evaporation by about 20% and 9% respectively and increased available soil water at planting by 10%. Farmers concurred that mulch improved the potential amount of water available to the crop. However, the improved water balance did not result in overall increase in average maize grain yield. Both 3 tha^{-1} and 10 tha^{-1} mulch gave higher yields than non-mulched maize fields, only in 13 out of the 28 years (Table 7.5).

Table 7.5. Summer growing seasons in which mulch or basin treatments gave higher maize grain yield than CP for SC403 variety grown on a sandy soil in Lower Gweru, under current climate from maximum of 28 years simulation

	Treatment		
	3 tha^{-1} mulch	**10 tha^{-1} mulch**	**Basin**
Total # years (of 28) when mulch or basin yielded better than CP	13 years	13 years	13 years
No. of years when mulch or basin yielded at least 50 kgha^{-1} grain > than CP	2 years 1988/89; 1994/95	6 years 1988/89; 1991/92; 1993/94; 1994/95; 2002/03; 2007/08	4 years 1982/83; 1988/89; 1994/95; 2007/08
No. of years when mulch or basin yielded at 10-50 kgha^{-1} grain > than CP	2 years 1998/99; 2007/08	3 years 1985/86; 1998/99; 2006/07	4 years 1983/84; 1993/94; 1998/99; 2006/07
No. of years when mulch or basin yielded less than 10 kgha^{-1} grain > than CP	9 years 1981/82; 1982/83; 1983/84; 1985/86; 1986/87; 2000/01 2001/02; 2002/03; 2006/07	4 years 1981/82; 1983/84; 1986/87; 2001/02	5 years 1981/82; 1985/86; 1986/87; 2001/02; 2002/03

Key: yellow = drought; grey = Below Normal rainfall; green = Normal rainfall and turquoise = Above Normal rainfall

Four of the seasons (1981/82, 1991/92, 1994/95 and 2001/02) in which mulch, particularly 10 tha^{-1} mulch, gave higher yields than zero mulch were drought seasons, while seven seasons had below normal (BN) rainfall and only two seasons had normal (N) rainfall amount (Table 7.5). The greatest yield benefit of 974 kgha^{-1} was obtained during the worst drought of 1992 from an application of 10 tha^{-1} and in this year, CP and 3 tha^{-1} mulch produced zero yield or a crop failure. Realization of yield benefits during poor rainfall seasons, established in this study, is consistent with Vogel (1993)'s findings that during drought years, mulch ripping systems give higher maize grain yield than clean-ripping and conventional mouldboard ploughing systems. Erenstein (2002) also points out that crop residue mulch does not normally have effects on grain yield under normal years, while Mupangwa *et al*. (2012) established no significant yield benefit from mulching, in maize and cowpea yield where soil water was not limiting.

On average, an application of 3 tha^{-1} of mulch reduced simulated maize grain yield for a relatively early maturing variety, SC403 by 1.4%, while 10 tha^{-1} reduced yield by about 5% from 2 297 kgha^{-1}, relative to conventional ploughing without mulch. However, as reported in section 6.3, these reductions are not statistically significant ($p>0.05$) (see Table 6.7a). Both 3 tha^{-1} and 10 tha^{-1} mulch treatments have lower standard deviations than conventional ploughing + no mulch, with 10 tha^{-1} mulch having the lower value of 1190 kgha^{-1}. and 3 tha^{-1} mulch, 1387 kgha^{-1}. Standard deviation for the CP treatment is 1348 kgha^{-1} (Fig. 6.1).

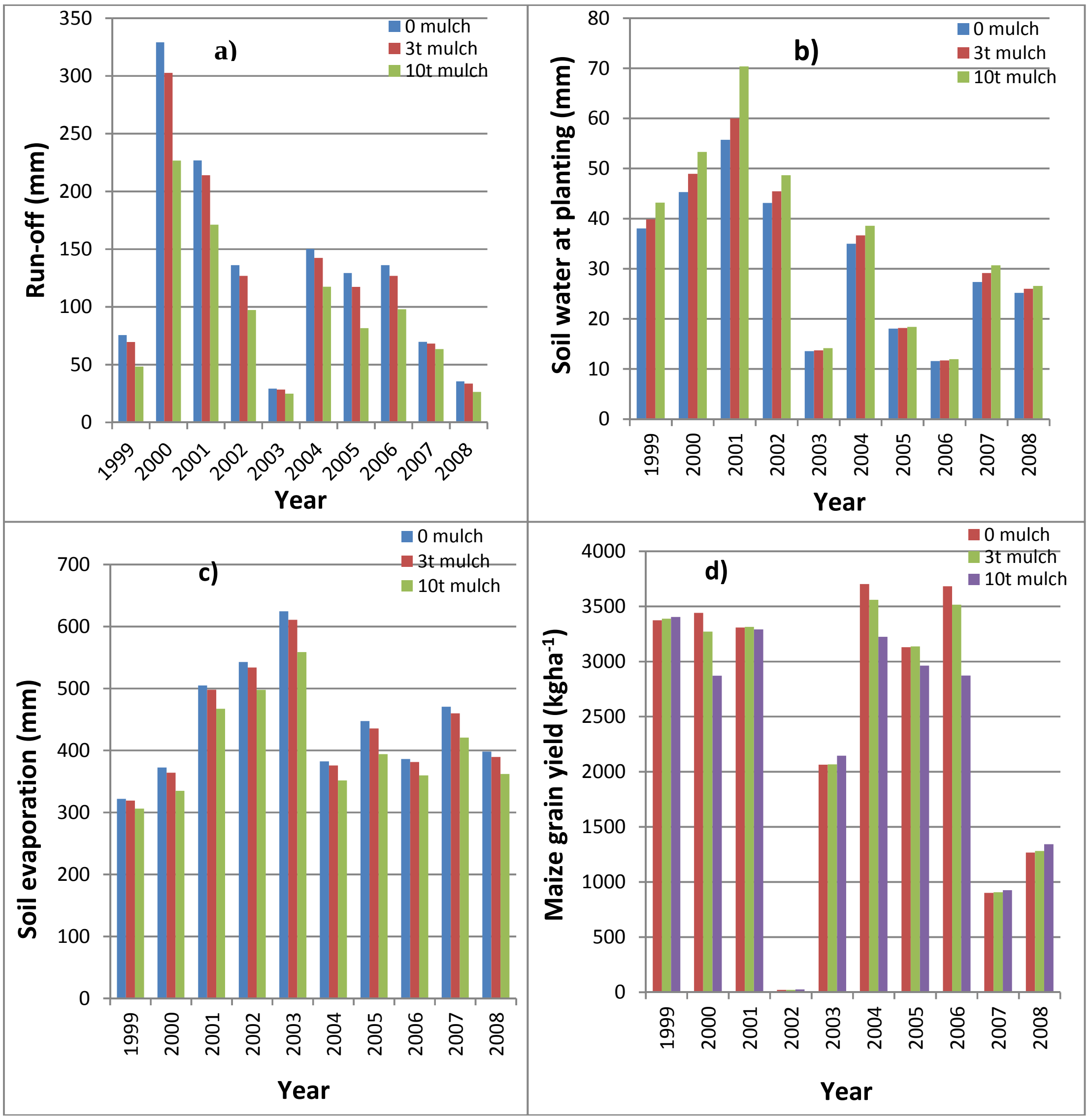


Fig. 7.7. Ten years of simulated seasonal runoff (a), soil water at planting (b), soil evaporation(c) and grain yield of SC403 maize variety (d) under different mulch treatments for a sandy soil in Lower Gweru

The most probable reason for the generally lower yields for a mulched crop compared to a non-mulched crop is limited nitrogen supply to the crop. Decomposition of crop residues can result in short-term nitrogen immobilization due to microbial activity (Giller *et al*., 2009; Verhulst *et al*., 2010, Grabowski, 2011; Mupangwa *et al*., 2011b), particularly for residues with a high C:N ratio (Erenstein, 2002; Giller *et al*., 2009). A relatively low total N-application rate of 84 $kgNha^{-1}$ was used in the simulations (farmer practice for those who use inorganic fertilizers) and this also probably contributed to lower yields for a mulched crop, consistent with Erenstein (2002)'s findings that at low nitrogen levels conventional systems (without mulch) out yielded systems that used crop residues. Farmers were informed that use of mulch required extra nitrogen application during the first years, to meet the requirements of microbes that decompose the applied dry matter (mulch) as microbes use nitrogen to decompose mulch. Farmers were advised to apply an extra 50 kg Ammonium Nitrate (34.5% N) fertilizer for the normally recommended 2-3 tha^{-1} of mulch (maize stover required to achieve about 30% soil cover after planting) and as a rule of thumb, for each extra 1 tonne of mulch, they needed to add 10 $kgha^{-1}$ of fertilizer (Dimes, 2011 - personal communication). They were also informed that immobilization of nutrients due to application of mulch occurs in the short-term periods while in the long-term, soil fertility would be improved. Farmers were also advised that when using manure, immobilization also occurs and as such the recommendation was to use manure in conjunction with a basal fertilizer (compound fertilizer) and then add nitrogen fertilizer as a top dressing during the vegetative growth stages.

Negligible effects of mulch on simulated maize grain yield obtained in this study are consistent with model simulation results obtained by Mupangwa *et al*. (2011b) for maize in southern Zimbabwe, using APSIM model (also used in current study) and Walker and Schulze (2006) on maize in South Africa using the CERES-Maize model. Variable mulch effects have been obtained from field experiments in Zimbabwe, with some showing marginal benefits of using mulch (e.g. Moyo, 2003; Mupangwa *et al*., 2007; Rusinamhodzi *et al*., 2011) and others indicating significant positive mulch effects on grain yield (e.g. Mupangwa *et al., undated).*

7.3.3.2. Effect of tillage practice (basin vs. conventional ploughing +no mulch) on soil water balance and maize grain yield

On average (28 years considered) planting basins reduced surface runoff by 57% (Fig. 6.1) and increased soil water available at sowing and drainage by 9% and 42%, respectively (Fig. 6.1), for a sandy soil in Mdubiwa ward of Lower Gweru. However, there was no overall maize grain yield advantage due to that improved water balance (reduced runoff and increased soil water at sowing) (Fig. 7.8). In 46% of the seasons where water was most limiting the average yield benefit due to basins was 34 $kgha^{-1}$ of grain, while the maximum benefit was 153 $kgha^{-1}$. In 54% of the seasons, where soil water was not limiting, the average grain yield loss with basins was 122 $kgha^{-1}$, while the maximum loss was as high as 477 $kgha^{-1}$. In four (1982/83; 1988/89; 1994/95 and 2007/08) out of 28 seasons maize grain yields were at least 50$kgha^{-1}$ less without basins compared to with basins, while basins yielded more than 100$kgha^{-1}$ more than conventional ploughing, in only one season (1988/89) (Table 7.5).The four years were dry years. Extra available water under basins did not translate into increased average grain yield, most probably due to increased nitrogen leaching caused by increased deep drainage of 42 % (see section 6.3).This is supported by the fact that in general, simulated maize yields under basin tillage were higher than yields simulated under conventional tillage in seasons with below average rainfall, while simulated yields were lower under basin than conventional tillage in above average rainfall seasons. Of the 13 years where basins yielded better than conventional tillage (Table 7.5), 11 of the years had below average rainfall (Table 7.5), while of the 15 years where basins yielded lower than conventional tillage, nine of the years had above average rainfall amounts During the severe drought of 1992, maize grain yield was zero for both basin and conventional tillage. Related to increased simulated drainage under basin tillage obtained in this study, Mupangwa and Jewitt (2011) established higher simulated deep drainage losses under no-tillage (ripping) system than under conventional ploughing for sandy clay loams in Potshini catchment in South Africa.

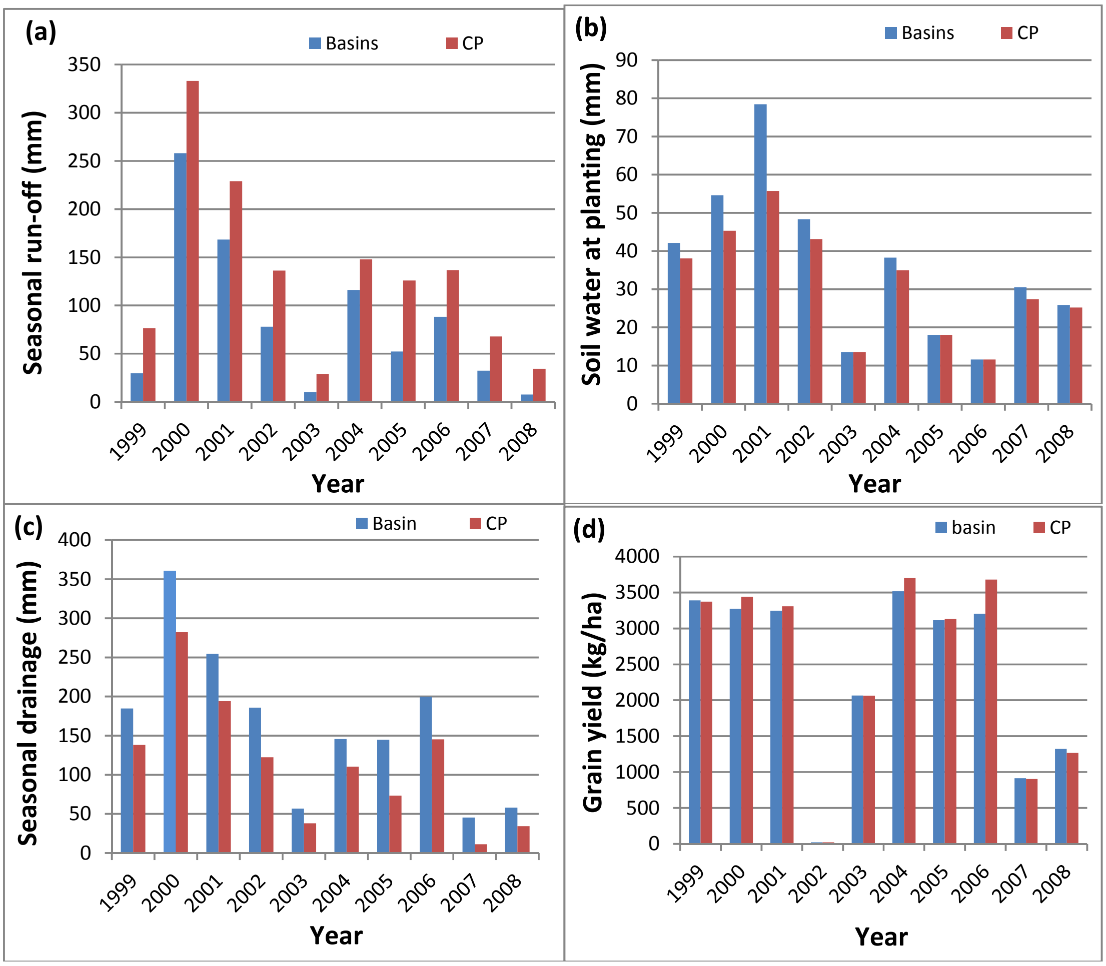


Fig. 7.8. Ten years of simulated runoff (a), soil water at planting (b), drainage (c) and grain yield of SC403 maize variety d), under basin and conventional ploughing (CP) tillage practices on a sandy soil in Lower Gweru

7.3.3.3. Effect of climate change on grain yield and days taken to reach maturity on early (SC403) and late (SC709) maturing maize varieties

Simulated grain yields under the drier climate of -15% rainfall were selected over the yields of the less dry climate of -10% rainfall, for presentation and discussion with farmers. Grain yield potential for the currently grown early maturing variety SC403 was reduced by about 16% under the A2 climate scenario (temperature increase of 3^{o}C, rainfall decrease of 15% and CO_2 concentration of 532ppm) compared to current climate, while growing the late maturing variety SC709 reduced the potential yield by 3% (Table 7.6). The most probable reason for the decrease in maize yield under climate change is the reduction in number of days to reach maturity caused by hastened crop growth rate, due to increased temperature and thus having less time to fill the grain. Time to maturity for SC403 was reduced from 138 to 115d while growing the late maturing variety SC709 reduced the number of days taken by this variety to mature from an average of 160 to 131d (Fig. 7.9). Thus, under climate change, the late maturing variety SC 709, behaved like an early maturing variety, taking about 7 days less than SC403 grown under the current climate. Under A2 climate scenario, rainfall is also likely to decrease by about 15% and this could also have contributed to the reduction in grain yield.

Table 7.6. Simulated mean grain loss for SC403 and SC709 (grown on a sandy soil in Lower Gweru) due to climate change

	Mean yield ($kgha^{-1}$)	Yield loss due to climate change ($kgha^{-1}$)
Current yield of SC403 (early maturing)	2314.5	-
Future yield of SC403	1937.7	376.8 (16%)
Future yield of SC709 (late maturing)	2233.5	81.0 (3%)

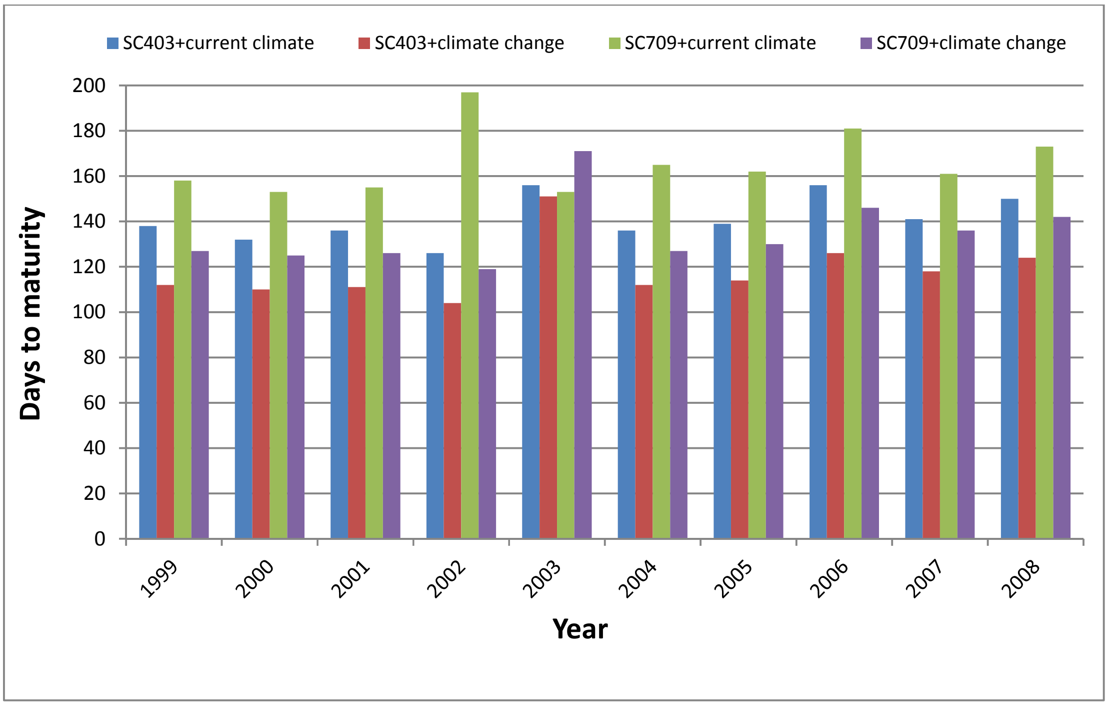


Fig. 7.9. Comparison of simulated number of days taken by early (SC403) and late (SC709) maize varieties, to reach physiological maturity under current and future climate, in Lower Gweru area

7.3.4. Readiness and non-readiness of farmers to adopt selected strategies to cope with climate variability and change

Farmers' responses to their likelihood of adopting the selected strategies, were made after discussing soil water balance components and maize grain yield simulated under the different agronomic strategies. Farmers, by then, knew the predicted effect of shifting from early to late maturing maize varieties, in the face of climate change. They also knew how they could benefit from using mulch and in which seasons good yields could be obtained from mulching and use of planting basins. The provided responses (Box. 7.4 - 6.6) are direct translations from vernacular languages (Shona or Ndebele) to English from discussions held during the focus group meetings held at Maboleni in Lower Gweru during November, 2010.

7.3.4.1. Shifting from early maturing to late maturing maize varieties

Farmers from all three categories indicated that they would readily shift from growing early maturing to late maturing maize varieties, if the need arose (Box. 7.3). This shift would not be a major challenge to the farmers as they are already planting certified hybrid seed of maize (Chapter 4 of this thesis). The only difference would be in choosing appropriate varieties. The shift will, however, call for a shift towards production of more seed of late maturing hybrid varieties by private and public seed producers. However, currently, the cost of certified hybrid seed is quite prohibitive to smallholder farmers and at times the seed is in short supply. Thus, assuming no changes in pricing policies and production costs for this important production resource, farmers will continue to experience difficulties in accessing hybrid seed. Open pollinated varieties (OPVs) which are relatively late maturing (taking approximately 160 days to reach maturity) are grown by at least a third of farmers in Lower Gweru (Chapter 4 of this thesis). Some farmers in semi-arid areas of southern Africa grow OPVs of maize as a coping strategy against climate variability and change, for example, farmers in Siyavonga and Sinazongwe districts in western and southern Zambia (Michigan State University Food Security Group, 2012) and farmers in Uzumba-Maramba-Pfungwe district in northern Zimbabwe (Progressio, 2009). Hence the use of these OPVs in future may help reduce the effect of climate change on maize yield. One group (the resource poor), raised concern about growing late maturing varieties under rain-fed conditions (Box. 7.4) as, currently, late maturing varieties are grown only under irrigation, in drier areas of the country such as Lower Gweru. The reduction in number of days to reach physiological maturity for the late maturing varieties, due to high temperature under climate change, should allow them to grow and mature using less soil water. However, under climate change growing crops under irrigation will be more important than it is now, since the amount of rainfall is expected to be less.

Box. 7.4
Lower Gweru farmers' responses on feasibility of adopting long season varieties

Resource rich farmers (Group A)

- "Given that SC709 (long season maize variety) will have reduced number of days to reach maturity and that it will yield better than SC403 (short season variety) under climate change, we will grow SC709."

Medium resource farmers (Group B)

- "By switching to SC709 we get high yields if there is climate change, so we can grow the long season varieties instead of the short season varieties."

Resource poor farmers (Group C)

- "Advantage of growing SC709 is that it will yield better than SC403, so it will be better to grow SC709."
- "The disadvantage is that long season varieties require more water. We will recommend SC709 to be grown in the irrigation schemes."

7.3.4.2. Use of mulch

There were mixed reactions from the three categories of farmers, with the resource rich farmers showing much willingness to use mulch (Box. 7.5). Some of them were even applying N-fertilizer to mulch. Their concern was on the limited area they were able to cover mainly due to limited supply of available stover as much of the stover was also used to feed animals during the dry season. About a third of farmers in this category were the keen farmers who often participated and worked closely with agricultural extension agencies whenever new technologies were introduced in their areas. For the medium category farmers, the main barrier was the high labour requirements to implement mulching and they also thought it better to use stover to feed the animals rather than to use it for mulching purposes. While some farmers who own cattle did not readily appreciate using crop residues for mulching purposes instead of using them to feed their cattle, some were of the view that if conventional ploughing was substituted by practices such as minimum tillage, then the need to feed draft cattle with crop residues would fall away, since for these farmers, crop residues were mostly used to feed draft animals. Trade-offs between these two uses (animal feed and mulching) and any other uses of crop residues are a concern for the farmers, similar to what has been noted for smallholder farmers elsewhere in the semi-arid areas (Lal, 2007; Siziba, 2008; Twomlow *et al*., 2008b; Giller *et al*., 2009; Mazvimavi *et al*., 2010; Mazvimavi, 2011; Rusinamhodzi *et al*., 2011). In addition to facing the dilemma on how best to use available crop residues, most smallholder farmers' production levels, particularly those of the resource poor, cannot meet the requirements of CA per se, where at least 3 tha^{-1} of mulch is recommended (Twomlow *et al*., 2008b; Mazvimavi *et al*., 2010; Rusinamhodzi *et al*., 2011).

The resource poor farmers emphasized advantages of using mulch and expressed concern about the need to apply N-fertilizer on the mulch (Box. 7.4). This response is expected since the majority of smallholder farmers in Lower Gweru and other semi-arid areas of Zimbabwe can hardly afford to apply adequate fertilizer in their crop fields (Mudhara, 1995; Ahmed *et al*., 1997; Ncube *et al*., 2009; Chapter 4 of this thesis). Despite this limitation, farmers need to be educated on the importance of applying adequate nitrogen to cater for microbial requirements for decomposition of mulch, for full benefits of mulch to be realized. This is important, since according to Giller *et al*. (2009), poor short-term effects of practices such as mulching may influence adoption rates. Labour shortage was cited as a limitation to the adoption of mulching as a practice, particularly by the medium and resource poor farmers who often rely only on family labour, which mostly comprises women, school children and elderly people. The resource rich farmers can at least manage to hire labour.

Box. 7.5
Lower Gweru farmers' responses to feasibility of adopting use of mulch

Resource rich farmers (Group A)

- "It is easy to adopt, because we have stover available. After harvesting, we have stover which we can use."
- "Some of us are already buying fertilizer and adding to mulch."
- "We work with extension officers and the meteorological office, so we can get rainfall forecasts to help us know whether to apply mulch or not."
- "The disadvantage is that in most cases we only manage small areas due to limited labour."

Medium resource farmers (Group B)

- "Applying mulch is labour intensive."
- "We need stover to feed cattle. It is better to give stover to the animals."

Resource Poor Farmers (Group C)

- "The disadvantage is that we can use mulch provided we have ammonium nitrate."
- "The advantage of using mulch is that weeds will be reduced".
- "Mulch also helps in water conservation."

7.3.4.3. Adoption of planting basins

Making planting basins and managing weeds through hand hoeing were cited as the major labour demanding practices associated with use of basins (Box. 7.6). According to the farmers, the other negative aspect of using planting basins, is the fact that the practice did not give them time to rest between harvest of one crop and establishment of the next, since basins had to be maintained and weeds controlled soon after harvest of the previous crop (Box. 7.6). This sentiment is supported by Erenstein (2002), who reports a short turn-around time between crops with the planting basin system of establishing crops. Use of planting basins has the potential to improve crop productivity of smallholder farmers in semi-arid Zimbabwe, particularly those without draft power (Mupangwa *et al*., 2008; Twomlow *et al.,* 2008b; Twomlow *et al.,* 2008c; Mazvimavi, 2011; Mupangwa *et al*., 2011b). Labour constraints have been identified as a major limiting factor in the adoption of planting basins elsewhere in Zimbabwe and Africa (Siziba, 2008; Twomlow *et al*., 2008c; Giller *et al*., 2009; Mazvimavi and Twomlow, 2009; Mazvimavi *et al*., 2010; Mazvimavi, 2011). Giller *et al.* (2009) suggested that implementing components of CA such as planting basins could shift the farming labour burden towards women given that, unless herbicides are used to control weeds, more hand hoeing (which is normally done by women) would be required. To enhance adoption of planting basins, constraints such as labour limitations need to be addressed, for example through use of appropriate equipment such as jab planters as noted by Mazvimavi *et al*. (2010). They also need to be educated about the long-term soil conservation and sustainability benefits of using mulch and basins as it has been noted that there are minimal benefits of these technologies in the short term (Mupangwa *et al*., 2007; Giller *et al*., 2009). Farmers could also be encouraged by the fact that in subsequent years, of using these components of CA, labour requirements are reduced since they would only have to maintain rather than dig basins and since weed pressure tends also to be reduced with time (Twomlow *et al*., 2008c), particularly where mulch is used, it may help suppress weeds (Mashingaidze *et al*., 2009).

Resource poor farmers indicated that adoption of basins and mulch could be constrained by the need to fence fields to protect the basins from being destroyed and mulch from being eaten by the animals during the dry season. Farmers could resort to using live fences which are durable and cost less cost in the long-term and as suggested by Mutsamba *et al*. (2012). Alternatively, crop residues/stover used as mulch could be treated with organic repellents such as cow dung and tobacco scrap to prevent animals from grazing them.

At the time of the study, use of planting basins and mulch were still in their infancy in the study area (Nyama and Mdubiwa wards in Lower Gweru). The few farmers who were using the technologies were doing so on small areas of less than 0.1 ha and they adopted the technologies from neighbouring wards, for example Bafana ward, where pilot projects initiated by Non-Governmental Organizations (NGOs) existed (Moyo, 2012 - personal communication). At the time of conducting the study, approximately 35-40% of the farmers in the study area had joined the CA programme spearheaded by Help Germany, an NGO (Fig.7.10) (Moyo, 2012-personal communication).

Fig. 7.10. a) From left, Johnson Moyo, extension officer with Help Germany, Mirirai Musasanuri, Acquiline Gumbira and Alfred Pawadyira (extension officers from AGRITEX) at the Help Germany Conservation Agriculture demonstration plot in Nsukunengi village in Mdubiwa Ward. In b) group of farmers from Nsukunengi village weed a sub-plot on the demonstration plot, in preparation for planting sunhemp.

Box. 7.6
Lower Gweru farmers' responses to feasibility of adopting planting basins

Resource rich farmers (Group A)

- "We would want to use basins because they improve water and nutrient retention. They also improve aeration."
- "The problem is, one has to go back to the field much earlier after the previous harvest. One hardly rests."

Medium resource farmers) (Group B)

- "Basins have advantages that they conserve water and prevent runoff".
- "They confine nutrients to one place."
- "They are however difficult to adopt for elderly people, who find it difficult to dig the basins. We recommend that a field be ploughed (conventional ploughing) first and then holes (basins) be made in the ploughed field."
- "Their other disadvantage is that if one goes for a large area, it becomes quite difficult to control weeds."

Resource poor farmers (Group C)

- "We recommend use of basins where fields are fenced out to guard them against animals."
- "Basins require young people and not old people, since it is hard to dig them."
- "We would need to work with agricultural extension officers because we need the knowledge and training from them."

7.3.5. Case studies on feasibility of adopting late maturing varieties, using mulch and planting basins to address negative impacts of climate variability and change

Responses from individual farmer interviews (Fig. 7.11) further reiterated the labour constraint associated with use of basins (Box. 7.7 and 7.8) as well as the competition for mulch among various uses (Box. 7.7) that were raised during group discussions with farmers. Similar to responses from group discussions, the two farmers interviewed did not consider shifting to late maturing maize varieties as a “new” challenge. Responses from the case studies show that farmers are observant and can learn from other farmers' experiences as revealed by Ms Getrude Bonde's observation of failure of a neighbour's maize crop grown in planting basins during a very wet season (Box. 7.7). They are also innovative and resourceful as indicated by the suggestion by Mrs Anna Moyo to collect cow dung outside cattle pens, to apply in planting basins (Box. 7.8) and by acquisition of planting seed by farmers, as a group (Box 7.7). As highlighted by some authors, for example Twomlow *et al.* (2008c), Mazvimavi (2011) and Mupangwa *et al*. (2011b), the case study of Mrs Moyo (Box. 7.8) shows that the use of planting basins is appropriate for those farmers who do not own draft animals and implements. On the other hand, responses by Ms Getrude Bonde (Box. 7.7), show that there is little chance of some farmers using mulch or planting basins to reduce impacts of climate variability and change.

Box. 7.7 Case study 1
Ms Getrude Bonde
of Mxotshwa village in Mdubiwa ward, Lower Gweru,
interviewed on 25 November, 2010

Ms Getrude Bonde is a widow with three adult children, one school going son and a grandchild. She is 49 years old and stays with two school going teenager boys (own son and relative). She has no cattle and owns a few goats. Ms Bonde relies on hired draft power (both oxen and plough) for her maize field preparation.

Strategy 1**: **Shift from growing short season maize varieties to long season ones
The farmer's response was that it was not a problem to think of shifting from growing short season maize varieties such as SC403 and SC513 to long season varieties such as SC709. "As a serious farmer, I will grow the variety because I am convinced that it will be the appropriate one to grow. I will be buying the seed just as I am doing now. For example we have just put our money together as a group and bought maize seed from the Grain Marketing Board. We got Pioneer seed variety PHB 3258. I also have Seed-Co variety SC513".

Strategy 2**: **Use of mulch
In her response the farmer said: "There are plenty of termites here. If there is little water, mulching is a non-starter. I have seen this in the garden where I use mulch." When asked whether she could get the mulch to use in the field, her response was: “Yes, I can get grass or stover from maize, but I would rather use it to make compost.” She also added that she would not be able to afford the extra fertilizer required, when one uses mulch.

Strategy 3**: **Use of planting basins
The farmer had this to say: “I certainly cannot go for “gatshompo” (planting basins). It has a high labour requirement for weeding since one sows seed on unploughed land. After planting, one has to quickly go back to the field to weed, so there is no rest. In addition, I have not seen a real good crop from those basins. Last year my neighbour had a bad crop from the basins. To begin with rains were not much, but later in the season there was much rain and her (neighbour) maize crop tasselled when it was very short. The crop was also yellowish”.

Box 7.7: Case study 2
Mrs Anna Moyo
of Msingondo village in Nyama ward, Lower Gweru,
interviewed on 25 November 2010

Mrs Moyo is 42 years old and is a widower. She has one son working in the army. She stays with her daughter in-law and two young grant children who are both below school-going age. She has no cattle and hires draft animals and implements.

Strategy 1: Shifting from growing early maturing to late maturing maize varieties

Mrs Anna Moyo saw no problem in shifting from short to long season maize varieties. When asked whether getting certified seed of the varieties she was currently growing was a challenge or not, her response was: "Seed is expensive, but I can afford to buy it if available.”

Strategy 2: Use of mulch

Her response was: "Since only a small area is grown under mulch, I can afford to use mulch, because stover is available."

Strategy 3: Use of planting basins

Mrs Moyo had the following to say, concerning use of basins: "The problem with basins is getting inputs in the form of manure or fertilizer (inorganic). However, use of basins is a good idea since I have no cattle. When one hires draft power, one always prepares land too late. I can collect and pick up cattle dung outside people’s kraals and use in the basins." Asked on whether labour availability would not be a hindrance to the use of basins she agreed that labour was a limiting factor, but said she could always give herself time to do the basins.

Fig. 7.11. Mrs Anna Moyo (with hat) of Siyabandela village in Nyama ward explains the advantages of planting crops in basins to researcher, Veronica Makuvaro and b) she shows the field where she planted maize in basins during the 2009/10 season

7.3.6. Lessons learnt

Focus group discussions and case studies held with farmers provided a learning platform for both farmers and researchers. Farmers acknowledged that they had learnt some concepts and facts concerning crop models, climate change and components of conservation agriculture namely use of mulch and planting basins (Box 7.9) via the focus group discussions.

Box. 7.9
Lower Gweru farmers' learning points, direct translation of their responses in vernacular languages

- "Under climate change we have to change varieties to long season varieties such as SC709."
- "We learnt about conservation farming especially the advantages and disadvantages of using mulch and basins."
- "We need to apply more fertilizer when we use mulch."
- "Basins can also reduce yields in high rainfall seasons."
- "It is important to keep records for one to be able to use a model."
- "It is important to work in collaboration with (Department of Agricultural Technical and Extension Services (AGRITEX)."
- "We got feedback on results of survey carried out in 2008 about, climate change."
- "We learnt about expected future climate."

7.4. Conclusion and Recommendations

In this chapter Lower Gweru farmers' opinions on the impacts of climate change as well as their suggestions on dealing with climate change were captured. Researchers also had an opportunity to inform farmers about the expected future climate for Zimbabwe, by 2050. Farmers expressed their opinions on possible adoption of late maturing varieties, mulch or planting basins as climate change adaptation strategies.

7.4.1. Farmers' envisaged effects of climate change and their suggestions for dealing with the effects

According to farmers in Lower Gweru, climate change is likely to have a negative impact on agricultural productivity, availability of water resources, food and nutrition security, health as well as on their socio-economic well-being. Possible effects of climate change spelt out by the farmers match those effects that have been established in literature, except that the former are not quantified. However, it appears that farmers overestimated the effect of increasing temperature as they envisaged "burning" of crops due to heat stress, which has not really been previously predicted. Farmers would benefit from learning about the degree of agricultural other losses they are likely to incur due to climate change, from researchers and agricultural extension agencies.

Generally, farmers' responses were similar among the wealth groups. It was also observed that farmers' responses pertaining to livestock production, particularly on adaptation issues, were rather limited in scope. As might be expected, it was only the rich farmers (owners of several cattle), who had some ideas on reducing climate change effects on livestock production. It appears farmers in Lower Gweru are more inclined to crop than livestock production, as could be expected of subsistence farmers. The opportunity to boost livestock production in the smallholder farming sector in semi-arid areas is provided by the changing climate. Extension agencies should encourage appropriate livestock production systems for smallholder farmers. These may include intensification of small livestock (e.g. goats and sheep) production, rearing more browsers (e.g. goats) than grazers and keeping indigenous animal breeds rather than exotic breeds or use cross breeds of indigenous with exotic breeds. Mixed crop-livestock systems should be encouraged and/or introduced where they are not well established.

Also worth noting is the fact that most of the strategies that farmers suggested for dealing with future climate are similar to those that they are currently using to cope with current climate variability and most of them address problems of climate change that affect crop productivity. Failure to produce alternate strategies is perhaps because they were somewhat depressed by the oppression of the poor state of the economy at that time. Farmers, researchers and agricultural extension agencies are challenged with identification of new and viable adaptation strategies that farmers can employ to reduce impacts of climate change.

It was encouraging to note that the majority of the strategies that farmers suggested involve farmers taking action themselves rather than strategies that could be initiated from outside communities. It was, however, discouraging to find that some of the current strategies of coping with climate variability, for example irrigation farming and use of water conservation technologies are not well adopted by farmers in Lower Gweru due to the requirement of extra resources to establish such infrastructure.

Farmers' strategies to reduce the effects of climate change should be re-enforced by the extension workers and NGOs. Government policies should promote capacity building of the farmers and promote development of technologies that reduce vulnerability of farmers to climate variability and change. These technologies include breeding for appropriate animal breeds and crop varieties as well as provision for investment to develop more and appropriate irrigation systems which need to be fed to the higher authorities in the district and at national level in Zimbabwe.

Although the farmer groups were formed according to wealth ranking, it emerged that the resultant three wealth groups fitted in identifiable age groups. More than half of the resource rich were within the age range of 45 to 60, the medium were mostly over 70 years old while for the resource poor, the age range spanned from to 25 to 70 years, with a third being in the range 25 to 35 and two-thirds in the range 45-70. It would be interesting to explore the association, if any, between age and wealth status among smallholder farming communities, in future research work.

7.4.2. Likelihood of farmers to shift to late maturing varieties and to use mulch and planting basins

Shifting from growing early maturing maize varieties to late maturing varieties, poses no serious challenges to the farmers, provided planting seed is available and seed cost affordable. Adoption of these varieties would thus, require supporting government policies to ensure adequate and affordable seed supplies. It was apparent that yield benefits from mulch or planting basin tillage were realized during low rainfall seasons. To this effect information about the nature of the rainfall season becomes vital as it will assist farmers to make decisions on whether or not to use mulch and/or planting basins. Farmers are therefore encouraged to use seasonal rainfall forecasts as a decision supporting tool. This would also entail meteorologists to produce credible forecasts and train extension agencies and farmers on the application of these forecasts.

Although farmers appreciated the benefits of using basins and mulch on sandy soils on the soil water balance and on crop yield (in some years), there are factors that hinder them from adopting these strategies. The main barrier to adoption of basins and mulch is inadequate labour especially for weed control and digging of basins. The need to fence fields, is also a challenge to the farmers, particularly the resource poor farmers. Farmers were concerned about the limited size of land they could cultivate using hand dug planting basins, due to the associated family labour limitations. There is need to introduce appropriate equipment for making planting basins and farmers who can afford herbicides can reduce the labour requirements for weeding.

There is competition for use of stover among different uses which include use as feed and use as mulching and composting material. Alternative sources of mulching material, for example grass could be used where such dilemma in use of stover exists. The need to apply "extra" N-fertilizer to address the problem of nutrient immobilization is also a limitation to effective use of mulch.

CHAPTER 8

SUMMARY OF FINDINGS AND RECOMMENDATIONS

This chapter highlights the implications of findings of this study and suggests how the findings can benefit communities, particularly smallholder farmers in semi-arid areas of Zimbabwe. Organizations and institutions which could participate in improving current and future cropping practices of farmers as well as in generating new information on effects of climate change on crop productivity and water resources are also indicated in this chapter. Although the findings are based on case studies conducted in Lower Gweru and Lupane communal areas in Gweru and Lupane districts of central and western Zimbabwe, they can be applied to other smallholder farmers with similar biophysical and socio-economic conditions across southern Africa.

8.1. Current practices and views of smallholder farmers on climate change effects on agricultural productivity

Lower Gweru and Lupane communal areas are located in Natural Regions III and IV, respectively and the farmers in these areas are from a range of wealth categories (and socio-economic status) as indicated mostly by differences in cattle ownership, possession of farming implements and standard of farmers' homesteads. Farming systems are broadly similar between the two communal areas, with differences in practices such as crop variety, type of seed (hybrid vs. open-pollinated varieties) and the amount of land planted to particular crops being determined by differences in biophysical conditions, mainly rainfall amount and soil type. Differences in practices also differ among the different farmers, due to different socio-economic status (represented by the wealth categories). For example, it was apparent that use of planting basins was more applicable to resource poor farmers due to their lower economic status and lack of draft power. These differences demand that more specific cropping recommendations be given to the different categories of farmers, rather than blanket recommendations, as is currently commonly done by agricultural extension agencies. This needs to receive attention from both research and extension staff so as to provide smallholder farmers with an improved service based on scientific evidence from field experiments.

Some of the identified farmer practices could be improved to increase household food and nutrition security as well as incomes of smallholder farmers. This could be achieved through various stakeholder participation, for example:

- Agricultural extension officers should promote and encourage farmers to grow improved varieties of small grain crops (millet and sorghum) as well as improved varieties of open-pollinated maize compared to the traditional varieties
- Farmers should use correct inter-row spacing when they use the "plant following the plough" method of establishing crops, by skipping the correct number of rows before dribbling seed into the furrow
- For the current cropping systems, seed companies and other seed multiplication agencies should produce adequate seed of legume crops, particularly that of improved groundnut varieties and cowpeas to enhance implementation of effective crop rotations or intercropping to promote adoption of balanced diets by smallholder farmers. Seed companies should also supply more seed for improved small grain crops, open pollinated maize varieties and sunflower
- Fertilizer use efficiency could be improved by employing techniques such as precision agriculture and micro-dosing, technologies which have been tested elsewhere in the country
- Effective implementation of the agronomic improvements suggested above can be achieved by having on-farm demonstration trials in these areas and this could be funded by seed companies and agro-chemical companies.

Previous studies have established perceptions of smallholder farmers in Lower Gweru and Lupane communal areas, on climate variability and change. In this study, farmers in Lower Gweru were formally informed of the expected climate scenario for Zimbabwe by 2050 and asked for their opinion on possible effects of climate change on agricultural productivity. It is recommended that relevant government ministries, for example the Ministry of Environment, Water and Climate and the Ministry of Agriculture initiate collaborative climate change awareness campaigns for farmers as this will enhance adaptation using identified adaptation strategies in future. Appropriate policies should also be developed to support such initiatives, for example, courses in climate change and its effects on agricultural productivity and water resources could be made compulsory in schools and agricultural training institutions to equip future agricultural practitioners with knowledge on the subject. To this effect text books could be written which can be used as resource materials at different training levels.

Farmers' initial suggestion to grow early maturing maize varieties as a strategy to reduce the impact of climate change on yield is likely to result in greater yield losses than if they grow late maturing varieties. Further evidence from research is required to support this view and if substantiated, farmers could be advised to grow late maturing crop varieties by 2050. Although farmers indicated that shifting from growing early maturing maize varieties to growing late maturing varieties, was relatively easy, they highlighted cost of seed as a likely prohibiting factor just as is the case currently. To this effect, the Ministry of Agriculture, Mechanization and Irrigation should subsidize prices of seed to afford smallholder farmers access to the most appropriate seed. The other strategies that farmers could possibly use to adapt to climate variability and change effects are use of planting basins and mulch. Mulch and basins resulted in improved soil water balance (reduced run-off, reduced soil evaporation) but this did not result in significant overall yield benefit in the long-term analysis. However, during low rainfall seasons there were yield benefits from use of these technologies. Thus, in poor rainfall seasons farmers can improve yields through adoption of mulch and planting basin techniques. Farmers could make informed decisions on whether to use these technologies or not if they have access to seasonal rainfall forecasts. The Meteorological Services Department is thus challenged with provision of timely and credible rainfall forecasts with added explanation and specific advisory messages for each Natural Region. This also needs training of farmers and intermediaries, such as agricultural extension officers, on use (meaning and interpretation) of seasonal rainfall forecasts. Similarly indigenous seasonal rainfall forecasts need to be tested for their credibility.

It was apparent that planting basins are labour intensive and the elderly farmers particularly find it difficult to implement them. Adoption of planting basins can be improved by use of appropriate equipment such as Jaba planters used elsewhere (e.g.

other areas of Zimbabwe and in Zambia) and modified animal drawn ploughs as used in parts of South Africa. For farmers to benefit from use of mulch, mulched crops need to get an extra dose of nitrogen fertilizer to reduce nitrogen immobilization by soil microbes during decomposition.

8.2. Extreme climate trends and simulated climate change effects on maize yield and water availability for western and central Zimbabwe

There is evidence of warming particularly during day-time and the frequency of hot days increases over the period 1978-2007 for western Zimbabwe. Maximum temperatures were found to increase at a faster rate (2-3 times) than minimum temperatures for Bulawayo Airport station for the period 1978-2007. Thus, future studies (in controlled environments or involving climate and crop modelling) concerning climate change effect on crop growth and development may have to consider an asymmetric change in maximum and minimum temperature for areas such as western and central Zimbabwe.

This warming could have effects on crop growth and development as well as on livestock performance. Changes in diurnal temperature range (DTR) are positive, but not significant for all seasons except for mean DTR during the winter season. Positive trends are inconsistent with climate change. Thus, the established warming trends could be due to factors other than global anthropogenic climate change and meteorologists could carry out attribution studies to establish reasons for warming in western Zimbabwe. There is, however, no evidence of changes in extreme rainfall amounts and proportion of rainfall from extreme rainfall events. Neither is there evidence of change in rainfall intensity (rain per rain day or greatest amount of rainfall received in 5 days). On dry-spells, it is only the duration of the longest dry spell during the first half of the season which is increasing significantly. Thus, for this part of the rainfall season farmers need to embark on *in situ* field studies of appropriate water conservation techniques to promote successful crop establishment. This also means that the short-term weather forecasts (1-14d) become very important for these farmers' decision making in the first part of the season. Therefore, the Meteorological Services Department should be sure to improve the accuracy and timeliness of these rainfall forecasts and the efficient dissemination to rural areas using appropriate methods.

In this study, trends in extreme rainfall and temperature were established from historical climate data for one meteorological station, Bulawayo Airport, in Natural Region IV, using STARDEX software. Future research work could improve the value of the current results by analyzing climate data from more stations, particularly selected from and representing all the five Natural Regions in the country. The results could then contribute to Geographical Information Systems (GIS) and provide input into the re-mapping of Natural Regions and reformulation of farming recommendations.

APSIM model was used to simulate maize yields and soil water balance components under current and future climate scenarios. Climate change significantly reduces the number of days taken by maize to reach physiological maturity, by 21 and 28 days for early and late maturing varieties respectively. Maize grain yields are projected to be reduced by about 17%, under the A2 climate change scenario, by 2050. This has implications on both household and national food security as maize is the staple crop. The increase in extreme temperatures particularly day-time temperatures and frequency of hot days, resulting in significant decrease in days to maturity of maize, calls for breeders to develop new heat and drought tolerant maize and other crop varieties and animal breeds. Government should also develop policies that ensure availability and access to adequate amounts of seed of appropriate crop varieties for smallholder farmers. Farmers need to diversify sources of income within and outside agriculture as agricultural production is negatively affected by current climate variability and change. The Ministry of Small and Medium Enterprises should put more thrust on "traditionally farming communities" and encourage and support them to take on viable agricultural as well as non-agricultural projects. The projects should ideally include product value addition through processing and marketing, as this would increase farmers' profits and agricultural sustainability and retain the resources in the rural farming area.

Run-off is significantly reduced under the A2 climate change scenario by about 36% and this reduces water supply from surface water resources. Decline in water resources will result in reduced water supply for irrigation as well as livestock and domestic consumption for both rural and urban communities. Water re-cycling, efficient irrigation methods and judicious use of water, supported by appropriate government policies, are some of the strategies that can be employed to reduce the negative effects of climate change on water supply.

From the view point of information generation, APSIM model can be used to explore climate change effects on growth and yield of other important cereal crops namely pearl millet and sorghum, in future. These crops are currently better suited to the drier regions, Natural Regions IV and V, than maize. The model could also be used to simulate and compare yields of legume crops such as cowpeas and groundnuts as well as open pollinated maize varieties under current and future climate, as these crops were found to be important crops grown by smallholder farmers in central and western areas of Zimbabwe. APSIM could also be used to simulate and compare crop yields under different climate scenarios and cropping systems, for example, rotations, sole cropping and intercropping. Simulated smallholder crop yield under climate change could be fed into economics models to assess the economic implications of climate change for example, income gains or losses. These topics hold potential for future Masters students research projects.

The following ministries and organizations are therefore identified as possible users of findings from this study, to improve food security and incomes of smallholder farmers under current and future climate conditions and to ensure availability of water to all communities, in the face of climate change.

- Ministry of Agriculture, Mechanization and Irrigation
- Ministry of Environment, Water and Climate
- Ministry of Local Government, Rural and Urban Development
- Ministry of Small and Medium Enterprise Development
- Non-Governmental Organizations
- Agrochemical companies
- Seed companies
- Researchers

However, climate change is cross-cutting and will affect all communities (rural and urban) and development as a whole. Therefore all development sectors should include climate change aspects in their long-term planning.

REFERENCES

Abrol, Y.P. and Ingram, K.T. 1996. Effects of higher day and night temperatures on growth of some crops. In: Bazzaz, F. and Sombroek, W. (Eds.). Global Climate Change and Agricultural Production – Direct and Indirect Effects of Changing Hydrological, Pedological and Plant Physiological Processes. FAO, Rome, Italy. 68p. Available on: http://www.fao.org/docrep/w5183e/w5183e00.htm#Contents (Accessed 21/08/2012).

Achberger, C. and Chen, D. 2006. Trend of extreme precipitation in Sweden and Norway during 1961-2004. Earth Science Centre, Göteborg University, Sweden. Research report C72. ISSN 1400-383X. 58pp. Available on: http://rcg.gvc.gu.se/pdf/report_final_1st.pdf (Accessed 07/09/2013).

Adger, W.N., Huq, S., Brown, K., Conway, D. and Hulme, M. 2003. Adaptation to climate change in the developing world. *Progress in Development Studies,* **3**(3):179-195.

Aguilar, E., Aziz Barry, E., Brunet, M., Ekang, L., Fernandes, A., Massoukina, M., Mbah, J., Mhanda, A., do Nascimento, D.J., Peterson, T.C., Thamba Umba, O., Tomou, M. and Zhang, X. 2009. Changes in temperature and precipitation extremes in western, central Africa, Guinea Conakry, and Zimbabwe. *Journal of Geophysical Research*, 114:1955-2006.

Aguilar, Y. 2001. Autonomous and planned adaptation: The low watershed of the Lempa River, UNFCCC-UNDP workshop on adaptation methodologies. Available on: http://unfccc.int/files/meetings/workshops/other_meetings/application/pdf/elsalvya.pdf (Accessed 12/11/2013).

Ahmed, M.M., Rohrbach, D.D., Gono, L.T., Mazhangara, E.P., Mugwira, L., Masendeke, D.D. and Alibaba, S. 1997. Soil fertility management in communal areas of Zimbabwe: Current practices, constraints and opportunities for change: Results of a diagnostic survey. Southern and Eastern Africa Region Working Paper no. 6, Bulawayo, Zimbabwe: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Southern and Eastern Africa Region. 27pp (Semi-formal publication).

Akpalu, W., Hassan, R.M. and Ringler, C. 2008. Climate variability and maize yield in South Africa: results from GME and MELE methods. Environment and production technology division IFPRI discussion paper; 2008. pp. 1-12.

Akponikpe, P.B., Johnston, P. and Agbossou, E.K. 2010. 2nd International Conference: Climate, sustainability and development in semi-arid regions. ICID+18. August 16-20, 2010, Fortaleza-Ceara, Brazil.

Alexandratos, N. and Bruinsma, J. 2012. World agriculture towards 2030/2050: The 2012 revision. *ESA Working paper No.* 12-03. Rome, FAO.

Alexandrov, V., Dubuisson, B., Moisselin, J-M. and Koleva, E. 2006. A case study on utilization of precipitation indices in Bulgaria. Proceedings of the International conference on Water Observation and Information System for Decision Support *(BALWOIS)*, Ohrid, Macedonia, 23-26 May 2006, (CD) 18pp. Available on : http://balwois.com/balwois/administration/full_paper/ffp-725.pdf (Accessed 21/08/2012).

Ali, A., Yazar, A., Aal, A.A., Oweis, T. and Hayek, P. 2010. Micro-catchment water harvesting potential of an arid environment. *Agricultural Water Management,* **98**:96-104.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and Drainage paper no. 56. 290pp.

Alumira, J. and Rusike, J. 2005. The Green Revolution in Zimbabwe. *Journal of Agricultural and Development Economics,* **2**(1):50-66.

Alvord, E. 1926. The Great Hunger: The story of how an African chieftaincy improved its farming methods under European guidance. *Native Affairs Department Annual (NADA), Report*, **6**:35-93.

Anagnostopoulou, C., Flocas, H., Maheras, P. and Patrikas, I. 2003. Relationship between atmospheric circulation over Greece and western-central Europe during the period 1958-1997. *International Journal of Climatology,* **24**:1745-1758.

Arnell, N.W. 1999. Climate change and global water resources. *Global Environmental Change,* **9**:31-49.

Arnell, N.W., Hudson, D.A. and Jones, R.G. 2003. Climate change scenarios from a regional climate model: Estimating change in runoff in southern Africa. *Journal of Geophysical Research*: *Atmosphere*, **108**(D16):4519-4536.

Aslam, M., Zamir, M.S.I., Afzal, I., Yaseen, M., Mubeen, M. and Shoaib, A. 2013. Drought stress, its effect on maize production and development of drought tolerance through potassium application. *Cercetări Agronomice în Moldova*, **46**(2):99-114. Available http://www.uaiasi.ro/CERCET_AGROMOLD/CA2-13-09.pdf (Accessed 10/01/2013).

Ayers, R.S. and Westcot, D.W. 1985. Water quality for agriculture. Food and Agricultural Organization (FAO) of the United Nations. FAO Irrigation and Drainage Paper 29.

Badawy, H.A. 2009. Effect of expected climate changes on evaporation losses from Aswan High Dam Reservoir (AHDR). Thirteenth International Water Technology Conference, IWTC 13 2009, Hurghada, Egypt. Available on: http://www.iwtc.info/2009_pdf/1-1.pdf (Accessed 04/11/2013).

Baker, B. and Viglizzo, J.F. 1998. Rangelands and livestock. Chapter 9. In: Feenstra, J.F, Burton. I, Smith, J.B and Tol, R.S.J. (Eds.). Handbook of Methods for Climate Change Impact Assessment and Adaptation Strategies. IVM/UNEP Version 2.0. Available on: http://130.37.129.100/ivm/pdf/handbook_range.pdf (Accessed 20/04/2013).

Balba, A.M. 1995. Management of Problem Soils in Arid Ecosystems. CRC Press. Boca Raton, Florida. 250pp.

Balnaves, M and Caputi, P. 2001. Introduction to Quantitative Research Methods: An Investigative Approach. Sage Publications, London. Thousand Oaks, California. New Delhi. 267pp.

Barbour, R.S. and Schostak, J. 2005. Interviewing and focuss groups. In: Somekh, B. and Lewin, C. (Eds.). Research Methods in the Social Sciences. Sage Publications. Los Angeles. London. New Dehli. Singapore. Washington DC. pp. 41-48.

Barrios, S., Ouattara, B and Strobl, E. 2008. The impact of climatic change on agricultural production: Is it different for Africa? *Food Policy*, **33**(3):287-298.

Baudron, F., Andersson, J.A., Corbeels, M. and Giller, K.E. 2012. Failing to yield? Ploughs, conservation agriculture and the problem of agricultural intensification: An example from the Zambezi Valley, Zimbabwe. *Journal of Development Studies*, **48**(3):393-412. Available on: http://peer.ccsd.cnrs.fr/docs/00/80/70/97/PDF/PEER_stage2_10.1080%252F00220388.2011.587509.pdf (Accessed 29/10/2013).

Bayer, B., Lerouge, E., Peglar, Rahimi, S. and Weshah, N. *(undated).* Presentation of two research methodologies: Interviews and discourse analysis. University of Calgary. Available on: http://analysis-interviews.weebly.com/index.html (Accessed 29/01/2013).

Bhebhe, S. and Nyathi, K. 2009. *Personal Communication.* Department of Agricultural Technical and Extension Services (AGRITEX), Lupane, Zimbabwe.

Bless, C. and Higson-Smith, C. 2000. Fundamentals of Social Research Methods: An African Perspective. 3rd edition. Juta Education (Pty) Ltd. 165pp.

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R. and Yanda, P. 2007: Africa. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. (Eds.). Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge UK, pp. 433-467.

Brady, N. and Weil, R. 2002. The Nature and Properties of Soils, 13th Edition. Prentice Hall. Upper Saddle River, New Jersey. 960pp.

Braganza, K., Karoly, D.J. and Arblaster, J.M. 2004. Diurnal temperature range as an index of global climate change during the twentieth century. *Geophysics Research Letters,* **31(**13**):** L13217 doi: 10.1029/2004GL019998. Available on: http://weather.ou.edu/~dkaroly/pdf%20files/Braganza_etal_GRL_2004.pdf (Accessed 21/08/2013).

Bratton, M. 1986. Farmer organizations and food production in Zimbabwe. *World Development,* **14**(3): 367-384. Available on: http://intranet.catie.ac.cr/intranet/Ambiente%20y%20Desarrollo%20Rural/PyMEs/Biblioteca_Virtual/BV-Organizaci%C3%B3n%20Inter-

Empresarial/Farmer%20orgs%20and%20food%20production%20in%20Zimbabwe.pdf (Accessed 02/01/2014).

Bratton, M. 1994. Land Redistribution, 1980-1990. In: Rukuni, M. and Eicher, C.K. (Eds.). Zimbabwe's Agricultural Revolution. University of Zimbabwe Publications, 1994. Harare.

Brown, D., Rance, R., Chanakira, R., Chatiza, K., Dhliwayo, M., Dodman, D., Masiiwa, M. Muchadenyika, D., Mugabe, P. and Zvigadza, S. 2012. Climate change impacts, vulnerability and adaptation in Zimbabwe. International Institute for Environment and Development (IIED) Climate Change Working Paper No.3. December 2012. Available on: http://pubs.iied.org/pdfs/10034IIED.pdf (Accessed 12/01/2013).

Brown, O. and Crawford, A. 2007. Climate change: A new threat to stability in West Africa? Evidence from Ghana and Burkina Faso. International Institute for Sustainable Development (IISD). *African Security Review,* **17**(3):39-57.

Brown, R.A. and Rosenberg, N.J. 1997. Sensitivity of crop yield and water use to change in a range of climatic factors and CO_2 concentrations: A simulation study applying EPIC to the central USA. *Agricultural and Forest Meteorology,* **83**:171-203.

Brunnetti, M., Colacino, M., Maugeri, M. and Nanni, T. 2001. Trends in the daily intensity of precipitation in Italy from 1951 to 1996. *International Journal of Climatology,* **21**:299-316.

Bryant, L. (*undated*). Structured interviews. Available on History Learning site: http://www.historylearningsite.co.uk/structured_interviews.htm (Accessed 29/01/2013).

Bunclark, L.A. and Lankford, B.A. 2011. Rainwater harvesting: A suitable poverty reduction strategy for small-scale farmers in developing countries. *Waterlines,* **30**(4):312-327.

Burton, I. and Lim B., 2005. Achieving adequate adaptation in agriculture. *Climatic Change,* **70**:191-200.

Butt, T.A., Mccarl, B.A., Angerer, J.P., Dyke, P.R.and Stuth, J.W. 2005. Food security implications of climate change in developing countries: Findings from a case study in Mali. *Climatic Change*, **68**(3):355-378.

Carberry, P. 2005. Increasing the effectiveness of research on agricultural resource management in the semi-arid tropics by combining cropping systems simulation with farming systems research (LWR2/1996/049). In: McWaters, V., Hearn, S. and Taylor R. (Eds.). Adoption of ACIAR project outputs: Studies of projects completed in 2000 - 2001. 2005. Available on: http://aciar.gov.au/files/node/686/ACRC138_layout_A4.pdf (Accessed on 13/11/2012).

Carberry, P.S., Hochman, Z., Hunt, J.R., Dalgliesh, N.P., McCown, R.L., Whish, J.P.M, Robertson, M.J., Foale, M.A., Poulton, P.L and van Rees, H. 2009. Re-inventing model-based decision support with Australian dryland farmers: Relevance of APSIM to commercial crops. *Crop and Pasture Science,* **60**:1044-1056. Available on: http://www.bob-mccown.com/wp -content/uploads/2011/10/143_CarberryEtAl2009FARMSCAPE_Paper31.pdf (Accessed 29/11/2012).

Case, M. 2006. Climate change impacts on East Africa: A review of the scientific literature. World Wide Fund for Nature (WWF). 12pp. Available on: http://www.wwf.or.jp/activities/lib/pdf_climate/environment/east_africa_climate_change_impacts_final.pdf (Accessed 20/05/2013).

Centre for Ecology and Hydrology, Natural Environment Research Council (CEH) (undated) Monitoring global water. Climate change and Water. Available on: http://www.waterandclimatechange.eu/evaporation (Accessed 03/11/2013).

Chagonda, I. 2013. Seasonal climate forecasting and participatory field experimentation as options to improved crop productivity in semi arid Zimbabwe. MSc thesis in Agronomy. Department of Agronomy, Faculty of Natural Resources Managemnt and Agriculture. University of Midlands State University, Gweru. Zimbabwe.

Chagonda, I., Munodawafa, A., Mugabe, F.T., Makuvaro, V., Masere, P. and Murewi, C.T.F. 2013. Comparative performance of scientific and indigenous knowledge on seasonal climate forecasts: A case study of Lupane, semi- arid Zimbabwe. *International Journal of Agronomy and Agricultural Research*, **3**(5):1-9.

Challinor, A.J. and Wheeler, T.R. 2008. Crop yield reduction in the tropics under climate change: Processes and uncertainties. *Agricultural and Forest Meteorology,* **148**:343-356.

Challinor, A., Wheeler, T., Garforth, C., Craufurd, P. and Kassam, A. 2007. Assessing the vulnerability of food crop systems in Africa to climate change. *Climatic Change*, **83**:381-399.

Challinor, A.J., Ewert, F, Arnold, S., Simelton, E and Fraser, E. 2009. Crops and climate change: Progress, trends, and challenges in simulating impacts and informing adaptation. *Journal of Experimental Botany*, **60**(10):2775-2789.

Chamaille´-Jammes, S., Fritza, H. and Murindagomo, F. 2007. Detecting climate changes of concern in highly variable environments: Quantile regressions reveal that droughts worsen in Hwange National Park, Zimbabwe. *Journal of Arid Environments*, **71**:321-326.

Chambers, R. 1994. The origins and practice of participatory rural appraisal. *World Development,* **22**(7):953-969.

Chatizwa, I. and Nazare, R.M. 2000. Animal power for weed control: Experiences in Zimbabwe. In: Starkey, P. and Kaumbutho, P. (Eds.). Animal power for weed control. A resource book of the Animal Traction Network for Eastern and Southern Africa *(ATNESA)* Harare, Zimbabwe: Intermediate Technology Publications, London. pp. 223-228.

Cheng, L., Zhu, J., Chen, G., Zheng, X., Oh, N.H., Rufty, T.W., Richter, de B.D. and Hu, S. 2010. Atmospheric CO_2 enrichment facilitates cation release from soil. *Ecology Letters*, **13**:284-291.

Chiduza, C., Waddington, S.R. and Mariga, K.I. 1994. Grain yield and economic performance of experimental OPVs and released hybrids of maize in a remote semi-arid area of Zimbabwe. *Zimbabwe Journal of Agricultural Research*, **32**(1):33-43.

Chiew, F. H. S.,Teng, J., Vaze, J., Post, D. A., Perraud, J.M., Kirono, D. G. C and Viney, N. R. 2009. Estimating climate change impact on runoff across southeast Australia: Method, results, and implications of the modeling method. *Water Resources Research*, **45**(10): W10414, doi: 10.1029/2008WR007338.

Chiputwa, B., Langyintuo, A, S. and Wall, P. 2011. Adoption of Conservation Agriculture Technologies by Smallholder Farmers in the Shamva District of Zimbabwe: A Tobit application. Paper accepted for the 2011 meeting of the Southern Agricultural Economics Association (SAEA) in Texas, USA, Feb 5-8. Available on: http://ageconsearch.umn.edu/bitstream/98851/2/Chiputwa_etal_SAEA_Paper.pdf (Accessed 09/07/2013).

Chiremba, S. and Masters, W. 2003. The experience of resettled farmers in Zimbabwe. *African Studies Quarterly,* **7**(2&3):97-117. Available on: http://www.africa.ufl.edu/asq/v7/v7i2-3.pdf (Accessed 29/01/13).

Chiwenga, E.F. 2010. The role of IPR on maize output in Zimbabwe. Trade Policy centre in Africa. MPRA Paper No. 38570. Available on: http://mpra.ub.uni-muenchen.de/38570/1/MPRA_paper_38570.pdf (Accessed 20/04/2012).

Choi, Y. 2004. Trends on temperature and precipitation extreme events in Korea. *Journal Korean Geographical Society,* **39**(5):711-721.

Christensen, J.H., Hewitson. B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A. and Whetton, P. 2007. Regional climate projections. In: Solomon, S.D., Qin, M., Manning, Z., Chen, M., Marquis, K.B., Averyt, M., Tigno, R. and Miller, H.L. (Eds.). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 847-940.

Chuma, E., Mvumi, B. and Nyagumbo. I. 2001. A review of sorghum and pearl millet - based production systems in the semi-arid regions of Zimbabwe. SADC /ICRISAT Sorghum and Millet Improvement Program (SMIP), P.O Box 776, Bulawayo, Zimbabwe: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 72pp.

Churi, A.J., Mlozi, M.R.S., Mahoo, H., Tumbo, S.D. and Casmir, R. 2013. A decision support system for enhancing crop productivity of smallholder farmers in semi-arid agriculture. *International Journal of Information and Communication Technology Research,* **3**(8):238-248. Available on: http://esjournals.org/journaloftechnology/archive/vol3no8/vol3no8_2.pdf (Accessed 05/01/2014).

CIA (Central Intelligence Agency) 2011. World Fact book 2011. Washington DC. Available on: https://www.cia.gov/library/publications/the-world-factbook/geos/iz.html (Accessed 02/03/2012).

Climate Change Office in Zimbabwe, 1998. Zimbabwe's initial national communication under the UNFCCC, 1998. Expected impacts of climate change vulnerability and adaptation assessments in Zimbabwe Available on: http://www.ohchr.org/Documents/Issues/ClimateChange/Submissions/Zimbabwe.pdf (Accessed 03/09/2011).

Climate Handbook of Zimbabwe, 1981. Department of Meteorological Services, Harare. 222pp.

Climate Systems Analysis Group (CSAG), University of Cape Town (undated). Data dissemination system. Available on: http://data.csag.uct.ac.za/docs/ (Accessed 25/11/2010).

Conway, D., Persechino, A., Ardoin-Bardin, S., Hamandawana, H., Dieulin, C. and Mahé, G. 2009. Rainfall and water resources variability in sub-Saharan Africa during the twentieth century. *Journal Hydrometeorology,* **10**:41-59.

Conway, G. 2009. The science of climate change in Africa: Impacts and adaptation. Grantham Institute for Climate Change Discussion paper No 1. October 2009. Available on: https://workspace.imperial.ac.uk/climatechange/public/pdfs/discussion_papers/Grantham_Institue_The_science_of_climate_change_in_Africa.pdf (Accessed 12/01/2013).

Cooper, P.J.M., Dimes, J., Rao K.P.C., Shapiro, B., Shiferaw, B. and Twomlow, S. 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture, Ecosystems and Environment*, **126**(1&2):24-35.

Crimp, S., Howden, M., Power, B., Wang, E. and De Voil, P. 2008. Global climate change impacts on Australia's wheat crops. *Garnaut Climate Change Review*. Available on: http://www.garnautreview.org.au/ca25734e0016131/WebObj/01-BWheat/$File/01-B%20Wheat.pdf (Accessed on 09/11/12).

Da Matta, F.M., Grandis, A., Arenque, B.C. and Buckeridge, M.S. 2010. Impacts of climate changes on crop physiology and food quality. *Food Research International,* **43**:1814-1823.

Dai, A., Trenberth, K.E. and Karl, T.R. 1999. Effects of clouds, soil moisture, precipitation, and water vapor on diurnal temperature range. *Journal Climate,* **12:**2451-2473.

Davis, A.S.C. 2001. Participatory rural appraisal. Rural Transport Knowledge Base Rural Travel and Transport Program 2001. TRL Limited.13pp. Available on: http://www.ctu.edu.vn/institutes/mdi/ntth/VN/PRA/PRA-016.pdf (Accessed 21/03/2013).

DEAT (Department of Environment Affairs and Tourism), 2000. South African Country Study on Climate Change. DEAT, Pretoria.

Decoteau, D.R. 2005. Principles of plant science: Environmental factors and technology in growing plants. Pearson Education, Upper Saddle River, New Jersey.United States of America. 432pp.

Department of Agricultural Research for Development, Ministry of Agriculture, Mechanization and Irrigation Development, 2009. Country report on the state of plant genetic resources for food and agriculture: State of Plant Genetic Resources for Food and Agriculture in Zimbabwe (1996-2008). Available on: http://www.fao.org/docrep/013/i1500e (Accessed 29/04/2012).

Deressa, T.D., Hassan, R.M., Ringler, C., Alemu, T. and Yesuf, M. 2009. Determinants of farmers' choice of adaptation methods to climate change in the Nile basin of Ethiopia. *Global Environmental Change,* **19**:248-255.

Desanker, P. and Magadza, C. 2001. Africa. In: McCarthy, J.J., Canziani, O.F. Leary, N.A., Doken, D.J. and White, K.S. (Eds.). Climate Change 2001: Impacts, Adaptation and Vulnerability. IPCC Working Group II, Third Assessment Report. Cambridge University Press. pp.489-531.

Dimes, J. 2011. *Personal Communication*. ICRISAT, Bulawayo. Zimbabwe.

Dimes, J., Cooper, P. and Rao, K.P.C. 2008. Climate change impact on crop productivity in the semi arid tropics of Zimbabwe in the 21st century. In: Humphreys, E. and Bayot, R.S. (Eds.).Proceedings of the workshop on increasing the productivity and sustainability of rainfed cropping systems of poor smallholder farmers. Tamale, Ghana, 22-25 September 2008. pp.189-198. The CGIAR Challenge Program on Water and Food, Colombo, Sri Lanka.

Dimes, J., Muza, L., Malunga, G. and Snapp, S. 2002. Trade-offs between investments in nitrogen and weeding: On-farm experimentation. In: Friesen, D.K. and Palmer, A.F.E. (Eds.). Integrated approaches to higher maize productivity in the new millennium: Proceedings of the seventh eastern and southern Africa regional maize conference. pp452-456. Nairobi, Kenya. 11 -15 February, 2001.

Dimri, A.P. and Dash, S.K. 2010. Winter temperature and precipitation trends in the Siachen Glacier. *Current Science,* **98**(12):1620-1625.

Donatelli, M. and Campbell, G.S. 1998. A simple model to estimate global solar radiation. Proceedings of the 5th European Society of Agronomy Congress, Nitra, Slovak Republic, 28 June-2 July 1998. **2**:133-134.

Downing, T.E. 1992. Climate change and vulnerable places: Global food security and country studies in Zimbabwe, Kenya, Senegal and Chile.: University of Oxford, Environmental Change Unit. Oxford. Available on: http://www.ciesin.org/docs/004-042/004-042.html (Accessed 09/12/2010).

Doré, D. 2012.The Nationalist Narrative and Land Policy in Zimbabwe, 4 May, Zimbabwe Land Series, Sokwanele: Available on: http://www.sokwanele.com/node/2373 (Accessed 02/01/2014).

Drummond, A.J. and Vowinckel, E. 1957. The distribution of solar radiation throughout southern Africa. *Journal of Meteorology*, **94**(4):343-353.

du Toit, A.S., Prinsloo, M.A., Durand, W. and Kiker. G. 2000. Vulnerability of maize production to climate change and adaptation assessment in South Africa. In: Kiker, G. (Ed.) *Climate change impacts in Southern Africa: Report to the National Climate Change Committee.* Pretoria: Department of Environmental Affairs and Tourism, Republic of South Africa.

Durham, B., Angelakis, A.N., Wintgens, T., Thoeye, C. and Sala, L. 2005. Water recycling and reuse. A water scarcity best practice solution**:** Paper prepared for the arid cluster, coping with drought and water deficiency: From research to policy making conference, Cyprus 12-13 May 2005. Available on: http://arid.chemeng.ntua.gr/Project/Default.aspx?t=69 (Accessed 12/01/2013).

Easterling, D.R., Horton, B. Jones, P.D., Peterson, T.C., Karl, T.R., Parker, D.E., James, M., Salinger, M.J., Razuvayev, V., Plummer, N., Jamason, P. and Folland C.K., 1997. Maximum and minimum temperature trends for the globe. *Science,* **277**:364-367.

Easterling, W.E., Aggarwal, P.K., Batima, P., Brander, K.M., Erda, L., Howden, S.M., Kirilenko, A., Morton, J., Soussana, J.F., Schmidhuber, J. and Tubiello, F.N. 2007. Food, fibre and forest products. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. (Eds.). Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 273-313.

Economics Division of the Ministry of Agriculture, 1996. Statistical Bulletin. Harare, Zimbabwe.

Eichberger, J. and Guerdjikova, A. 2012. Technology adoption and adaptation to climate change: A case-based approach. *Climate Change Economics*, **3**(2):701-741.

Ellis-Jones, J. and Mudhara, M. 1995. Factors affecting adoption of soil and water conservation technologies in semi-arid Zimbabwe. In: Twomlow, S., Jones, J.E., Hagman, J. and Loos, H. (Eds.). Soil and water conservation for smallholder farmers in semi-arid Zimbabwe: Transfers between research and extension. Proceedings of a national technical workshop held on 7 April, 1995. Masvingo, Zimbabwe. pp.106 -117.

Elwell, H.A. 1993. Development and adoption of conservation tillage practices in Zimbabwe. Chapter 10. In: FAO (Ed.). Soil tillage in Africa: Needs and challenges. FAO Soils Bulletin 69. Soil Resources, Management and Conservation Service Land and Water Development Division, FAO, Rome, pp. 129-165.

Erenstein, O. 2002. Crop residue mulching in tropical and semi-tropical countries: An evaluation of residue availability and other technological implications. *Soil & Tillage Research*, **67**:115-133.

Eriksen, S., O'Brien, K and Rosentrater, L. 2008. Climate change in eastern and southern Africa: Impacts, Vulnerability and Adaptation. Department of Sociology and Human Geography University of Oslo, Norway. GECHS Report 2008:2

Fand, B.B., Kamble, A.L. and Kumar, M. 2012. Will climate change pose serious threat to crop pest management: A critical review. *International Journal of Scientific and Research Publications*, **2**(11):1-14. Available on: http://www.ijsrp.org/research-paper-1112/ijsrp-p1109.pdf (Accessed 09/07/2013).

FAO (Food and Agricultural Organization of the United Nations). 1990. The community's toolbox: The idea, methods and tools, for participatory assessment, monitoring and evaluation in forestry. Available on: http://www.fao.org/docrep/x5307e/x5307e08.htm. (Accessed 02/07/2011).

FAO (Food and Agricultural Organization of the United Nations). 1999. A fertilizer strategy for Zimbabwe. FAO, Rome, Italy. Available on: ftp://ftp.fao.org/agl/agll/docs/fszimb.pdf (Accessed 29/01/2013).

FAO (Food and Agricultural Organization of the United Nations). 2000. Socio-economic impact of smallholder irrigation development in Zimbabwe: Case studies of ten irrigation schemes. FAO Sub-Regional Office for East and Southern Africa (SAFR), Harare, Zimbabwe.

FAO (Food and Agricultural Organization of the United Nations). 2003. World Agriculture: Towards 2015/2030. An FAO perspective. Bruinsma, J. (Ed.). Earthscan publications Ltd. London. 444pp. Available on: http://www.fao.org/fileadmin/user_upload/esag/docs/y4252e.pdf (Accessed 05/07/2013).

FAO (Food and Agricultural Organization of the United Nations). 2004. Drought impact mitigation and prevention in the Limpopo River Basin: A situation analysis. Land and Water Discussion Paper 4. Rome, Food and Agricultural Organisation of the United Nations.

FAO (Food and Agricultural Organization of the United Nations). 2006. Fertilizer use by crop in Zimbabwe. FAO Land and Plant Nutrition Management service - Land and Water Development Division. Rome, Italy. Available on: ftp://ftp.fao.org/agl/agll/docs/fertusezimbabwe.pdf (Accessed 29/01/2013).

FAO (Food and Agricultural Organization of the United Nations). 2006. Zimbabwe's Natural Regions and farming systems. In: Fertilizer use by crop in Zimbabwe. Land and plant nutrition management service, Land and water devlopment Division Food and Agriculture Organization of the United Nations, Rome. 2006. Available on: http://www.fao.org/docrep/009/a0395e/a0395e06.htm (Accessed 01/07/2013).

FAO (Food and Agricultural Organization of the United Nations). 2009. State of food and agriculture: Livestock in the balance. 180pp. Available on: http://www.fao.org/docrep/012/i0680e/i0680e.pdf (Accessed 03/07/2013).

FAO (Food and Agricultural Organization of the United Nations). (*undated*). Water management (Chapter 5). In: Save and Grow. A policy maker's guide to the sustainable intensification of smallholder crop production. Available on: http://www.fao.org/ag/save-and-grow/en/5/index.html (Accessed 01/07/2013).

FAO/WFP (Food and Agriculture Organization of the United Nations and the World Food Programme, Rome). 2010. Crop and food security assessment mission to Zimbabwe. FAO/WFP-Rome. Available on: http://ebookbrowsee.net/al997e-pdf-d459586612 (Accessed 05/01/2014).

Flick, U. 2006. An Introduction to Qualitative Research. Third Edition. Sage Publications. London. Thousand Oaks, California. New Delhi. 448pp.

Fosu-Mensah, B.Y. 2012. Modelling maize (*Zea mays* L.) productivity and impact of climate change on yield and nutrient utilization in sub-humid Ghana. Ecology and Development Series No. 87. 171pp. Available on:

http://www.zef.de/fileadmin/webfiles/downloads/zefc_ecology_development/eds_87_fosu-mensah_text.pdf (Accessed 10/10/2013).

Fowler, F.J. 1998. Design and evaluation of survey questions. In: Bickman L. and Rog, D.J. (Eds.). Handbook of Applied Social Research Methods. Sage Publications. Thousand Oaks. London. New Delhi. pp. 343-374.

Francis, J., Mudamburi, B. and Chikwanda, B. 1999. Animal draft power challenges in Zimbabwe. In: P Starkey, P. and Kaumbutho, P. (Eds.). Meeting the Challenges of Animal Traction. A Resource Book of the Animal Traction Network for Eastern and Southern Africa (ATNESA), Harare, Zimbabwe: Intermediate Technology Publications, London, pp. 274-277.

Gandure, S., Walker, S. and Botha, J.J. 2013. Farmers' perceptions of adaptation to climate change and water stress in a South African rural community. *Environmental Development,* **5**(1):39-53.

Ge, Z.M., Kellomäki, S., Zhou, X., Wang, K.Y, Peltola, H., Väisänen, H. and Strandman, H. 2011. Effects of climate change on evapotranspiration and soil water availability in Norway spruce forest in southern Finland: A model-based approach. *Ecohydrology*, **6**(1):51-63.

Geerts, B. 2003. Empirical estimation of the monthly-mean daily temperature range. *Theoretical and Applied Climatology,* **74**:145-165. Available on: http://www.dvfu.ru/meteo/library/30740145.pdf (Accessed 28/09/13).

Ghannoum, O. 2009. C_4 photosynthesis and water stress**.** *Annals of Botany*, **103**(4):635-644.

Ghannoum, O., von Caemmerer, S. and Conroy J.P. 2002. The effect of drought on plant water use efficiency of 9 NAD-ME and 9 NADP-ME C_4 grasses. *Functional Plant Biology*, **29**:1337-1348.

Ghannoum, O., von Caemmerer, S., Ziska, L.H. and Conroy, J.P. 2000. The growth response of C4 plants to rising atmospheric CO_2 partial pressure: A reassessment. *Plant, Cell and Environment,* **23**:931-942.

Ghooshchi, F., Seilsepour, M and Jafari, P. 2008. Effects of Water Stress on Yield and Some Agronomic Traits of Maize [SC 301]. *American-Eurasian Journal*

Agriculture and Environmental Science, **4**(3):302-305. Available on: http://www.idosi.org/aejaes/jaes4(3)/5.pdf (Accessed 14/10/2013).

Gill, P., Stewart, K., Treasure, E. and Chadwick, B. 2008. Methods of data collection in qualitative research: interviews and focus groups. *British Dental Journal*, **204**(6):291-295. Available on: http://www.academia.edu/746649/Methods_of_data_collection_in_qualitative_research_interviews_and_focus_groups (Accessed 28/01/2013).

Giller, K.E., Rowe, E.C., de Ridder, N. and Van Keulen, H. 2006. Resource use dynamics and interactions in the tropics: Scaling up in space and time. *Agricultural Systems*, **88**:8-27.

Giller, K. E., Witter, E., Corbeels, M. and Tittonell, P. 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research*, **114**:23-24.

Global Daily Weather Data from the National Climate Data Center (NCDC). http://www.infochimps.com/datasets/global-daily-weather-data-from-the-national-climate-data-center (Accessed 29/04/2012).

Global Daily Weather Data from the National Climate Data Center, http://www.ncdc.noaa.gov/oa/ncdc.html (Accessed 13/03/2009).

Goodess, C.M. 2007. ENSEMBLE-based predictions of climate changes and their impacts, project. Project no. GOCE-CT-2003-505539. Deliverable D2B.18: Technical protocol for the construction of ENSEMBLES statistical downscaling and scenario generator tools, Version 1. Available on: http://ensembles-eu.metoffice.com/project_reporting/year3reporting/publicly_completed_deliverables/D2B.18_tech_protocol_statistical_tools.pdf (Accessed 28/12/2013).

Goodess, C.M. 2013. *Personal Communication*. Climatic Research Unit, University of East Anglia, United Kingdom.

Gordo, O. and Sanz, J.J. 2010. Impact of climate change on plant phenology in Mediterranean ecosystems. *Global Change Biology*, **16**:1082-1106.

Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K. and Wiltshire, A. 2010. Implications of climate change for agricultural productivity in the early twentyfirst century. *Philosophical Transactions of the Royal Society - Biological Sciences*, **365**:2973-2989.

Grabowski, P.P. 2011. Constraints to adoption of conservation agriculture in the Angonia Highlands of Mozambique: Perspectives from smallholder hand-hoe farmers. Master of Science thesis. Michigan State University. Department of Community, Agriculture, Recreation and Resource Studies. USA.

Grant, P.M. 1981. The fertilization of sandy soils in peasant agriculture. *Zimbabwe Agricultural Journal,* **78**:169-175.

Groisman, P.Y., Knight. R.W., Easterling D.R., Karl, T.R., Hegerl, G.C. and Razuvaev, V.N. 2005. Trends in precipitation intensity in the climate record. *Journal of Climate,* **18**:1326-1350.

Gwenzi, W., Taru, M., Mutema, Z., Gotosa, J. and Mushiri, S. M. 2008. Tillage system and genotype effects on rainfed maize (*Zea mays L.*) productivity in semi-arid Zimbabwe. *African Journal of Agricultural Research*, **3**(2):101-110.

Gyampoh, B.A., Amisah, S., Idinoba, M. and Nkem, J. 2009. Using traditional knowledge to cope with climate change in rural Ghana. *Unasylv*a, 231/232, **60**:70-74.

Hanson, B. Grattan, S.R. and Fulton. A. 2006. Agricultural salinity and drainage. Division of Agriculture and Natural Resources, Water Management Series publication 3375. University of California Irrigation Program, University of California, USA.180pp. Available on: http://hos.ufl.edu/sites/default/files/faculty/gdliu/HansonGrattan2006_0.pdf (Accessed 10/10/2013).

Hargreaves, J.N.G. 1999. Tav_Amp. Documentation. Available on: http://www.apsim.info/Wiki/public/Upload/OtherProducts/tav_amp.pdf (Accessed 15/10/2009).

Hargreaves, J.N.G. 2009. *Personal communication.* Department of Ecosystem Sciences, Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia.

Harmsen, E.W., Miller, N.L., Schlegel, N.J. and Gonzalez, J.E. 2009. Seasonal climate change impacts on evapotranspiration, precipitation deficit and crop yield in Puerto Rico. *Agricultural Water Management*, **96**(7):1085-1095.

Harrell, M.C. and Bradley, M.A. 2009. Data collection methods: Semi-structured interviews and focus groups. Santa Monica, CA: RAND Corporation. Available on: http://www.rand.org/content/dam/rand/pubs/technical_reports/2009/RAND_TR718.pdf (Accessed 29/01/2013).

Hassan, R.M. 2010. Implications of climate change for agricultural sector performance in Africa: Policy challenges and research agenda. *Journal of African Economies*, **19** (AERC supplement 2):77-105.

Haylock, M.R., 2004: STARDEX Diagnostic Extremes Indices Software - User information. Available on: http://www.cru.uea.ac.uk/projects/stardex/deis/Diagnostic_tool.pdf (Accessed 23/10/2010).

Haylock, M. and Nicholls, N. 2000. Trends in extreme rainfall indices for an updated high quality data set for Australlia, 1910-1998. *International Journal of Climatology,* **20**:1533-1541.

Haylock, M.R. and Goodess, C.M. 2004. Interannual variability of European extreme winter rainfall and links with mean large-scale circulation. *International Journal of Climatology,* **24**:759-776.

Haylock M.R., Peterson, T.C. Alves, L.M., Ambrizzi, T., Anunciação, Y.M.T. Baez, J., Barros, V.R., Berlato, M.A., Bidegain, M., Coronel, G., Corradi, V.,. Garcia, V.J., Grimm, A.M., Karoly, D., Marengo, J.A., Marino, M.B., Moncunill, D.F., Nechet, D., Quintana, J., Rebello, E., Rusticucci, M., Santos, J.L., Trebejo, I. and Vincent, L.A. 2006. Trends in total and extreme south American rainfall in 1960–2000 and links with sea surface temperature. *Journal of Climate,* **19**:1490-1512.

Hayman, P., Wilhelm, N., Alexander, B. and Nidumolu, U. 2010. Using temporal and spatial analogues to consider impacts and adaptation to climate change in the South Australian grain belt. In: Food Security from Sustainable Agriculture. Dove, H. and Culvenor, R. A (Eds.). Proceedings of 15th Agronomy Conference, 15-18 November 2010, Lincoln, New Zealand. Available on:

http://www.regional.org.au/au/asa/2010/climate-hange/prediction/7093_haymanp.htm (Accessed 28/01/2013).

Heinz, I., Salgo, M. and Dávila, J.M. 2011. Evaluating the costs and benefits of water reuse and exchange projects involving cities and farmers. *Water International,* **36**(4):455-466.

Hennessy, D.A. 2009. Crop yield skewness and the normal distribution, *Journal of Agricultural and Resource Economics,* **34**(1):34-52. (Western Agricultural Economics Association) Available on: http://ageconsearch.umn.edu/bitstream/50084/2/Hennessy.pdf (Accessed 15/01/2013).

Hertel, T.W and Rosch, S.D. 2010. Climate change, agriculture, and poverty. *Applied Economic Perspectives and Policy,* **32**(3):355-385.

Hewitson, B. 2003. Developing perturbations for climate change impact assessments. *EOS, Transactions, American Geophysical Union*, **84**(35):337-348. Available on: http://unfccc.int/resource/cd_roms/na1/v_and_a/Resoursce_materials/Climate/Hewitson_EOS.pdf (Accessed 05/08/2013).

Hitz, S. and Smith, J. 2004. Estimating global impacts from climate change. *Global Environmental Change Part A*, **14**(3):201-218.

Horton, B. 1994. Geographical distribution of changes in maximum and minimum temperature. *Atmospheric Research,* **37**:101-117.

Hove, L. and Twomlow, S. 2007. Is conservation agriculture an option for vulnerable households in Southern Africa? In: FAO (Ed.). Paper Presented at the Conservation Agriculture for Sustainable Land Management to Improve the Livelihood of People in Dry Areas Workshop, United Nations Food and Agricultural Organization, 7–9 May, 2007. Damascus, Syria.

Howden, S.M., Soussana, J.F., Tubiello, F.N., Chhetri, N., Dunlop, M. and Meinke, H. 2007. Adapting agriculture to climate change. *Proceedings National Academy Sciences USA*, **104** (50):19691-19696. Available on: http://www.pnas.org/content/104/50/19691.full (Last accessed 03/01/2013).

Hox, J.P. and Boeije, H.R. 2005. Data collection, primary vs secondary. *Encyclopedia of Social Measurement*, **1**:593-599. Available on:

http://igitur-archive.library.uu.nl/fss/2007-1113-200953/hox_05_data%20collection,primary%20versus%20secondary.pdf (Accessed 09/06/2013).

HPI (Heifer Project International). 1999. Building capacity through the cornerstone model. A matching grant report for USAID. 2nd Annual Report October1998 - September 1999. Available on: http://pdf.usaid.gov/pdf_docs/PDABR898.pdf (Accessed 12/01/2014).

Huho, J.M, Ngaira J.K.W, Ogindo, H.O. and Masayi, N. 2012. The changing rainfall pattern and the associated impacts on subsistence agriculture in Laikipia East District, Kenya. *Journal of Geography and Regional Planning,* **5**(7):198-206. Available online at: http://www.academicjournals.org/JGRP. (Accessed 20/08/2012).

Hulme, M., Doherty, R., Ngara, T., New, M. and Lister, D. 2001. African climate change: 1900-2100. *Climate Change,* **17**:145-168.

Hundecha, Y. and Bárdossy, A. 2005. Trends in daily precipitation and temperature extremes across western Germany in the second half of the 20th century. *International Journal of Climatology,* **25**:1189-1202.

Huth, N. *undated.* APSIM-Page History: Other products. Available on: http://www.apsim.info/wiki/(S(2edr3dfgyhsuolithxmdat45))/History.aspx?Page=OtherProducts&Revision=10). (Accessed 20/11/2012).

Ibraimo, N.A. 2009. Rainwater harvesting: Management strategies in semi-arid areas. MSc Thesis. Department of Plant Production and Soil Science. University of Pretoria, South Africa.

Ibraimo, N. and Munguambe, P. 2007. Rainwater harvesting technologies for small scale rainfed agriculture in arid and semi-arid areas. Integrated Water Resource management for improved rural livelihoods – CGIAR - Challenge Program on Water and Food - Waternet. Available on: http://www.waternetonline.ihe.nl/challengeprogram/IR25.pdf (Accessed 20/08/2012).

IIRR (International Institute of Rural Reconstruction) and ACT (African Conservation Tillage Network), 2005. Controlling weeds - Chapter 7. In: Conservation

Agriculture: A manual for farmers and extension workers in Africa. International Institute of Rural Reconstruction, Nairobi; African Conservation Tillage Network, Harare. Available on: http://www.fao.org/ag/ca/africatrainingmanualcd/pdf%20files/07WEEDS.PDF (Accessed 02/01/2014).

IPCC, 2000. Emissions scenarios. Nakicenovic, N. and Swart, R. (Eds.) Cambridge University Press, UK. 570pp. Available on: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0 (Accessed 08/07/2013).

IPCC, 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

IPCC, 2007a: Climate change 2007: Impacts, Adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden P.J., and Hanson (Eds.), Cambridge University Press, United Kingdom, 976pp.

IPCC, 2007b. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report (FAR) of the Intergovernmental Panel on Climate Change. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 996pp.

IPCC, 2007c: Summary for policymakers. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M.L. Parry, O.F. Canziani,J.P. Palutikof, P.J. van der Linden and C.E. Hanson, (Eds.), Cambridge University Press, Cambridge, UK, pp 7-22. Available on:

http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-spm.pdf (Accessed 01/07/2013).

Ismail, A.M.A. and Ali, A.H. 1996. Plant population density effects on yield of sorghum grown in a dryland farming system. *Qatar University of Science Journal,* **16**(1):89-93.

Ivanova, V. and Alexandrov, V. 2012. Precipitation variations along the Bulgarian Black Sea coast from 1950 to 2009. *Proceedings of the International Conference on Water Observation and Information System for Decision Support (BALWOIS)*, Ohrid, Macedonia, 28 May-2 June 2012, (CD) 9pp. Available on: http://balwois.com/2012/USB/papers/442.pdf (Accessed 21//08/2012).

Jacobs, K., Adams, D. and Gleick, P. 2000. Potential consequences of climate variability and changes for the water resources of the United States. Report by the National Assessment and Synthesis Team, US Global Change Research. Available on: http://www.usgcrp.gov/usgcrp/Library/nationalassessment/14Water.pdf (Accessed 21//08/2012).

Johnson, R.B. and Onwuegbuzie, A.J. 2004. Mixed methods research: A research paradigm whose time has come. *Educational Researcher,* **33**(7):14-26.

Jones, L. 2010. Overcoming social barriers to adaptation. ODI background note. Overseas Development Institute 2010. ISSN 1756-7610. Available from http://www.odi.org.uk (Accessed 30/03/2012).

Jones, P.G. and Thornton, P.K. 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change,* **13**:51-59.

Jules, P., Subramanian, S., Ananthakrishnan, D., Jayanthi, C., Muralikrishnasamy.S. and Renganayaki, K. 1992. Finding the poorest in a Tamil Nadu village: A sequence of mapping and wealth ranking *RRA Notes,* **15**:39-42. Available on: http://pubs.iied.org/pdfs/G01428.pdf (Accessed 30/03/2013).

Kabamba, H. and Muimba-Kankolongo, A. 2009. Adoption and impact of conservation farming on crop productivity among smallholder farmers in Kapiri Mposhi District of Zambia. *Journal of Animal & Plant Sciences*, **3**(2):205-214. Available on: http://www.m.elewa.org/JAPS/2009/3.2/4.pdf (Accessed 20/07/2013).

Kalisa, A. and Nshimyumukiza, N. 2007. Characterization of farming systems in southern Rwanda. Bachelor Degree Dissertation. Université nationale du Rwanda-ingenieur Agronome. Available on: http://www.memoireonline.com/02/09/1949/Characterisation-of-farming-systems-in-southern-rwanda.html (Accessed 18/04/2013).

Kandji S.T., Verchot, L. and Mackensen, J. 2006. Climate change and variability in Southern Africa: Impacts and adaptation in the agricultural sector. UNDP and ICRAF report – Nairobi, Kenya.

Kang, S.Z., Zhang, F.C., Hu, X.T., Zhang, J.H. 2002. Benefits of CO_2 enrichment on crop plants are modified by soil water. *Plant Soil,* **238**:69-77.

Karl, T.R., Jones, P.D., Knight, R.W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K.P., Lindseay, J., Charlson, R.J. and Peterson, T.C. 1993. Asymmetric trends of daily maximum and minimum temperature. *Bulletin of the American Meteorological Society,* **74**(6):1007-1023.

Karrou, M. and Oweis, T. 2010. Climate change and water: Challenges and technological solutions in dry areas. In: Food Security and climate change in dry areas. Proceedings of an International Conference. 1-4 February, 2010. Amman, Jordan. pp. 130-135.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Siburn, M., Wang, E., Brown, S., Bristow, K.L, Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy,* **18**:267-288.

Kendall, M.G. 1975. Rank Correlation Methods. 4th edition. Charles Griffin & Company Ltd. London.

Kimball, B.A., Kobayashi, K. and Bindi, M. 2002. Responses of agricultural crops to free-air CO_2 enrichment. *Advanced Agronomy*, **70**:293-368.

King'uyu, S.M., Ogallo L.A. and Anyamba, E.K. 2000. Recent trends of minimum and maximum surface temperatures over eastern Africa. *Journal of Climate,* **13**:2876-2886.

Kinsey, B.H. 2002. Who benefits from asset redistribution in Zimbabwe? Targeting, beneficiary selection and economic performance. University of Zimbabwe, Harare and Free University, Amsterdam.

Kinsey, B., Burger, K. and Gunning, J.W. 1998. Coping with drought in Zimbabwe: Survey evidence on responses of rural households to risk. *World Development*, **26**(1):89-110.

Kinuthia, J. H. 1997. Global warming and climate impacts. In: Kinuthia, J.H. 1997. Global warming climate impacts in southern Africa: How might things change. *Internet Journal of African Studies,* **1**(2):13-13.

Klein-Tank, A.M.G. and Können, G.P. 2003. Trends in indices of daily temperature and precipitation extremes in Europe, 1946-99. *Journal of Climate,* **16**:3665-3680.

Kramarenko, V., Engstrom, L., Verdier, G., Fernandez, G., Oppers, S.E., Hughes, R., McHugh, J. and Coats, W. 2010. Zimbabwe: Challenges and policy options after hyperinflation. Washington, D.C.: International Monetary Fund. Available on: http://www.imf.org/external/pubs/ft/dp/2010/afr1003.pdf (Accessed 22/12/2013).

Kramer, E. 1997. The early years: Extension services in peasant agriculture in colonial Zimbabwe, 1925-1929. *Zambezia*, **24**(2):159-179. Available on: http://archive.lib.msu.edu/DMC/African%20Journals/pdfs/Journal%20of%20the%20University%20of%20Zimbabwe/vol24n2/juz024002005.pdf (Accessed 15/07/2013).

Kruger, A.C. and Shongwe, S. 2004. Temperature trends in South Africa: 1960-2003. *International Journal. Climatology,* **24:**1929-1945.

Kumwenda, J.D.T. and Kabambe, V.H. 1995. Critical period of weed interference in pure maize and maize- pigeon pea and maize-soyabean intercrops in Malawi. In: Jewell, D.C., Waddington, S.R., Ransom, J.K. and Pixley, K.V. (Eds.). Maize Research for Stress Environments. Proceedings of the 4th Eastern and Southern Africa Regional Maize Conference, Harare, Zimbabwe. 28 March – 1 April 1994: Mexico, CIMMYT, pp. 234-237.

Kurukulasuriya, P. and R. Mendelsohn. 2008a: A Ricardian analysis of the impact of climate change on African cropland. *African Journal of Agricultural and Resource Economics,* (**2**)1:1-23.

Kurukulasuriya, P. and Mendelsohn, R. 2008b. Crop switching as a strategy for adapting to climate change. *African Journal of Agricultural Research*, **2**(1):105-126.

Kurukulasuriya, P., Mendelsohn, R., Hassan, R., Benhin, J., Deressa, T., Diop, M., Eid, H.M., Fosu, K.Y., Gbetibouo, G., Jain, S., Mahamadou, A., Mano, R., Kabubo-Mariara, J., El-Marsafawy, S., Molua, E., Ouda, S., Ouedraogo, M., Se´ne, I., Maddison, D., Seo, S.N. and Dinar, A. 2006. Will African agriculture survive climate change? *The World Bank Economic Review*, **20**(3):367-388.

Lal, R. 2007. Constraints to adopting no-till farming in developing countries. *Soil and Tillage Research*, **94**:1-3.

Lawlor, D.W. 2005. Plant responses to climate change: Impacts and adaptation. In: Omasa, K., Nouchi, I. and De Kok, L.J. (Eds.). Plant Responses to Air Pollution and Global Change. Springer - Verlag, Tokyo, Japan. p81-88.

Leakey, A.D.B., Bernacchi, C.J., Dohleman, F.G., Ort, D.R. and Long, S.P. 2004. Will photosynthesis of maize (*Zea mays*) in the US Corn Belt increase in future [CO_2] rich atmosphere? An analysis of diurnal courses of CO_2 uptake under free-air concentration enrichment. *Global Change Biology*, **10**:951-962.

Li, F., Kang, S. and Zhang, J. 2004. Interactive effects of elevated CO_2, nitrogen and drought on leaf area, stomatal conductance, and evapotranspiration of wheat. *Agricultural Water Management,* **67**:221-233.

Loader, R. and Amartya, L. 1999. Participatory Rural Appraisal: Extending the research methods base. *Agricultural Systems*, **62**:73-85.

Lobell, D.B and Field, C.B. 2007. Global scale climate-crop yield relationships and the impacts of recent warming. *Environmental Research Letters*, **2**(1):1-7.

Louw, A., Ndanga L., Chikazunga, D. and Jagwe, J. 2007. Restructuring food markets in the Southern African region: Dynamics in the context of the fresh produce sub-sector. A synthesis of country findings. International Institute for Environment and Development (IIED). London.

Love, D., Uhlenbrook, S., Twomlow, S. and van der Zaag, P. 2010. Changing hydro-climatic and discharge patterns in the northern Limpopo Basin, Zimbabwe. *Water SA,* **36**(3):335-350. Available on:

http://www.waternetonline.ihe.nl/challengeprogram/A10%20Love%20hydroclimatics.pdf (Accessed 08/08/2012).

Lundquist, J.D. and Cayan, D.R. 2007. Surface temperature patterns in complex terrain: Daily variations and long-term change in the central Sierra Nevada, California. *Journal of Geophysical Research,* **112**:D11124, doi: 10.1029/2006JD007561. Available on: http://depts.washington.edu/mtnhydr/publications/Lundquist_Cayan_Tpatterns_2006JD007561.pdf (Accessed 03/01/2014).

Ma, S., Churkina, G., Trusilova, K. 2012. Investigating the impact of climate change on crop phenological events in Europe with a phenology model. *International Journal of Biometeorology,* **56**(4):749-63.

Mabasa, S. and Nyahunzi, S. 1995. Maize competition with natural weed infestation in communal areas in three agro-ecological zones of Zimbabwe. In: Jewell, D.C., Waddington S.R., Ransom J.K. and Pixley, K.V. (Eds.). Maize research for stress environments. Proceedings of the 4th Eastern and Southern Africa Regional Maize Conference, Harare, Zimbabwe, 28 March – 1 April 1994. Mexico, CIMMYT, pp. 219-222.

Mabasa, S., Shamudzarira, Z., Makanganise, A., Bwakaya, F. and Sithole, T. 1999. Weed management under different tillage systems in smallholder farming areas of Zimbabwe. In**:** Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) (Eds.). Maize production technology for the future: Challenges and opportunities. Proceedings of the Eastern and Southern Africa Regional Maize Conference 6*,* Addis Ababa, Ethiopia. 21-25 September, 1998. pp. 310-313.

Macoloo, C., Recha, J., Radeny, M. and Kinyangi, J. 2013. Empowering a local community to address climate risks and food insecurity in Lower Nyando, Kenya. In: Hunger, Nutrition and Climate Justice. A New Dialogue: Putting People at the Heart of Global Development. Dublin, Ireland 15-16 April 2013.. Available on: http://cgspace.cgiar.org/bitstream/handle/10568/27889/Nyando.pdf?sequence=1 (Accessed 02/01/2014).

Maddison, D. 2007. The perception of and adaptation to climate change in Africa. *World Bank Policy Research Working Paper No*. 4308. 51pp. Available on: http://wwwwds.worldbank.org/servlet/WDSContentServer/WDSP/IB/2007/08/06/000158349_20070806150940/Rendered/PDF/wps4308.pdf (Accessed 05/06/2013).

Magadza, C.H.D. 2000: Climate change impacts and human settlements in Africa: Prospects for adaptation. *Environmental Monitoring*, **61**:193-205.

Mahalakshmi, V. and Bidinger, F.R. 1986. Water deficit during panicle development in pearl millet: Yield compensation by tillers. *The Journal of Agricultural Science,* **106**(1):113-119.

Makadho, J.M. 1996. Potential effects of climate change on corn production in Zimbabwe. *Climate Research*, **6**:147-151.

Makowski, K., Wild, M. and Ohmura. A. 2008. Diurnal temperature range over Europe between 1950 and 2005. *Atmospheric Chemistry and Physics Discussions*, **8**:7051-7084. Available on: http://www.atmos-chem-phys-discuss.net/8/7051/2008/acpd-8-7051-2008-print.pdf (Accessed 22/08/2013).

Maman, N., Mason, S., Lyon, D.J. and Dhungana, P. 2004. Yield components of pearl millet and grain sorghum across environments in the Central Great Plains. Panhandle Research and Extension Center. Paper 3. Available on: http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1002&context=panhandleresext (Accessed 05/01/2014).

Mango, L.M., Melesse, A.M., McClain M.E., Gann, D. and Setegn, S.G. 2011. Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: Results of a modeling study to support better resource management. *Hydrology and Earth System Sciences*, **15**:2245-2258. Available on: http://www.hydrol-earth-syst-sci.net/15/2245/2011/hess-15-2245-2011.pdf (Accessed 05/01/2013).

Mano, R. and Nhemachena, C. 2007. Assessment of the economic impacts of climate change on Agriculture in Zimbabwe: A Ricardian approach. *Policy Research Working paper series* 4292, The World Bank.

Mapfumo, A. 2012. Agricultural expenditure for economic growth and poverty reduction in Zimbabwe. Master of Science Degree Thesis. Faculty of Science and Agriculture. Department of Agricultural Economics and Extension. University of Fort Hare. South Africa.

Mare, V. 2010. *Personal Communication.* Department of Agricultural Technical and Extension Services (AGRITEX). Gweru District Office, Zimbabwe.

Marongwe, L.S., Nyagumbo, I., Kwazira, K., Kassam, A. and Friedrich, T. 2012. Conservation agriculture and sustainable crop intensification: A Zimbabwe case study. *Integrated Crop Management*, **17**:1-28. Available on: http://www.fao.org/ag/ca/CA-Publications/17_ZIMBABWE_LR.pdf (Accessed 09/07/2013).

Martin, R.V., Washington, R. and Downing, T.E. 2000. Seasonal maize forecasting for South Africa and Zimbabwe derived from an Agro-climatological model. *Journal Applied Meteorology*, **39**:1473-1479.

Masere, P.T. 2011. The applicability of the APSIM model to decision-making in small-scale, resource constrained farming systems: A case study in the Lower Gweru communal area, Zimbabwe. MSc Thesis. Department of Agricultural Extension and Rural Resources Management. School of Agricultural, Earth and Environmental Sciences. University of KwaZulu Natal, South Africa.

Mashingaidze, A.B. 2004. Improving weed management and crop productivity in maize systems in Zimbabwe. PhD Thesis. Department of Theoretical Production Ecology, Wageningen University. Wageningen. The Netherlands.

Mashingaidze, N., Twomlow, S.J. and Hove, L. 2009. Crop and weed responses to residue retention and method of weeding in first two years of a hoe-based minimum tillage system in semi-arid Zimbabwe. *Journal of SAT Agricultural Research,* **7**:1-10.

Mashiringwani, N.A. 1983. The present nutrient status of the soil in communal lands of Zimbabwe. *Zimbabwe Agricultural Journal*, **80**:73-75.

Mashiringwani, N.A. 1983. The present nutrient status of the soil in the communal lands of Zimbabwe. *Zimbabwe Agricultural Journal,* **80**:73-75.

Mason, J. 2004. Semi-structured interviews. In: Lewis-Beck, M., Bryman, A. and Liao. T. (Eds.). *Encyclopaedia of Social Science Research Methods.* Thousand Oaks, CA: Sage Publications. pp. 1021-1022.

Mason, S.J. and Jury, M.R. 1997. Climatic variability and change over southern Africa: A reflection of underlying processes. *Progress in Physical Geography*, **21**:23-50.

Mason, S.J., Waylen, P.R., Mimmack, G.M., Rajaratnam, B. and Harrison, J.M. 1999. Changes in extreme rainfall events in South Africa. *Climatic Change,* **41:**249-257.

Matiza, G. 1999. Drought relief and irrigation. In: Manzungu, E., Senzanje, A. and van der Zaag, P. (Eds.). Water for Agriculture in Zimbabwe: Policy and Management Options for the Smallholder Sector, 197-201. University of Zimbabwe Publications Harare, Zimbabwe.

Mazvimavi, D. 2010. Investigating changes over time of annual rainfall in Zimbabwe. *Hydrology Earth Systems Science*, **14**:2671-2679.

Mazvimavi, K. 2011. Socio-economic analysis of conservation agriculture in southern Africa. FAO. Regional Emergency Office for Southern Africa (REOSA) 2011 Network paper No. 2. January 2011. Available on: http://www.fao.org/docrep/013/i2016e/i2016e00.pdf (Accessed 21/01/2012).

Mazvimavi, K. and Twomlow, S. 2009. Socioeconomic and institutional factors influencing adoption of conservation farming by vulnerable households in Zimbabwe. *Agricultural Systems,* **101**:20-29.

Mazvimavi, K., Ndlovu, P.V., Nyathi, P. and Minde, I.J. 2010. Conservation agriculture practices and adoption by smallholder farmers in Zimbabwe. Poster presented at the Joint 3rd African Association of Agricultural Economists (AAAE) and 48th Agricultural Economists Association of South Africa (AEASA) Conference, Cape Town, South Africa, September 19-23, 2010. Available on: (http://ageconsearch.umn.edu/bitstream/96822/2/130.Conservation Agriculture Practices in Zimbabwe.pdf (Accessed 21/01/2012).

McCauley, A. and Jones, C. 2005. Salinity and sodicity management. Soil and Water Management Module 2. Montana State University Extension Service Publications 4481-2. Available on:
http://landresources.montana.edu/SWM/PDF/SW%202%20updated.pdf
(Accessed 24/01/2013).

MCCIP (Marine Climate Change Impacts Partnership). 2012. Marine climate change impacts on fish, fisheries and aquaculture. In: Frost, M., Baxter, J.M., Buckley, P.J., Cox, M., Dye, S.R. and Withers, H.N. (Eds.). Summary Report, MCCIP, Lowestoft, 12pp. Marine climate change impacts: Fish, Fisheries and Aquaculture. Available on: http://www.mccip.org.uk/media/8911/37453%20mccip%20english%20lorez.pdf (Accessed 22/12/2013).

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P. and Freebairn D.M. 1996. APSIM: Anovel software system for model development, model testing and simulation in agricultural systems research. *Agricultural Systems*, **50**:255-271.

McElroy, M. and Baker, D.J. 2012. Climate extremes: Recent trends with implications for United States national security. Available on: http://environment.harvard.edu/sites/default/files/climate_extremes_report_2012-12-04.pdf (Accessed 22/12/2013).

Meadows, M.E. 2006. Global change and Southern Africa. *Geographical Research,* **44**:135-145.

Mearns, R., Shombodon, D., Narangerel, G., Turul, U., Enkbamgalan, A., Myagmarzhav, B., Bayanjargal, A. and Bekhsuren, B. 1992. Direct and indirect uses of wealth ranking in Mongolia. *RRA Notes,* **15**:29-38.

Mendelsohn, R. 2009. The Impact of climate change on agriculture in developing countries. *Journal of Natural Resources Policy Research*, **1**(1):5-19.

Mendelsohn, R. and Dinar, A. 2009. Climate Change and Agriculture: An Economic Analysis of Global Impacts, Adaptation, and Distributional Effects. Cheltenham, UK: Edward Elgar Publishing.

Mertz, O., Mbow C., Reenberg, A. and Diouf, A. 2009. Farmers' perceptions of climate change and agricultural adaptation strategies in Rural Sahel. *Environmental Management*, **43**:804-816.

Michigan State University Food Security Group, 2012. Climate Change Impact on Agricultural Production and Adaptation Strategies: Farmers' Perception and Experiences Summary Results of Focus Group Interviews in Zambia. Available on: http://fsg.afre.msu.edu/climate_change/Climate_change_FGD_synthesis_Zam.pdf (Accessed 05/10/2013).

Midlands Province, Gweru District 1: 250 000 soils map.1994. Department of AGRITEX. Midlands Province. Gweru, Zimbabwe.

Ministry of Agriculture, Mechanization and Irrigation Development in Zimbabwe. 2011. Farm Management Handbook. 485pp.

Ministry of Mines, Environment and Tourism in Zimbabwe. 1998a. Zimbabwe Biodiversity, unmet needs, strategies and actions. s.l. GEF, UNDP, 148pp. Available on: http://www.cbd.int/doc/world/zw/zw-nbsap-01-en.pdf (Accessed 29/04/2012).

Ministry of Mines, Environment and Tourism in Zimbabwe. 1998b. Zimbabwe's initial national communication on climate change. Expected impacts of climate change, vulnerability and adaptation assessments in Zimbabwe. Government of Zimbabwe, Ministry of Mines, Environment and Tourism, Harare, Zimbabwe.

Misiko, M., Tittonell, P., Giller, K.E. and Richards, P. 2011. Strengthening understanding and perceptions of mineral fertilizer use among smallholder farmers: evidence from collective trials in western Kenya. *Agriculture and Human Values,* **28**(1):27-38.

M'Khaitir, Y.O. and Vanderlip, R.L. 1992. Grain sorghum and pearl millet response to date and rate of planting. *Agronomy Journal*, **84**(4):579-582.

Moberg, A. and Jones, P.D. 2005. Trends in indices for extremes in daily temperature and precipitation in Central and Western Europe, 1901-99. *International Journal of Climatology,* **25**:1149-1171.

Mohsin, T. and Gough, W.A. 2010. Trend analysis of long-term temperature time series in the Greater Toronto Area (GTA). *Theoretical and Applied Climatology,* **101**:311-327.

Moratiel, R., Duran, J.M. and Snyder, R.L. 2010. Responses of reference evapotranspiration to changes in atmospheric humidity and air temperature in Spain. *Climate Research,* **44**:27-40.

Morgan, J.A., Milchunas, D.G., LeCain D.R., West, M. and Mosier, A.R. 2007. Carbon dioxide enrichment alters plant community structure and accelerates shrub growth in the shortgrass steppe. *Proceedings of the National Alcademy of Science* (PNAS), **104**:14724-14729.

Moyo, A. 2003. Assessment of the effect of soil erosion on nutrient loss from granite-derived sandy soils under different tillage systems in Zimbabwe. Ph.D. Thesis, Department of Soil Science and Agricultural Engineering. University of Zimbabwe, Harare, Zimbabwe.

Moyo, S. 2010. *Personal Communication*. Department of Agricultural Technical and Extension Services, Gweru District, Zimbabwe.

Moyo, S. 2012. *Personal Communication.* Department of Agricultural Technical and Extension Services (AGRITEX), Gweru, Zimbabwe.

Moyo, S and Musasanuri, M.N. 2009. *Personal Communication*. Department of Agricultural Technical and Extension Services (AGRITEX), Gweru, Zimbabwe.

Moyo, S. and Musasanuri, M.N. 2010. *Personal Communication.* Department of Agricultural Technical and Extension Services (AGRITEX), Gweru, Zimbabwe.

Mpatane, O., Kayombo, B. & Patrick, C. 2012. Preliminary assessment of socio-economic potential for rain water harvesting (RWH) in semi-arid Bobirwa Sub-district of eastern Botswana. 3rd RUFORUM Biennial Meeting 24 - 28 September 2012, Entebbe, Uganda. pp 711-715. Available on: http://www.ruforum.org/system/files/Mpatane%20711.pdf (Accessed 05/01/2014).

Mubaya C.P. 2010. Farmer strategies towards climate variability and change in Zimbabwe and Zambia. PhD Thesis. Faculty of Economic and Management Sciences, Centre for Development Support, University of the Free State, Bloemfontein, South Africa.

Mubaya, C.P., Njuki, J., Liwenga, E., Mutsvangwa, E.P. and Mugabe, F.T. 2010. Perceived impacts of climate related parameters on smallholder farmers in Zambia and Zimbabwe. *International Journal of Sustainable Development in Africa*, **12**(5):170-186.

Mubaya, C.P., Njuki, J., Mutsvangwa. E.P., Mugabe, F.T. and Nanja, D. 2012. Climate variability and change or multiple stressors? Farmer perceptions regarding threats to livelihoods in Zimbabwe and Zambia. *Journal of Environmental Management*, **102**:7-17.

Muchadeyi, F.C., Wollny, C.B.A., Eding, H., Weigend, S., Makuza, S.M. and Simianer, H. 2007. Variation in village chicken production systems among agro-ecological zones of Zimbabwe. *Tropical Animal Health Production,* **39**:453-461.

Mudhara, M. 1995. Maize production in the face of unreliable rainfall. A case study of Chivi communal area. In: Jewell D.C., Waddington, S.R., Ranson, J.K. and Pixley, K.V. (Eds.). *Maize Research for Stress Environments. Proceedings of the Fourth Eastern and Southern Africa Regional maize Conference*, Harare, Zimbabwe. 28 March – 1 April 1994: Mexico D.F. CIMMYT, pp. 285-290.

Mudhara, M., Hildebrand, P.E. and Gladwin, C.H. 2002. Gender-sensitive LP models in soil fertility research for smallholder farmers: Reaching de jure female headed households in Zimbabwe. *African Studies Quarterly*, **6**(1&2):295-309. Available on: http://www.africa.ufl.edu/asq/v6/v6i1-2a12.pdf (Accessed 01/07/2013).

Mugabe, F.T., Munodawafa, A., Dimes, J., Nanja, D.H., Carberry, P., Mwale, M., Mubaya, C., Makuvaro, V., Chagonda, I., Masere, P., E. Mutsvangwa and Murewi, C. 2010. Building Adaptive Capacity to Cope with Increasing Vulnerability Due to Climate Change. Final technical report submitted to IDRC Project Number 104144: "Climate Change and Adaptation in Africa (CCAA)" 175pp. Available on: http://idl-bnc.idrc.ca/dspace/bitstream/10625/46033/1/132519.pdf (Accessed 20/05/2012).

Munodawafa, A., Makuvaro, V., Masere, P.T., Murewi, C.T.F. and Chagonda, I. 2009. Report on case studies on climate change and variability conducted in Lower Gweru and Lupane (Zimbabwe). *Unpublished IDRC - MSU project report*

Mupangwa, W. 2008. Water and nitrogen management for risk mitigation in semi-arid cropping systems. Ph.D Thesis in Agricultural Meteorology. Department of Soil, Crop and Climate Sciences, Faculty of Natural and Agricultural Sciences. University of the Free State. Bloemfontein, South Africa.

Mupangwa, W. and Jewitt, G.P.W. 2011. Simulating the impact of no-till systems on field water fluxes and maize productivity under semi-arid conditions. *Physics and Chemistry of the Earth*, **36**:1004–1011.

Mupangwa, W., Love, D. and Twomlow, S. 2006. Soil-water conservation and other rainwater harvesting strategies in the semi-arid Mzingwane Catchments Limpopo Basin Zimbabwe. *Physics and Chemistry of the Earth,* **31:**893-900.

Mupangwa, W., Twomlow, S. and Walker, S. 2008. The influence of conservation tillage methods on soil water regimes in semi-arid southern Zimbabwe. *Physics and Chemistry of the Earth,* **33**:762-767.

Mupangwa, W., Walker, S. and Twomlow, S. 2011a. Start, end and dry spells of the growing season in semi-arid southern Zimbabwe. *Journal of Arid Environments,* **75**:1097-1104.

Mupangwa, W., Twomlow, S. and Walker, S. 2012. Reduced tillage, mulching and rotational effects on maize *(Zea mays* L.*)*, cowpea *(Vigna unguiculata (Walp)* L.*)* and sorghum *(Sorghum bicolor* L. (Moench)) yields under semi-arid conditions. *Field Crops Research*, **132**:139-148.

Mupangwa, W., Twomlow, S. and Walker, S. *(undated).* Minimum tillage and mulching effect on cowpea yield and soil water content. Waternet Challenge Program Project 17 "Integrated water resource management for improved rural livelihoods: Managing risk, mitigating drought and improving water in the water scarce Limpopo Basin." Available on: http://www.waternetonline.ihe.nl/challengeprogram/P61%20Mupangwa%20Cowpea.pdf (Accessed 20/06/2013).

Mupangwa, W., Twomlow, S., Walker, S. and Hove, L. 2007. Effect of minimum tillage and mulching on maize (*Zea mays* L.) yield and water content of clay and sandy soils. *Physics and Chemistry of the Earth,* **32**:1127-1134.

Mupangwa, W., Dimes, J., Walker, S. and Twomlow, S. 2011b. Measuring and simulating maize (*Zea mays* L.) yield responses to reduced tillage and mulching under semi-arid conditions. *Agricultural Sciences,* **2**(3):167-174.

Murewi, C.T.F., Makuvaro, V., Dimes, J., Munodawafa, A., Chagonda, I., Masere, P.T., Mubaya, C.P., Mutsvangwa, E.P. and Mugabe, F.T. 2012: Verification of smallholder farmer perceptions on climate variability and change, using historical climate data: A case study of semi-arid central Zimbabwe. In: Compendium of abstracts on Building a Climate Resilient Society - National climate change adaptation symposium. 6-8 June 2012. Harare, Zimbabwe. 52pp.

Murthy, V.R.K. 2004. Crop growth modeling and its applications in agricultural meteorology. In: Sivakumar, M.V.K., Roy, P.S., Harmsen, K. and Saha, S.K. (Eds.). Satellite remote sensing and GIS applications in agricultural meteorology. pp. 235-261.

Musasanuri, M.N. and Pawadyira, A. 2013. *Personal Communication*. Department of Agricultural Technical and Extension Services (AGRITEX), Gweru, Zimbabwe.

Mushunje, A. 2005. Farm efficiency and land reform in Zimbabwe. PhD Thesis. Department of Agricultural Economics and Extension, Faculty of Science and Agriculture. University of Fort Hare. South Africa.

Mutekwa, V. and Kusangaya, S. 2006. Contribution of rainwater harvesting technologies to rural livelihoods in Zimbabwe: The case of Ngundu ward in Chivi District. *Water SA*. **32**(3):437-444.

Mutezo, W.T. 2013. Early crop growth and yield responses of maize (*Zea mays*) to biochar applied on soil. Natural Resources, Agricultural Development and Food Security, International Research Network (NAF-IRN). International Working Paper Series no. **13** (03): pp50. Available on: http://economia.unipv.it/naf/Working_paper/WorkingPaper/gab/Mutezo.pdf (Accessed 19/07/2013).

Mutsamba, E.F., Nyagumbo, I. and Mafongoya, P.L. 2012. Dry season crop residue management using organic livestock repellents under conservation agriculture in Zimbabwe. *Journal of Organic Systems*, **7**(1):9pp. Available on: http://www.organic-systems.org/journal/Vol_7(1)/pdf/JOS_7(1)_2012_05-13_Mutsamba.pdf (Accessed 20/06/2013).

Muzari, W., Gatsi, W. and Muvhunzi, S. 2012. The impacts of technology adoption on smallholder agricultural productivity in Sub-Saharan Africa: A review. *Journal of Sustainable Development*, **5**(8):69-77.

Narwal, S.S., Sarmah, M.K. and Tamak, J.C. 1998. Allelopathic strategies for weed management in the rice-wheat rotation in North-western India: In: Olofsdotter, M. (Ed.). Proceedings of workshop on Allelopathy in rice, 117-131. Manila\, Phillipines. 25-27 November, 1996: IRRI. 154pp.

NCDC (National Climatic Data Centre) of NOAA (National Oceanic and Atmospheric Administration) in the United States Department of Commerce in Washington DC. *undated*. Global Summary of Day Data. Available on: http://www.ncdc.noaa.gov/oa/ncdc.html (Accessed 25/11/2009)

Ncube, B., Dimes, J.P., Twomlow S.J., Mupangwa W. and Giller, K.E. 2007. Raising the productivity of smallholder farms under semi-arid conditions by use of small doses of manure and nitrogen: A case of participatory research. *Nutrient Cycling in Agro-ecosystems*, **77**:53-67.

Ncube, B., Twomlow, S.J., Dimes, J.P., van Wijk, M.T. and Giller, K.E. 2009. Resource flows, crops and soil fertility management in smallholder farming systems in semi-arid Zimbabwe. *Soil Use and Management,* **25**:78-90.

New, M., Hewitson, B., Stephenson, D.B., Tsiga, A., Kruger, A., Manhique, A., Gomez, B.,Coelho, C.A.S., Masisi, D.N., Kululanga, E., Mbambalala, E., Adesina, F., Saleh, H., Kanyanga, J., Adosi, J., Bulane, L., Fortunata, L., Mdoka, M.L. and Lajoie, R. 2006. Evidence of trends in daily climate extremes over Southern and West Africa. *Journal of Geophysical Research,* **111**:1-11.

Newton, N. 2010. The use of semi-structured interviews in qualitative research: Strengths and weaknesses. Available on: http://www.academia.edu/1561689/The_use_of_semi-structured_interviews_in_qualitative_research_strengths_and_weaknesses (Accessed 01/02/2013).

Ngaira, J.K.W. 2007. Impact of climate change on agriculture in Africa by 2030. *Scientific Research and Essays*, **2**(7):238-243. Available online at http://www.academicjournals.org/SRE (Accessed 13/12/12).

Ngigi, S.N. 2009. Climate change adaptation strategies: Water resources management options for smallholder farming systems in Sub-Saharan Africa. The MDG centre for east and southern Africa, The Earth Institute at Columbia University, New York. 189pp. Available on: (http://www.rockefellerfoundation.org/uploads/files/9eacd477-e2ef-4b72-9207-5a18135dceb3.pdf (Accessed 18/01/2012).

Nhemachena, C. and Hassan, R. 2007. Micro-level analysis of farmers' adaptation to climate change in southern Africa, IFPRI Discussion Paper No. 714 (Washington, DC: International Food Policy Research Institute, 2007). Available on: http://www.gaiafoundation.org/sites/default/files/documents/IFPRI%20-%20Adaptation%20Climate%20Change.pdf (Accessed 02/06/2013).

Nhemachena, C., Hassan, R. and Chakwizira, J. (*undated).* Economic Impacts of Climate Change on Agriculture and Implications for Food Security in Southern Africa. 33pp. Available on: http://climsec.prio.no/papers/Economic%20Impacts%20of%20Climate%20Change%20on%20Agriculture%20and%20Implications%20for%20Food%20Security%20in%20Southern%20Africa.pdf (Accessed 19/05/2013).

Nhemachena, C., Hassan, R. and Kurukulasuriya, P. 2010. Measuring the economic impact of climate change on African agricultural production systems. *Climate Change Economics*, **1**(1):33-55.

Norton, A. 1988. A systematic method of selecting and recommending tillage systems in Natural Regions III, IV and V. In: Cropping in semi-arid areas of Zimbabwe. Proceedings of a workshop held in Harare, 24-28 August, 1987. AGRITEX / DR&SS / GTZ. pp. 495-530.

Norton, A. 1995. Soil and water conservation for smallholder farmers: Past, present and future. In: Twomlow, S., Jones, J.E., Hagman, J and Loos, H. (Eds.). Soil and Water Conservation for Smallholder Farmers in Semi-arid Zimbabwe: Transfer between Research and Extension. Proceedings of a Technical Workshop, Masvingo, Zimbabwe 3-7 April 1995, pp. 5-21.

Nyagumbo, I., Munamati, M., Chikwari, E. and Gumbo, D. 2009. *In-situ* water harvesting technologies in semi-arid southern Zimbabwe: Part I. The role of biophysical factors on performance in Gwanda district. Paper presented at the 10th WaterNet/WARFSA/GWP-SA Annual Symposium, Entebbe, Uganda, 2009. Amsterdam, Netherlands: WaterNet. Available on: http://www.waternetonline.ihe.nl/challengeprogram/p81%20nyagumbo%20water%20harvesting.pdf (Accessed 29/07/2013).

Nyamadzawo, G., Wuta, M., Nyamangara, J. and Gumbo, D. 2013. Opportunities for optimization of in-field water harvesting to cope with changing climate in semi-arid smallholder farming areas of Zimbabwe. *Springer Plus* 2013, **2**(100):9pp. Available on: http://www.springerplus.com/content/pdf/2193-1801-2-100.pdf (Accessed 29/07/2013).

Nyamangara, J., Mashingaidze, N., Masvaya, E.N., Nyengerai, K., Kunzekweguta, M., Tirivavi, R. and Mazvimavi, K. 2013. Weed growth and labor demand under hand-hoe based reduced tillage in smallholder farmers' fields in Zimbabwe. International Crop Research Institute for the Semi-Arid Tropics, Matopos Research Station, Bulawayo, Zimbabwe. Available on: http://oar.icrisat.org/7219/7/WeedGrowth_Nyamangara_etal_Post-print_2013.pdf (Accessed 22/12/2013).

Nyamapfene, K. 1991. Soils of Zimbabwe. Nehanda Publishers, Harare, Zimbabwe, 179pp.

Oikonomou, C., Flocas, H.A., Hatzaki, M., Asimakopoulos, D.N. and Giannakopouls, C. 2008. Future changes in the occurrence of extreme precipitation events in eastern Mediterranean. *Global Nest Journal,* **10**(2):255-262.

Oikonomou, C., Flocas, H.A., Hatzaki, M., Nisantzi, A. and Asimakopoulos, D.N. 2010. Relationship of extreme dry spells in Eastern Mediterranean with large-scale circulation ranges between 1950 and 2000. *Theoretical Applied Climatology,* **100**:137-151.

Oldrieve B. 1993. Conservation farming for small-scale resettlement and co-operative farmers of Zimbabwe. A Farm Management Handbook. Harare, Zimbabwe. Rio Tinto Foundation.

Ortiz, R., Sayre, K.D. and Govaerts, B. 2008. Climate change: Can wheat beat the heat? *Agricultural Ecosystems and Environment,* **26**:46-58.

Oweis, T. and Hachum, A. 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. *Agricultural Water Management,* **80**:57-73.

Patt, A., Suarez, P. and Gwata, C. 2005. Effects of seasonal climate forecasts and participatory workshops among subsistence farmers in Zimbabwe. *Proceedings of National Academy of Sciences USA*, **102**:12673-12678.

Parry, M.L. 2007. The implications of climate change for crop yields, global food supply and risk of hunger. *SAT eJournal* **4**(1):1-44. Available on: http://www.icrisat.org/journal/SpecialProject/sp14.pdf (Accessed 09/12/2011).

Parry, M.L, Canziani, O. and Palutikof, J. 2008. Key IPCC conclusions on climate change impacts and adaptations. *WMO Bulletin,* **57** (1):78-85 Available on: https://www.wmo.int/pages/publications/bulletin_en/archive/57_2_en/documents/parry_sub_en.pdf (Accessed 04/07/2013).

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, A. and Fischer, G. 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change*, **14**(1):53-67.

Petzoldt, C. and Seaman, A. 2010. Climate change effects on insects and pathogens. Climate change and agriculture: Promoting practical and profitable responses. p. III 1–16. Available on: http://umaine.edu/oxford/files/2012/01/III.2Insects.Pathogens1.pdf (Accessed 09/07/2013)

Phillips, C.I., Gregg, J.W. and Wilson, J.K. 2011. Reduced diurnal temperature range does not change warming impacts on ecosystem carbon balance of Mediterranean grassland mesocosms. *Global Change Biology,* **17**:3263-3273.

Pixley, K. and Bänziger, M. 2001. Open-pollinated maize varieties: A backward step or valuable option for farmers? In: Friesen, D.K. and Palmer, A.F.E. (Eds.). Seventh Eastern and Southern Africa Regional Maize Conference proceedings, 11 – 16 February, 2001, pp. 22-28.

Prescott, J.A. 1940. Evapotranspiration from water surface in relation to solar radiation. *Transactions of the Royal Society of Science*, **64**:114-118.

PreventionWeb. 2012. Zimbabwe Disaster Statistics. Available on: <http://www.preventionweb.net/english/countries/statistics/?cid=193>. (Accessed 06/07/2013).

Price, C., Michaelides, S., Pashiardis, S. and Alpert, P. 1999. Long term changes in diurnal temperature range in Cyprus. *Atmospheric Research,* **51**:85-98.

Progressio Zimbabwe, 2009. Seed saving and climate change in Zimbabwe. Progressio Zimbabwe. Available on: http://www.progressio.org.uk/sites/default/files/Zimbabwe-seedsaving.pdf (Accessed 05/10/2013).

Provisional 1:1 000 000 soils map of Zimbabwe-Rhodesia. 1979. Surveyor General Department, Harare. Zimbabwe-Rhodesia.

Punch, K.F. 2005. Introduction to social research: Quantitative and qualitative approaches. 2nd edition. Sage Publications. London. Thousand Oaks, California. New Delhi. Singapore**.** 325pp.

Qiao, Y., Zhang, H., Dong, B., Shi, C., Li, Y., Zhai, H. and Liu, M. 2010. Effects of elevated CO_2 concentration on growth and water use efficiency of winter wheat under two soil water regimes. *Agricultural Water Management*, **97**:1742-1748.

Rai, A., Joshi, M. K. and Pandey, A.C. 2012. Variations in diurnal temperature range over India: Under global warming scenario. *Journal of Geophysical Research,* ***117****, D02114, doi: 10.1029/2011JD016697.*

Ramirez, O.A. 1997. Estimation and use of multivariate parametric model for simulating heteroscedsatic, correlated, non-normal variables. The case study of Corn Belt corn, soybean and wheat yields. *American Journal of Agricultural Economics,* **79**:191-205.

Ramirez, O.A., Misra, S. and Field, J. 2003. Crop yield distributions revisited. *American Journal of Agricultural Economics*, Agricultural and Applied Economics Association, **85**(1):108-120. Available on: http://ageconsearch.umn.edu/bitstream/20695/1/sp01ra02.pdf (Accessed 15/01/2013).

Rasmussen, K. 2003. Effects of climate change on agriculture and environment in the semi-arid tropics: With Senegal as an example. Impacts of future climate change. Available on: http://glwww.dmi.dk/f+u/publikation/dkc-publ/klimabog/CCR-chap-21.pdf (Accessed 26/03/2008).

Reddy, R.V. 1997. Wealth ranking in socio-economic research: Substitute or complement? Discussion Paper 65: Diskussionsschriften der Forschungsstelle für Internationale Wirtschafts- und Agrarentwicklung eV (FIA), Nr. 65, Heidelberg 1997. Available on: http://www.sai.uni-heidelberg.de/intwep/fia/DISKUS65.htm (Accessed 19/04/2013).

Rijnsdorp, A.D., Peck, M.A., Engelhard, G.H., Möllmann, C. and Pinnegar, J.K. 2009. Resolving the effect of climate change on fish populations. *ICES Journal of Marine Science,* **66**:1570-1583.

Roberts, E.H. and Summerfield, R.J. 1987. Measurement and prediction of flowering in annual crops. In: Atherton, J.G. (Ed.). Manipulation of flowering. Butterworths, London, pp. 17-50.

Rockström, J. 1999. On–farm green water estimates as a tool for increased food production in water scarce regions. *Physics and Chemistry of the Earth Part B,* **24**(4):375-383.

Rockström, J., Kaumbutho, P., Mwalley, P. and Temesgen, M. 2001. Conservation farming among smallholder farmers in east Africa: Adapting and adopting innovative land management options. Conservation agriculture, a worldwide challenge. In: Proceedings of the First World Congress on Conservation Agriculture, vol. 1: Keynote Contributions, Madrid, Spain, 1-5 October, 2001, pp. 363-374.

Rockström, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis,T., Bruggeman, A., Farahani, J. and Qiang, Z. 2010. Managing water in rainfed agriculture: The need for a paradigm shift. *Agricultural Water Management*, **97**(4):543-550.

Rohrbach, D. 1989. The economics of smallholder maize production in Zimbabwe: Implications for food security. MSU International Development Paper No. 11, pp. 8-17. MSU International Development Papers. Department of Economics, Michigan State University. U.S.A

Rosegrant, M.W., Cai, X. and Cline, S.A. 2002. World water and food to 2025: Dealing with scarcity. International Food Policy Research Institute (IFPRI). Washington, D.C. Available on:

http://www.ifpri.org/sites/default/files/pubs/pubs/books/water2025/water2025.pdf (Accessed 14/01/2012).

Rosenzweig, C. and Hillel, D. 1995. Potential impacts of climate change on agriculture and world food supply. *Consequences,* **1**(2):24-32.

Rosenzweig, C. and Liverman, D. 1992. Predicted effects of climate change on agriculture: A comparison of temperate and tropical regions. In: Global climate change: Implications, challenges, and mitigation measures. Majumdar, S. K. (Ed.).pp. 342-361. PA: The Pennsylvania Academy of Sciences. Available on: http://www.ciesin.org/docs/004-145/004-145.html (Accessed 12/01/2013).

Rosenzweig, C. and Tubiello, F.N. 2007. Adaptation and mitigation strategies in agriculture: An analysis of potential synergies. *Mitigation and Adaptation Strategies for Global Change*, **12**:855-873.

Rosenzweig, C., Iglesius, A., Yang, X.B., Epstein, P.R. and Chivian, E., 2001. Climate change and extreme weather events: Implications for food production, plant diseases, and pests. *Global Change & Human Health,* **2(2)**:90-104.

Rukuni, M. 1994. Report of the commission of inquiry into appropriate agricultural land tenure systems. Volume II: Technical Reports. Government Printers, Harare.

Rusinamhodzi, L., Corbeels, M., van Wijk, M.T., Rufino, M.C., Nyamangara, J. and Giller, K.E. 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. *Agronomy for Sustainable Development,* **31**:657-673.

Saarikko, R.A. and Carter, T.R. 1996. Estimating the development and regional thermal suitability of spring wheat in Finland under climatic warming. *Climate Research,* **7**:243-252. Available on: http://www.int-res.com/articles/cr/7/c007p243.pdf (Accessed 05/01/2014).

Salick, J. and Byg, A. 2007. Indigenous peoples and climate change. Oxford, UK, Tindall Centre for Climate Research. Available on: http://www.ecdgroup.com/docs/lib_004630823.pdf (Accessed 17/06/11).

Sawa, B.A. and Ibrahim, A.A. 2011. Forecast models for the yield of millet and sorghum in the semi-arid region of northern Nigeria using dry spell parameters. *Asian Journal Agricultural Sciences,* **3**(3):187-191.

Schlenker, W. and Lobell D.B. 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters,* **5**(1):1-8.

Schlenker, W. and Roberts, M.J. 2006. Estimating the impact of climate change on crop yields: The importance of non-linear temperature effects. Available on: http://agecon.ucdavis.edu/research/seminars/files/michaelroberts_climatechangecropyields.pdf (Accessed 29/01/2013).

Schlenker, W. and Roberts, M.J. 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of National Academy of Sciences USA,* **106**(37):15594-15598. Available on: http://www.pnas.org/content/106/37/15594.long (Accessed 21/08/2013).

Schmidhuber, J. and Tubiello, F.N. 2007. Global food security under climate change. Proceedings of the National Academy of Science USA. Climate Change and Food Security Special Feature, **104**(50):19703-19708. Available on: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2148361/ (Accessed 20/05/13).

Schmidli, J. and Frei, C. 2003. 20th century trends of extreme precipitation conditions in the Swiss Alps. ETH partner report for deliverable D9 28 Oct 2003. Available on:http://www.cru.uea.ac.uk/projects/stardex/deliverables/D9/D9_ETH.pdf (Accessed 23/10/2010).

Schmidli, J. and Frei, C. 2005. Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century. *International Journal Climatology,* **25**:53-771.

Schulze, R.E. 2000. Modelling hydrological response to land use and climate change: A southern African perspective. *Ambio,* **29**:12-22.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C. and Zhang, X. 2012: Changes in climate extremes and their impacts on the natural physical environment. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.K., Allen, S.K., Tignor, M. and Midgley, P.M. (Eds.). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation - A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC).

Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230. Available on: http://ipcc-wg2.gov/SREX/images/uploads/SREX-Chap3_FINAL.pdf (Accessed 22/12/2013).

Seo, S.N. and Mendelsohn, R. 2008. A Ricardian analysis of the impact of climate change on south American farms. *Chilean Journal of Agricultural Research*, **68**(1):69-79. Available on: http://www.scielo.cl/pdf/chiljar/v68n1/at07.pdf (Accessed 28/01/2013).

Seo, S.N., Mendelsohn, R., Dinar, A., Hassan, R. and Kurukulasuriya, P. 2009. A Ricardian analysis of the distribution of climate change impacts on agriculture across agro-ecological zones in Africa. *Environmental and Resource Economics*, **43**:313-332.

Shively, G. 2008. Likely impacts of climate change on agriculture in Indiana. In: Impacts of climate change for the state of Indiana. Purdue University Climate Change Research Centre (2008). Available on: http://www.purdue.edu/discoverypark/climates/assets/pdfs/ClimateImpactsIndiana.pdf (Accessed 12/01/2013).

Shumba, E. 1983. Factors contributing to a decline in groundnut production in the Mangwende – Murewa district and the need for a technical research input. *Zimbabwe Agricultural Journal,* **80**:251-254.

Shumba, E. 1984. Animals and the cropping system in the communal areas of Zimbabwe. *Zimbabwe Science News,* **18(**7-8):235-238.

Shumba, E. 1989. Maize technology research in Mangwende, a high potential communal area environment in Zimbabwe. Part 2: The on-farm experimental program. *Farming Systems Bulletin, Eastern and Southern Africa,* **1**:1-13.

Shumba, E.M. 1994. Constraints in the smallholder farming systems of Zimbabwe. In: Soil fertility and climatic constraints in dryland areas. ACIAR proceedings. ACIAR proc.1994, **54**:69-73. Available on: http://aciar.gov.au/files/node/13648/soil_fertility_and_climatic_constraints_in_dryland_82505.pdf (Accessed 29/01/2013).

Shumba, E. 2001. Biodiversity and planning support programme Zimbabwe case study. International workshop on Integration of Biodiversity in National Forestry Planning Programme held in CIFOR Headquarters, Bogor, Indonesia on 13-16 August 2001.

Sibanda, S. 2005. Evaluation of three animal powered weeding implements in cotton based systems of the Zambezi valley in Zimbabwe. Master of Philosophy Thesis, Department of Soil Science and Agricultural Engineering, Faculty of Agriculture. University of Zimbabwe. Harare, Zimbabwe.

Sikwela, M.M. 2008. Determinants of household food security in the semi-arid areas of Zimbabwe: A case study of irrigation and non-irrigation Farmers in Lupane and Hwange Districts. Master of Science in Agriculture (Agricultural Economics). Faculty of Science and Agriculture, University of Fort Hare, South Africa.

SIPEAA, 2004. Tools for agrometeorological and agricultural modelling, ISCI-CRA Available on: http://www.sipeaa.it/ASP/ASP2/index_tools.asp (Accessed 29/09/2011).

Sivakumar, M.V.K., 1992. Empirical analysis of dry spells for agricultural applications in West Africa. *Journal of Climate*, **5**:532-539.

Siziba, S. 2008. Assessing the adoption of conservation agriculture in Zimbabwe's smallholder sector. PhD Thesis. Institute of Agricultural Economics and Social Sciences in the Tropics and Sub-tropics. University of Hohenheim, Germany.

Slater, R., Peskett, L., Ludi, E. and Brown, D. 2007. Climate change, agricultural policy and poverty reduction – how much do we know? Overseas Development Institute (ODI). *Natural Resource Perspectives,* **109**:1-6. Available on: http://www.odi.org.uk/resources/download/1231.pdf (Accessed 20/05/2013).

Smale, M. and Jayne, T. 2003. Maize in Eastern and southern Africa: "Seeds" of success in retrospect. Discussion paper No. 97. Environment and Production Technology Division. Washington, D.C. International Food Policy Research Institute. Available on: http://www.fao.org/docs/eims/upload/166420/Smale,Jayne.pdf (Accessed 14/05/2012).

Smith, A., Lott, N. and Vose, R. 2011. The integrated surface database: Recent developments and partnerships. *Bulletin American Meteorological Society*, **92**:704-708.

Snapp, S.S., Blackie, M.J. and Donovan, C. 2003. Realigning research and extension to focus on farmers' constraints and opportunities. *Food Policy*, **28**:349-363.

Snyder, R.L., Moratiel, R., Song, Z., Swelam, A., Jomaa, I. and Shapland, T. 2011. Evapotranspiration response to climate change. *Acta Horticulture* (ISHS), **922**:91-98. Available on: http://www.actahort.org/books/922/922_11.htm (Accessed 04/11/2013).

Sombroek, W.G. and Gommes, R. 1996. The climate change - agriculture conundrum: In Global climate change and agricultural production. Direct and indirect effects of changing hydrological, pedological and plant physiological processes. FAO, 1996. Bazzaz, F. and Sombroek, W. (Eds.). Rome, Italy. 68pp. Available on: http://www.fao.org/docrep/w5183e/w5183e00.htm#Contents (Accessed 21/08/2012).

Southworth, J., Randolph J.C., Habeck, M., Doering, O.C., Pfeifer, R.A, Raoc, D.G. and Johnston, J.J. 2000. Consequences of future climate change and changing climate variability on maize yields in the midwestern United States. *Agriculture, Ecosystems and Environment,* **82**:139-158.

STARDEX Diagnostic Extremes Indices Software User Information Version 3.3.1, June 2004. Available on: http://www.cru.uea.ac.uk/projects/stardex/deis/Diagnostic_tool.pdf (Accessed 29/04/2009).

Steward, D.W. and Shamdasan, P.N. 1998. Focus group research: Exploration and discovery: In Bickman, L. and Rog, D.J. (Eds.). Handbook of Applied Social Research Methods. Sage Publications. Thousand Oaks. London. New Delhi. pp. 505-526.

Streck, N.A. 2005. Climate change and agroecosystems: The effect of elevated CO_2 and temperature on crop growth, development and yield. *Ciência Rural,* **35**:730-740. Available on: http://www.scielo.br/pdf/cr/v35n3/a41v35n3.pdf (Accessed 20/06/2013).

Stringer, L.C., Dyer, J.C., Reed, M.S., Dougill, A.J., Twyman, C. and Mkwambisi, D. 2009. Adaptations to climate change, drought and desertification: Local insights to enhance policy in southern Africa. *Environmental Science and Policy*, **12**(7):748-765.

Sukume, C., Makudze, E., Mabeza-Chimedza, R. and Zitsanza, N. 2000. Comparative economic advantage of production in Zimbabwe. *Technical Paper No.99*, Department of Agricultural Economics and Extension. University of Zimbabwe, Harare.

Surface of Day Dataset, (undated) http://gosic.org/ios/MATRICES/ECV/ATMOSPHERIC/SURFACE/ECV-GCOS-ATM-SURFACE-airpressure-GSOD-data-context.htm (Accessed 29/04/2012).

Sutherland, A. 1998. Participatory research in natural resources. Socio-economic Methodologies Best Practice Guidelines. Chatham, UK: Natural Resources Institute. Available at: http://www.fao.org/docs/eims/upload/agrotech/1911/BPG03.pdf. (Accessed 17/06/2011).

Swathi Lekshmi, P.S., Venugopalan, R. and Padmini, K. 2008. Livelihood analysis using wealth ranking tool of PRA. *Indian Research Journal of Extension Education,* **8**(2&3):75-77. Available on: http://eprints.cmfri.org.in/7121/1/182-INDIAN_RES.JOURNAL_OF_EXT_.EDU.2008.pdf (Accessed 30/03/2013).

Tadross, M. 2011. Climate science, projections and interpretations. Available on: http://weadapt.org/knowledge-base/using-climate-information/climate-science-projections-and-interpretation (Accessed 09/07/2013).

Tadross, M.A., Hewitson, B.C. and Usman, M.T. 2005. The interannual variability of the onset of the maize growing season over South Africa and Zimbabwe. *Journal of Climate*, **18**:3356-3372.

Tadross, M., Suarez, P., Lotsch, A., Hachigonta, S., Mdoka, M., Unganai, L., Lucio, F., Kamdonyo, D. and Muchinda, M., 2009. Growing-season rainfall and scenarios of future change in southeast Africa: Implications for cultivating maize. *Climate Research,* **40:**147-161.

Tang, J., Chen, J. and Chen, X. 2006. Response of 12 weedy species to elevated CO_2 in low-phosphorus-availability soil. *Ecological Research,* **21**:664-670.

Tao, F., Yokozawa, M., Xu, Y., Hayashi, Y. and Zhang, Z. 2006. Climate changes and trends in phenology and yields of field crops in China, 1981–2000. *Agricultural and Forest Meteorology,* **138**:82-92.

Tekere, M. and Hurungo, J. 2003. The status of agriculture trade liberalization in SADC countries: A case for Zimbabwe. Trade and Development Studies Centre –Trust, 2003. March 2003 Newsletter, Issue No.9. Available on: http://www.tradescentre.org.zw/newsletters/2003/march/article5.htm. (Accessed 09/01/2008).

Teng, J., Chiew, F.H.S., Vaze, J. Marvanek, S. and Kirono, D.G.C. 2012: Estimation of climate change impact on mean annual runoff across continental Australia using Budyko and Fu equations and hydrological models. *Journal of Hydrometeorology,* **13**:1094-1106.

Tesfuhuney, W.A. 2012. Optimising runoff to basin ratios for maize production with in-field rainwater harvesting. Ph.D Thesis in Agricultural Meteorology. Department of Soil, Crop and Climate Sciences, Faculty of Natural and Agricultural Sciences. University of the Free State. Bloemfontein, South Africa.

Tesfuhuney, W.A., van Rensburg, L.D. and Walker, S. 2013. Surface treatments effect on rainfall, canopy interception and runoff-rainfall ratio for in-field rainwater harvesting. *Journal of Agricultural Science and Technology*, **3**(6):423-435.

Thierfelder, C. and Wall, P.C. 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil and Tillage Research*, **105**:217-227.

Thomas, D.S.G, Twyman. C., Osbahr, H. and Hewitson, B. 2007. Adaptation to climate change and variability: Farmer responses to intra-seasonal precipitation trends in South Africa*.* *Climatic Change,* **83**(3):301-322.

Thompson, J.G. and Purves, W.D. 1978. A guide to the soils of Rhodesia. *Rhodesian. Agricultural Journal*. *Technical. Bulletin,* **3**(3):1-64

Thornton, P., Herrero, M., Freeman, A., Mwai,O., Rege, E., Jones, P. and McDermott, J. 2007. Vulnerability, climate change and livestock – Research opportunities and challenges for poverty alleviation*.* *SAT eJournal,* **4**(1):1-23. Available on: http://www.icrisat.org/journal/SpecialProject/sp7.pdf (Accessed 19/05/2013).

Tilya, F. and Mhita, M. 2007. Frequency of wet and dry spells in Tanzania-Chapter 10: In: Sivakumar, M.V.K. and Ndiang'ui, N (Eds.). Climate and Land Degradation:. p.197-204.

Timms, W.A., Young, R.R. and Huth, N. 2012. Implications of deep drainage through saline clay for groundwater recharge and sustainable cropping in a semi-arid catchment area, Australia. *Hydrology and Earth System Sciences,* **16**:1203-1219.

Tinsley, R.L. 2009a. Post Harvest Handling & Seed Quality Evaluation for Selected Value Chain Commodities in Nigeria. 61pp. Available on: http://lamar.colostate.edu/~rtinsley/WASANigeria.pdf (Accessed 29/07/2013).

Tinsley, R.L. 2009b. Value Chain Analysis for Soybeans in Malawi. Citizens Network for Foreign Affairs (CNFA) – Farmer-to-Farmer Volunteer. 67pp. Available on: http://lamar.colostate.edu/~rtinsley/ValueChainAnalysisSoybeansMalawi.pdf (Accessed 29/07/2013).

Topp, C.F.E. and Doyle, C.J. 1996. Simulating the impacts of global warming on milk and forage production in Scotland: The effects on dry matter yield of grass and grass-white clover stands. *Agricultural Systems*, **52**:213-242.

Tsimba, S., Chawatama, R., Ndlovu, L.R., Mutimba, J., Ndhovu, P., Dzama, K., Topps, J.H., Hawk, D. and Mudhara, M. 1999. Socio-economic aspects of draft power: a diagnostic study in Zimbabwe. In: Starkey, P. and Kaumbutho, P. (Eds.). Meeting the Challenges of Animal Traction: A Resource Book of the Animal Traction Network for Eastern and Southern Africa (ATNESA) Harare, Zimbabwe. Intermediate Technology Publications, London. 173pp.

Tubiello, F.N. and Rosenzweig, C. 2008. Developing climate change impact metrics for agriculture. *Integrated Assessment Journal*, **8**:165-184.

Tubiello, F.N., Jagtap, S., Rosenzweig, C., Goldberg, R. and Jones, J.W. 2002. Effects of climate change on US crop production from the National Assessment. Simulation results using two different GCM scenarios. Part I: Wheat, Potato, Corn, and Citrus. *Climate Research*, **20**(3):259-270.

Tubiello, F.N., Soussana, J.F. and Howden, S.M., 2007. Crop and pasture response to climate change. *Proceedings National Academy Sciences USA,* **104**(50):19686-19690.

Tumbo, S.D., Kahimba, F.C., Mbilinyi, B.P., Rwehumbiza, F.B., Mahoo, H.F., Mbungu, W.B. and Enfors, E. 2012. Impact of projected climate change on agricultural production in semi-arid areas of Tanzania: A case of same district. *African Crop Science Journal*, **20**(2):453-463.

Turpie, J., Winkler, H., Spalding-Fecher, R. and Midgley, G. 2002. Economic impacts of climate change in South Africa: A preliminary analysis of unmitigated damage costs. Energy and Development Research Centre (EDRC), University of Cape Town. Available on: http://www.eldies.org/static/DOC1183.htm (Accessed 09/09/2010).

Twomlow, S., Mugabe, F.T., Mwale, M., Delve, R., Nanja, D.H., Carberry, P. and Howden, M. 2008a. Building adaptive capacity to cope with increasing vulnerability due to climatic change in Africa – A new approach. *Physics and Chemistry of the Earth*, **33**:780-787.

Twomlow, S., Urolov, J.C., Jenrich, M. and Oldrieve B. 2008b. Lessons from the field - Zimbabwe's Conservation Agriculture Task Force. *Journal of Semi-Arid Tropics (SAT) Agricultural Research*. **6**:1-11.

Twomlow, S., Hove, L., Mupangwa, W., Masikati, P. and Mashingaidze, N. 2008c. Precision conservation agriculture for vulnerable farmers in low-potential zones. In: Humphreys, E. and Bayot, R.S. (Eds). Proceedings of the workshop on increasing the productivity and sustainability of rainfed cropping systems of poor smallholder farmers. Tamale, Ghana, 22-25 September 2008. pp. 37-54. The CGIAR Challenge Program on Water and Food, Colombo, Sri Lanka.

Twomlow, S., Rohrbach, D., Rusike, J., Mupangwa, W., Dimes, J and Ncube, B. 2006. Spreading the Word on Fertilizer in Zimbabwe. Global Theme on Agro-ecosystems. Report no. 24. P.O Box 776, Bulawayo, Zimbabwe: International Crops Research Institute for the Semi-Arid Tropics. 16pp.

Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube, B., Hove, L., Moyo, M., Mashingaidze, N. and Maphosa, P. 2010. Micro-dosing as a pathway to Africa's Green Revolution: Evidence from broad-scale on-farm trials. *Nutrient Cycling in Agro-ecosystems*, **88**:3-15.

Unganai, L.S. 1996. Historic and future climatic change in Zimbabwe. *Climate Research,* **6**:137-145.

Unganai, L.S. 1997. Surface temperature variation over Zimbabwe between 1897 and 1993. *Theoretical and Applied Climatology,* **56**:89-101.

Unganai, L.S. 2009. *Personal Communication*. Department of Meteorological Services, Harare, Zimbabwe.

Unganai, S.L. and Mason, S.J. 2001. Spatial characterization of Zimbabwe summer rainfall during the period 1920-1996. *South African Journal of Science,* **97**:425-431.

UNFCCC (United Nations Framework Convention on Climate Change). 2007. Climate change: Impacts, Vulnerabilities and Adaptation in developing countries. Available on: http://unfccc.int/resource/docs/publications/impacts.pdf (Accessed 20/08/2012).

University of Zimbabwe (UZ). 2006. A guide to for farmers on good land husbandry: Alternative soil and water conservation ideas. Available on: http://ir.uz.ac.zw/jspui/bitstream/10646/391/1/13%20More%20soil%20and%20water%20conservation.pdf (Accessed 20/07/2013).

Vadez, V., Hash, T., Bidinger, F.R. and Kholova, J. 2012. *Frontiers in Physiolology*; **3**(article 386):1-12. Available on: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3475983/pdf/fphys-03-00386.pdf (Accessed 05/01/2014).

van Ittersum, M.K., Howden, S.M and Asseng, S. 2003. Sensitivity of productivity and deep drainage of wheat cropping sysstems in a Mediterranean environment to changes in CO_2, temperature and precipitation. *Agriculture, Ecosystems and Environment*, **97**:255-273.

Varallyay, G. 2010. The impact of climate change on soils and on their water management. *Agronomy Research*, **8**(2):385-396.

Verburg, K. and Bond, W.J. 2003. Use of APSIM to simulate water balances of dryland farming systems in south eastern Australia. Technical Report 50/03, CSIRO Land and Water, Canberra, Australia. Available on:

http://www.clw.csiro.au/publications/technical2003/tr50-03.pdf (Accessed 04/01/2013).

Verhulst, N., Govaerts, B., Verachtert, E., Castellanos-Navarrete, A., Mezzalama, M., Wall, P. and Sayre, K. 2010. Conservation agriculture, improving soil quality in sustainable production systems. In: Food Security and Soil Quality. Lal, R. and Stewart, B. (Eds.), Boca Raton, FL: CRC Press. 55pp.

Vicente-Serrano. S.M. and Beguería-Portugués, S. 2003. Estimating extreme dry-spell risk in the middle Ebro valley (Spain): A comparative analysis of partial duration series with a general pareto distribution and annual maxima series with a gumbel distribution. *International Journal of Climatology*, **23**:1103-1118.

Vincent, V. and Thomas, R.G. 1962. An agricultural survey of Southern Rhodesia Part I Agro-ecological Survey: Harare, Government Printer. 147pp.

Vogel, H. 1993. Tillage effects on maize yield, rooting depth and soil water content on sandy soils in Zimbabwe. *Field Crops Research*, **33**:367-384.

Vogel, H. 1994**.** Conservation tillage in Zimbabwe - Evaluation of several techniques for the development of sustainable crop production systems in smallholder farming. *African Studies Series, A 11*. Geographica Bernensia, Bern. 150pp.

Waddington, S.R, Sakala, W.D. and Mekuria, M. 2004. New directions for a diverse planet. Proceedings of the 4th International Crop Science Congress. 26 Sep – 10 Oct 2004. Brisbane, Australia. Published on CD-ROM. Available on: http://www.cropscience.org.au/icsc2004/pdf/1004_waddingtons.pdf (Accessed 26/05/2010*)*.

Waddington, S.R. and Karigwindi, J. 2001. Productivity and profitability of maize and groundnut rotations compared with continuous maize on smallholder farms in Zimbabwe. *Experimental Agriculture*, **37**(1):83-98.

Walker, N.J. and Schulze, R.E. 2006. An assessment of sustainable maize production under different management and climate scenarios for smallholder agro-ecosystems in Kwazulu-Natal, South Africa. *Physics and Chemistry of the Earth*, **31**(15-16):995-1002.

Wall, B.H. 1977. TAMET: Computer program for processing meteorological data. CSIRO Australia. Division of Tropical Crops and Pastures. *Tropical Agronomy Technical Memorandum,* **4**:13pp.

Wall, E. and Smit, B. 2005. Climate change adaptation in light of sustainable agriculture. *Journal of Sustainable Agriculture*, **27**(1):113-123.

Wall, E. and Smit, B. 2006. Agricultural adaptation to climate change in the news. *International Journal of Sustainable Development*, **9**(24):355-69.

Wang, H., Xu, S. and Sun, L. 2006. Effects of climatic change on evapotranspiration in Zhalong Wetland, Northeast China. *Chinese Geographical Science,* **16**(3):265-269.

Wang, M., Li,Y., Ye, W., Bornman, J.F. and Yan, X. 2011. Effects of climate change on maize production, and potential adaptation measures: A case study in Jilin Province, China. *Climate Research*, **46**:223-242.

Watson, A.J., Davie, T.J.A., Bowden, W.B. and Payne, J.J. 2004. Drainage to groundwater under a closed canopy radiatapine plantation on the Canterbury plain, South Island, New Zealand. *Journal of Hydrology* (NZ), **43**(2):111-123.

Wegehenkel, M. and Kersebaum, K.C. 2009. An assessment of the impact of climate change on evapotranspiration, groundwater recharge, and low-flow conditions in a mesoscale catchment in Northeast Germany. *Journal of Plant Nutrition and Soil Science,* **172**(6):737-744**.** Available on: http://onlinelibrary.wiley.com/doi/10.1002/jpln.200800271/pdf (Accessed: 04/11/2013).

Wheeler, D. 2007. Greenhouse Emissions and Climate Change: Implications for Developing Countries and Public Policy. Commission on Growth and Development Workshop on Global Trends and Challenges 28-29 September, 2007.

Wilk, J. and Hughes, D.A. 2002. Simulating the impacts of land-use and climate change on water resource availability for a large south Indian catchment. *Hydrological Sciences~Journal-des Sciences Hydrologiques,* **47**(1):19-30. Available on: http://iahs.info/hsj/470/hysj_47_01_0019.pdf (Accessed 05/01/2012).

WMO (World Meteorological Organization), 2011. Guide to Climatological Practices. WMO No.100. Available on: http://www.wmo.int/pages/prog/wcp/ccl/guide/documents/WMO_100_en.pdf (Accessed 28/04/2012).

Wolmer, W. and Scoones, I. 2000. The science of "civilized" agriculture: The mixed farming discourse in Zimbabwe. *African Affairs*, **99**:575-600.

World Bank, 2009. World Development Report 2010. Development and Climate Change. Chapter 4, pp. 188-230. Available on: http://siteresources.worldbank.org/INTWDRS/Resources/477365-1327504426766/8389626-1327510418796/Chapter-4.pdf (Accessed 03/04/2013).

World Bank, 2013. Zimbabwe Overview. Available on: http://www.worldbank.org/en/country/zimbabwe/overview (Accessed 22/12/2013).

You, L., Ringler, C., Nelson, G., Wood-Sichra, U., Robertson, R., Wood, S., Guo, Z., Zhu, T. and Sun, Y. 2010. What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach IFPRI Discussion Paper 00993 June 2010. International Food Policy Research Institute, Environment and Production Technology Division. Available on: http://www.ifpri.org/sites/default/files/publications/ifpridp00993.pdf (Accessed 05/07/2013).

Zhou, L., Dai, A., Dai, Y., Vose, R.S., Zou, C.Z, Tian, Y. and Chen, H. 2009. Spatial dependence of diurnal temperature range trends on precipitation from 1950 to 2004. *Climate Dynamics,* **32**:429-440. Available on: http://www.cgd.ucar.edu/cas/adai/papers/Zhou_etal_CD08_2007CD-00165-1.pdf (Accessed 22/08/2013).

Zhu, T. and Ringler, C. 2010. Climate change implications for water resources in the Limpopo River Basin. IFPRI Discussion Paper 00961. Available on: http://www.ifpri.org/sites/default/files/publications/ifpridp00961.pdf (Accessed 09/07/2013).

Ziervogel, G. 2004. Targeting seasonal climate forecasts for integration into household level decisions: The case of smallholder farmers in Lesotho. *The Geographical Journal,* **170**: 6-21.

Ziervogel, G., Cartwright, A., Tas, A., Adejuwon, J., Zermoglio, F., Shale, M. and Smith, B. 2008. Climate change and adaptation in African agriculture. Report prepared for Rockefeller Foundation By Stockholm Environment Institute. Available on: http://knowledgebase.terrafrica.org/fileadmin/user_upload/terrafrica/docs/Final_Rockefeller_Report4April08.pdf (Accessed 20/02/2012).

Zimbabwe Vulnerability Assessment Committee. 2005. Zimbabwe Livelihood Profiles. www.fews.net/livelihood/zw/National.pdf. (Accessed 26/05/ 2009).

Zingore, S., Gonzalez-Estrada E., Delve, R.J., Herrero, M., Dimes, J.P. and Giller, K.E. 2009. An integrated evaluation of strategies for enhancing productivity and profitability of resource-constrained smallholder farms in Zimbabwe. *Journal of Agricultural Systems*, **101**(1-2):57-68.

Ziska, L.H. 2010. Climate change impacts on weeds. Climate change and agriculture: Promoting practical and profitable responses. p. III 2–5. Available on: http://www.climateandfarming.org/pdfs/FactSheets/III.1Weeds.pdf (Accessed 09/07/2013).

Appendix I. The emission scenarios of the IPCC special report on emission scenarios (SRES)

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

Source: Adapted from IPCC, (2007).

Appendix IIa. Questionnaire on agronomic practices,crop production constraints and coping /adaptation strategies to climate variability change

Preliminary data

Enumerator:................... **Date**:..

Name of Farmer:............. **Age..........** **Sex**..............

District: 1 = Lower Gweru 2 = Lupane

Ward: 1=Mdubiwa 2=Nyama 3=Menyezwa 4=Daluka

Village: 1= Mxotshwa; 2=Madinga 3=Nsukunengi 4=Guduza
5= Mathonsi 6=Msingondo 7=Menyezwa 8=Masenyane
9=Banda 10=Daluka 11=Strip road 12=Mafinyela

	Code
1. What tillage system do you use?	
Conventional Tillage	1
Zero tillage	2
hand digging of entire field	3
Planting basins	4
Other /specify	5

2. Which crops do you grow?	
Maize	1
Groundnuts	2
Bambara nuts	3
Sweet potatoes	4
Sorghum	5
Pearl millet	6
Cowpeas	7
Rapoko	8
Melons	9
Other	10

3. What crop varieties do you grow?	
Maize: Very early maturing hybrids(400 series)	1
Early maturing hybrids(500 series)	2
Medium maturing hybrids(600 series)	3
Late maturing hybrids (700 series)	4
Local/traditional OPVs	5
Improved OPVs (ZM series)	6
other	7

Groundnuts:	Natal common	1
	Valencia white	2
	Valencia red	3
	Other	4
Sorghum:	Tsveta	1
	Pannar	2
	Macia	3
	DC 75	4
	Red Swazi	5
	Other	6
Pearl millet:	Tsholotsho bearded	1
	PMV1	2
	PMV2	3
	PMV3	4
	Okatshana	5
	Other	6

4. What types of fertilizer do you use, if any?

Kraal manure	1
Anthill	2
Compound D	3
Ammonium Nitrate or Urea	4
Leaf litter	5
Ash	6
Other (specify)	7

5. How many times do you weed fields planted to the major crop(s)?

Once	1
Twice	2
Thrice	3

6. What methods of weeding do you use?

Cultivator hand hoe	1
Hand hoeing	2

7. Which water management techniques do you use?

Winter ploughing	1
Contour ridging	2
Ridging	3
Deep weeding	4
Pot holing	5
Mulching	6
Furrow drainage	7
Other (specify)	8

8. Which factors influence your investment decisions?

Input availability	1
labour	2
Food security	3
Draft power	4
Climate	5
Implements	6
Cash	7
Other	8

9. Which cropping decisions are influenced by climate?

Planting date	1
Fertilizer application	2
Choice of crop	3
Varieties to grow	4
other	5

10. Are there any deviations from usual agronomic practices, this year?

Increased range of crops	1
Reduced range of crops	2
More area planted to maize	3
Less area planted maize	4
More sweet potatoes	5
Different varieties	6
Conservation tillage	7
Hired draft power	8
Fertilizer not applied at planting	9
Other (specify)	10

11. What are the reasons for deviations in 10?

Seed unavailability	1
Draft power	2
Climate-related	3
Fertilizer unavailability	4
Other (specify)	5

12. What major crop production constraints do you face?

Seed shortages	1
Labour shortages	2
Draft power shortages	3
Shortage of fertilizers	4
Other (specify)	5

13. How do you cope with and adapt to climate variability and change

Nature of rainfall pattern or problem arising from climate variability & change	**Coping / Adaptation strategies**
1. Short season length	
2. Low rainfall	
3. Mid-season dry spells	
4. Abrupt end of season	
5. Late rains	
6. High rainfall (Higher than normal)	
7. Water-logging	
8. Weak draft animals	
9. Inadequate grazing	

Appendix IIb. Check list for semi- structured interviews

What are livelihoods of communities?

What infrastructure and institutional arrangements are in place?

What are farming systems employed by farmers?

What influences farmer investment decisions?

What agronomic practices do farmers employ?

Which are the common constraints to agricultural productivity?

APPENDIX III: Format for the met_file used in APSIM

[weather.met.weather]
! Gweru: Record 1-Jan-1970 to 30-Jun-2008
!---
latitude = -19.45 (DECIMAL DEGREES)
!longitude = 29.85 (DECIMAL DEGREES)
!altitude = 1429 (m)

! TAV and AMP inserted by "tav_amp" on 21/11/2009 at 13:23 for period from 1/1970 to 182/2008 (ddd/yyyy)
tav = 18.15 (oC) ! annual average ambient temperature
amp = 9.34 (oC) ! annual amplitude in mean monthly temperature

site	year	day	mint	maxt	Rs	rain	
()	()	()	(°C)	(°C)	(MJ/m^2)	(mm)	
Gweru	1970	1	16.4	27.9	29	0.7	! Rainfall from RMP, Rsfrom sunshine hrs
Gweru	1970	2	12	28.4	32.7	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	3	15.3	26.9	28.6	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	4	14.4	27.3	31.9	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	5	12.8	28.3	30.6	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	6	13.9	25.1	31.3	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	7	12.4	23.8	24.3	1.3	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	8	10.1	23.3	32.7	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	9	8.8	25.2	33.1	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	10	9	26.6	32.9	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	11	10.2	28.8	32.7	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	12	13.9	32.2	32.3	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	13	17.3	28.2	30.5	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	14	15.8	28.6	24.7	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	15	16.1	29.4	28.6	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	16	16.2	27.6	30.7	0	! Rainfall from RMP, Rs from sunshine hrs
Gweru	1970	17	13.3	25.7	24.2	0	! Rainfall from RMP, Rs from sunshine hrs