CLIMATE CHANGE IMPACT ON CROP PRODUCTIVITY IN THE SEMI-ARID TROPICS OF ZIMBABWE IN THE 21ST CENTURY

J.P. Dimes *[a], P. Cooper[b] and K.P.C. Rao[b]
[a] ICRISAT – Bulawayo, Zimbabwe, j.dimes@cgiar.org
[b] ICRISAT – Nairobi, Kenya.

Abstract

The Intergovernmental Panel for Climate Change projections for Southern Africa (based on output of 21 GCM, using the A1B greenhouse gas emission scenario) suggests average annual temperature increases of 3.1°C and changes in annual rainfall of between -12 and +6%. Atmospheric carbon dioxide levels for this scenario are expected to increase to around 700ppm from the current 370ppm. How might these changes impact crop productivity in the drier semi-arid cropping systems of the region? This paper reports an analysis of the combined positive (CO_2 fertilisation) and negative (higher temperature, lower rainfall) impacts of these projected climate changes on crop productivity using the crop systems simulation model APSIM, its climate change module, together with the long-term daily climate data from Bulawayo (1951–2001). In undertaking these simulations, the effect of the climate change scenarios on the potential crop yield of maize, sorghum, pigeonpea and groundnut was examined.

APSIM output shows that increasing CO_2 concentrations will increase crop yields in the order of 6–8%. Similarly, reduction in rainfall amount had the expected negative impact on grain yield. However, it is increasing temperature (and not reduced rainfall) that has the most dramatic impact on crop grain yields; a reduction of 16% for the two cereals, 31% for groundnut, but only 3% for pigeonpea. Hence, for the combined effects of climate change, it appears that pigeonpea will be the least affected crop, incurring an 8% reduction in potential grain yield. In contrast, groundnut can be expected to incur a 30% reduction compared to current potential, sorghum a 22% reduction and maize a 25% reduction. Model output on crop duration, water use and stover yield is further analyzed to explain the differences between crop species in response to climate change and implication for animal feed.

An important implication of this analysis is that adoption of longer duration rather than shorter duration germplasm would seem the more appropriate response in dealing with the main effects of climate change. Another is preliminary indication that opportunities for increased cropping intensity and increased use of legumes in the farming system could emerge under climate change. However, the largest scope for dealing with reduced crop yields and food insecurity under future climate change is to raise the productivity of smallholder rainfed cropping systems.

Introduction

In 2002, the Intergovernmental Panel for Climate Change (IPCC) provided strong evidence of accelerated global warming. In Paris in February 2007 they released the most recent assessment that reinforced the link between human activity and global warming beyond any reasonable doubt (IPCC, 2007). Since then many key investors and stakeholders in agricultural development in the developing world have recognized that, while the exact nature and extent of the impacts of climate change on temperature and rainfall distribution patterns remain uncertain, it is the poor and vulnerable who will be the most susceptible to changes in climate. This is especially true for those communities who live in the drylands of Africa and who rely largely or totally on rainfed agriculture for their livelihoods. It is they who are currently most vulnerable to existing climate variability and shocks.

While climate change predictions point with a high degree of certainty to a warming world within the next 50 years, the impact of rising temperatures on rainfall distribution patterns in Africa remains far less certain (IPCC, 2007). However, climate change is likely to make matters worse with increases in rainfall variability being predicted for the semi-arid tropics (SAT) region. The prognosis for rainfall in Southern Africa is particularly poor, with almost the entire region having a reduction in rainfall (unlike India for example where the predictions are for areas of increase and decrease and in equal proportions), and up to 20% reduction in length of growing season with consequent effects for cropping area, distribution, productivity and ultimately food production in a region that consistently experiences food deficits (Scholes 2008, Bwalya, 2008, Ager, 2008). At the same time, Conservation Agriculture is being strongly promoted as an appropriate response to climate change in rainfed cropping systems because of its better management of the rainfall resource for crop production (Bwalya, 2008, Nyagumbo, 2008).

What has been less forthcoming is quantitative information on the likely extent of crop yield reductions. This is to be expected given the uncertainties in how rainfall patterns will change with rising temperatures, but also because there is likely to be positive (eg CO_2 fertilization) as well as negative impacts on crop productivity with climate change, and how the interaction of these effects will play out is difficult to analyze.

In this study we have applied a soil-crop simulation model in conjunction with actual and modified long-term historical climate data to assess the potential impact of climate change on crop productivity in semi-arid regions of Zimbabwe. The soil-crop modeling tool is APSIM (Keating et al., 2003) which contains well-tested algorithms that deal with temperature effects on crop growth and development as well as soil water and nitrogen dynamics (including in Zimbabwe, Bongani 2007). The model includes a ‘climate change’ module that allows temperature and rainfall data to be adjusted by nominated amounts and, for some crop modules, includes carbon assimilation algorithms that respond to increased CO_2 concentrations.

In the analysis we disaggregate the effects of increased temperature, reduced rainfall and increased CO_2 concentrations on crop productivity as well as investigate the combined effects. The focus of the analysis is assessments of climate change on crop productivity at the field level with the aim of identifying the main mechanisms by which climate change will impact crop yields and the extent of such impacts. It does not attempt to extrapolate the findings to national or regional level and does not make inferences for future food security.

Materials and Methods

Climate Change Scenario examined

We have referenced the climate change scenario for the greenhouse gas emission scenario associated with Storyline A1B.

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). The expected climate change impacts of this scenario across the 21 Global Circulation Models (GCM) used by IPCC are given for southern Africa in Table 1.

Table 1. Regional predictions for climate change in southern Africa by the end of the 21st century (IPCC, 2007)

Region	**Season**	**Temp. Response (°C)**					**Precipitation Response (%)**				
		Min	25	50	75	Max	Min	25	50	75	Max.
Southern Africa	DJF	1.8	2.7	3.1	3.4	4.7	-6	-3	0	5	10
	MAM	1.7	2.9	3.1	3.8	4.7	-25	-8	0	4	12
	JJA	1.9	3.0	3.4	3.6	4.8	-43	-27	-23	-7	-3
	SON	2.1	3.0	3.7	4.0	5.0	-43	-20	-13	-8	3
	Annual	1.9	2.9	3.4	3.7	4.8	-12	-9	-4	2	6

For Zimbabwe, we have taken the 50% percentile values for temperature change (3.1°C) in the growing season (DJF+MAM) and explored a 10% reduction in rainfall, even though the prediction is that rainfall in the growing months will, on balance, be unchanged. We have also examined the impact of increased greenhouse gas emission. For the A1B storyline, CO_2 levels will reach 700ppm by the end of the 21st century.

Cropping Scenarios examined.

We have used the ‘climate change’ module associated with the cropping systems model APSIM, together with the long-term daily climate data from Bulawayo (1951–2001) for this analysis. A summary climatic description is given in Table 2. At Bulawayo the cropping season rainfall falls predominantly between November and April. Bulawayo has an altitude of 1350 masl.

Table 2. Summary climatic characteristics of Bulawayo, Zimbabwe (Numbers in parenthesis are CV's of the mean rainfalls)

Location	**Bulawayo (1951- 2001)**	
Season	**Nov-Apr**	**Annual**
Average rainfall (mm)	548 (40%)	597 (30%)
Average max $T^{O}C$	27	26
Average min $T^{O}C$	16	13
Average $T^{O}C$.	22	19

The legume growth modules in APSIM are able to respond to increased carbon dioxide levels by modifying the transpiration efficiency coefficient and the N concentration optimum for photosynthesis. Neither the sorghum nor maize modules currently have this capability; hence different scenarios are simulated for the cereal and legume crops.

Based on the climate change predictions given in Table 1, we have examined the following scenarios through APSIM simulations:

1. Baseline. This scenario looked at simulations derived from the unmodified current climate data.

Grain legumes

2. Carbon dioxide fertilization. This scenario examined the impact of increasing the CO_2 level to 700ppm, keeping all other parameters constant.
3. Increased temperature. This scenario examined the impact of increasing the maximum and minimum temperatures, keeping all other parameters constant.
4. Reduced rainfall. This scenario examined the impact of decreasing daily rainfall by 10%, keeping all other parameters constant.
5. Carbon dioxide, plus temperature plus % rainfall changes.

Cereal crops

6. Increased temperature. This scenario examined the impact of increasing the maximum and minimum temperatures on cereal production, keeping all other parameters constant.
7. Reduced rainfall. This scenario examined the impact of decreasing rainfall by 10%, keeping all other parameters constant.
8. Temperature plus rainfall. This scenario looked at the combined impact of increased temperature and reduced rainfall for cereal production.

We examined these scenarios for sorghum (early hybrid cultivar), short-duration pigeonpea and short-duration groundnut varieties. As a matter of interest, we also examined the impact of these climate change scenarios on maize (early hybrid), which currently is widely grown by smallholder farmers in Zimbabwe's SAT.

Simulation details

A common planting moisture criterion (20mm over 5 days, 15mm plant available water in profile) and window (Nov 20 to Jan 10) was adopted for all simulations. Simulated plant populations (plants m^{-2}) for the respective crops were: sorghum – 6 , maize – 3.7 and groundnut – 10. The soil was shallow sand (1m rooting depth, PAWC = 59mm), Curve number for runoff was set to 85 and crop residues were removed after harvest. The soil water balance was simulated with accumulated effects of crop growth and rainfall across years (i.e., there were no resets).

In undertaking these simulations, we examined the effect of the climate change scenarios on the *potential* crop yield. In other words, we ran the simulations under nutrient non-limiting conditions, with no pest occurrences or weed infestation. In regard to N supply, soil N03-N was maintained at 75kg N ha^{-1} distributed throughout the profile for each day of crop growth. Where low N treatment for maize is simulated, soil mineral N was re-set to 16kg N ha^{-1} at each crop sowing.

If water balance conditions for planting within the nominated window were not met, a sowing was simulated to take place on the last day of the window regardless (i.e., a 'dry sow' on Jan 10th). As reliable information is not available on how climate change will affect distribution of rainfall within the cropping season, the aim was to sample all available seasons of rainfall distribution in quantifying the effects of climate change on plant growth. The implication is that crop failures due to lack of sowing rains is not included in the simulated yield distributions in this analysis.

Results

Grain yield, crop duration and water use.

Simulated average potential grain yield of sorghum, maize, groundnut and pigeonpea at Bulawayo are presented in Table 3, along with the average main effects of the climate change scenarios. APSIM output shows that increasing CO_2 concentrations will have a positive effect on crop yields, on average 8% and 6% for the two legume test crops. Similarly, a reduction in rainfall amount had the expected negative impact on grain yield, although with 6–8% yield reduction across species, it is to a lesser extent than the 10% reduction in rainfall. This suggests some improvement in water use with reduced rainfall amount in this environment, probably as a result of less runoff.

Table 3. APSIM simulations of the impact of climate change scenarios on average potential grain yield of sorghum, maize, groundnut and pigeonpea at Bulawayo, Zimbabwe.

Crop	Potential** grain yield kg ha^{-1}	CO_2 effect on yield	Rainfall effect on yield	Temp. effect on yield	CC* effect on yield
Sorghum	2753		-6%	-16%	-22%
Maize	2125		-8%	-16%	-25%
Groundnut	1979	+8%	-7%	-31%	-30%
Pigeonpea	1230	+6%	-7%	-3%	-8%

* Climate change – combined effects of increased temperature and CO_2, and reduced rainfall
** Potential yield of the current water, temperature and radiation environment averaged over 50 seasons, with no nutrient, pest or disease constraints.

Clearly, the scenario of increasing temperature has the most dramatic impact on crop grain yields, at least for the two cereals, which had a reduction of 16%, and particularly for groundnut, which had a 31% reduction. Interestingly, pigeonpea yield was little affected by the temperature increase – its 3% reduction in yield was even less than the reduction due to rainfall. Hence, for the combined effects of climate change, it appears that pigeonpea will be the least affected crop, incurring an 8% reduction in potential grain yield. In contrast, groundnut can be expected to incur a 30% reduction compared to current potential, sorghum a 22% reduction and maize a 25% reduction. However, it must be noted that of the four test crops, short-duration pigeonpea has by far the lowest current yield potential at Bulawayo.

What explains these differences in response to climate change between crop species? It is primarily related to a shortening of crop development phases with increased temperatures and consequent change in plant use of available resources, namely, solar radiation and soil water.

Under climate change, all crops are associated with a large reduction in days to maturity (13–18%) and reduction in total biomass (18–27%) except pigeonpea, which shows a 4% increase (Table 4). For maize and groundnut, there is also a decrease in average harvest index (HI) and water-use efficiency (WUE) because the grain filling period for these two crops suffers a larger reduction (19 and 14%) compared to the vegetative phase (17 and 11%). Sorghum, on the other hand, experiences greater shortening of the vegetative phase (18%) relative to the grain filling phase (14%), resulting in an increased HI while retaining a WUE of 6.7 kg ha^{-1} mm^{-1}. (However, the higher HI for sorghum is in relation to a much lower total biomass, resulting in the 22% reduction in grain yield shown in Table 3.)

In contrast, pigeonpea has the largest reduction in crop duration (18%), yet shows an increase in total biomass and an increase in WUE. An improved soil water balance for the pigeonpea explains this result. Under the current uni-modal rainfall conditions (and latitude), the crop has unfavorably long crop duration such that grain filling takes place under declining rainfall and increasing water stress. Higher temperatures under climate change shorten the crop duration so that it matures when the wet season is still active. This is particularly so for the grain filling period, which is reduced by 31% on average.

Table 4. APSIM simulations of the impact of climate change on potential total biomass, crop duration, in-crop rainfall, harvest index and water-use efficiency of sorghum, maize, groundnut and pigeonpea at Bulawayo, Zimbabwe.

	Baseline					Climate Change				
Crop	Total biomass kg ha^{-1}	Duration (d)	In-crop rain (mm)	HI	WUE* kg ha^{-1} mm^{-1}	Total biomass kg ha^{-1}	Duration (d)	In-crop rain (mm)	HI	WUE* kg ha^{-1} mm^{-1}
Sorghum	6398	107	396	0.41	6.7	4663	88	320	0.44	6.7

Maize	6403	129	433	0.29	4.3	4747	107	352	0.28	3.9
Groundnut	4628	122	416	0.42	4.5	3782	106	345	0.37	3.8
Pigeonpea	4288	165	463	0.27	2.3	4445	136	397	0.24	2.4

* WUE was calculated as kg of grain / (soil water at sowing – soil water at harvest + in-crop rainfall)

In terms of relative change, sorghum and pigeonpea grain yield demonstrated most resilience of the four test crops under climate change as a consequence of increased HI and WUE. However, it can be seen in Table 4 that WUE itself is dependent on crop duration and in-crop rainfall, both of which are reduced by climate change. An important associated result is the increase in residual soil water under climate change, from 8–22mm to 11–34mm across species. If, under climate change, the length of the rainy season is assumed to be unchanged (as in this analysis), then the predicted shortening of crop duration and higher residual soil water are indicative of opportunities for increased cropping intensity, especially on soils of higher water holding capacity.

Stover production.

In extensive mixed farming system in SAT regions, grain production is important for food security purposes. However, in these systems, crop stover is of equal or higher value as a feed source for livestock during the long dry season. Cereals provide the bulk of this feed source because there are limited plantings of legume, typically less than 10% of croplands. This is the situation even though legumes have a higher stover N content and therefore higher nutrient value than the cereal crops.

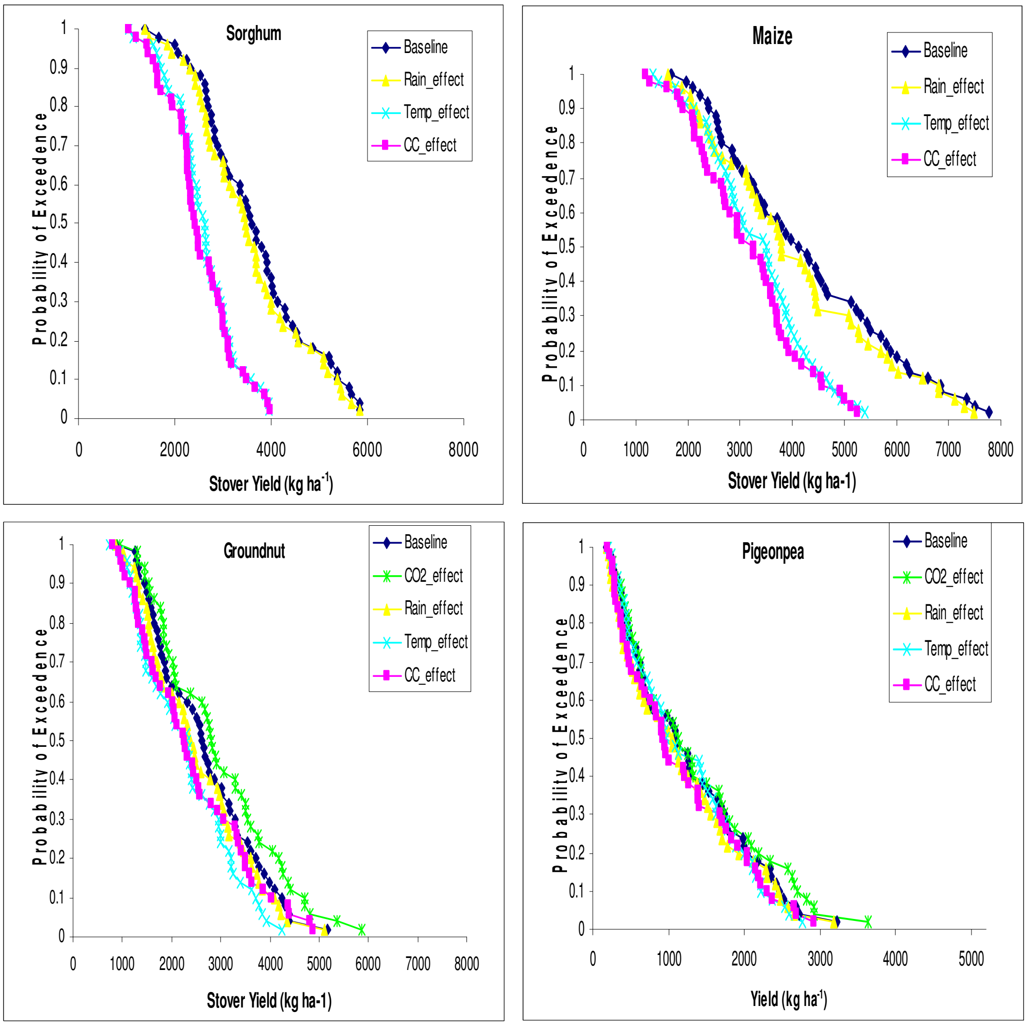

Figure 1. Cumulative probability distributions of exceedence for stover yields of sorghum, maize, groundnut and pigeonpea under various climate change scenarios at Bulawayo, Zimbabwe.

The probability distributions for crop stover yields (Figure 1) show that, under current conditions (and with non-limiting N supply), cereal crops compared to the legumes potentially produce more stover. However, under conditions of climate change, the cereal stover yields are more sensitive to the shortened crop durations compared to the legumes, and show dramatically reduced stover yield distributions, especially in the more favorable seasons. Under climate change, the 50 percentile yield for groundnut stover is similar to that of maize and sorghum and because of its higher N content may become a more attractive crop as a source of animal feed under the climate change scenario.

Climate change and farmer yields.

A comparison of simulated maize yield probability distributions at low levels of N fertility typical of farmer management in the SAT and at non-limiting N is shown in Figure 2, along with the respective responses under climate change conditions. The distributions show that in the drier 15% of years, maize yields at low N are higher than at N non-limiting, illustrating the strong interaction of N supply and water supply in determining grain yields in these environments (Bongani 2007). Also evident is the fact that for N constrained crops, climate change will adversely affect yields in the driest 30% of seasons but will have no or a slight increase in yield for the majority of seasons (the simulated small increases in yield with climate change are probably related to more favorable plant N balance as a result of shortened crop duration, smaller biomass production and higher soil N mineralization with higher soil temperatures). In other words, if farmers in the SAT maintain their current management practices and yield levels, climate change will be largely inconsequential due to the over-riding constraint of fertility on crop yield.

For the potential yield scenario (high N), climate change substantially reduces maize yield for the better 85% of the seasons. However, for almost all of these better seasons the potential yield under climate change still exceeds the distribution of current farmer practice (low N) by a much larger margin then the reduction in potential yield due to climate change. This highlights the large yield gap that smallholder farmers in these rainfed farming systems are forgoing in the better seasons, and points to the large scope that exists for dealing with future climate change impacts on food production if we could only find solutions to the chronic low productivity of these farming systems under current climate conditions.

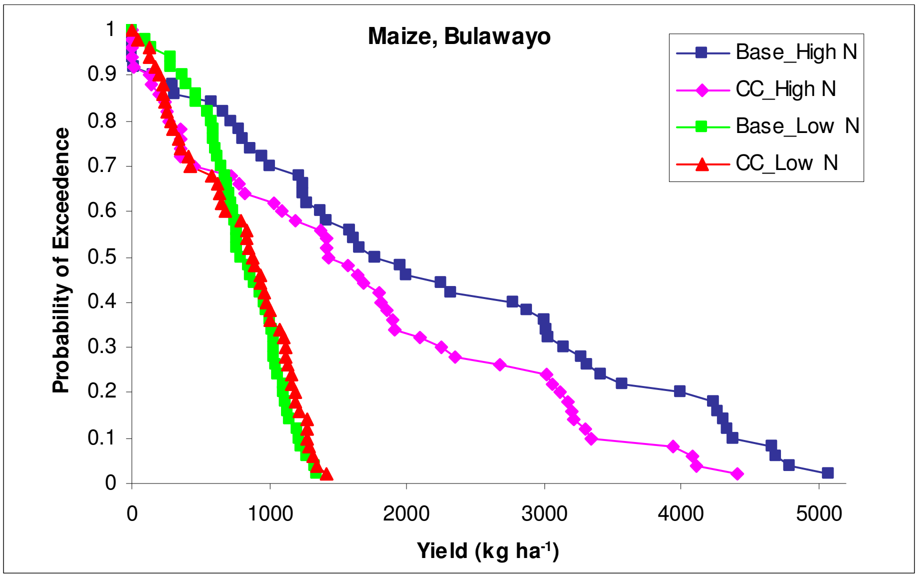

Figure 2. Cumulative probability distributions of exceedence for maize grain yield under current (Base_) and climate change scenario (CC_) for high (non-limiting) and low (farmer fields) levels of N at Bulawayo, Zimbabwe.

Summary

The crop simulation analysis has shown that for the chosen climate change scenario (A1B), potential crop yields in the Zimbabwe SAT will be substantially reduced under climate change: from 8–30% for the crop cultivars chosen in this analysis. The results also point to increased temperatures (the aspect of climate change that is seemly most certain) as the main mechanism by which climate change will have significant impact on crop productivity (through reduced crop duration, radiation interception and biomass accumulation). By comparison, the effects of predicted reductions in rainfall or increased CO_2 concentrations are relatively small in this analysis. This could be an important insight because much current thinking points to a need to breed shorter duration crop cultivars to deal with assumed shorter growing periods and increased moisture stress under climate change. This analysis suggests that the easy and readily available solution would be to adopt current longer duration germplasm under climate change conditions. At the same time, the simulation output on soil moisture, crop duration and stover yields is indicative of possible opportunities for increasing productivity under climate change, for example, an increased opportunity for relay cropping and increased use of legumes in the cropping system.

However, it should not be overlooked that this analysis has considered the effects of a climate change scenario that is predicted to take place at the end of the 21st century. The analysis also adopted potential grain yield (in relation to rainfall, temperature and radiation conditions of the test environment) in assessing the impact of the climate change scenario. The yield levels for the analysis are therefore much higher than that which smallholder farmers are typically producing, especially in the SAT where soil fertility is generally poor and investment in fertilizer by farmers is very low. While the analysis has shown that future climate change could have significant impact on crop productivity in the SAT, and there is need to prepare for this outcome, the research agenda should not lose sight of the fact that there is much to do in the present to help smallholder farmers increase their current crop productivity. Doing this in the context of current climatic risk is perhaps the best way of providing smallholder farmers with appropriate strategies for coping with future climate change (Cooper et al. 2007).

References

Ager, M. 2008. Perspectives on Food Security in Sub-Saharan Africa. Proceedings 3rd SADC-EU International Scientific Symposium – Towards Meeting the Challenges of Climate Change: Institutional structures and best practices in land and water management in southern Africa, 27-30 May, 2008, Lusaka, Zambia. (to be published)

Bwalya, M. 2008. Towards meeting the challenges of Climate Change: Institutional structures and best practices in land and water management in southern Africa. Proceedings 3rd SADC-EU International Scientific Symposium – Towards Meeting the Challenges of Climate Change: Institutional structures and best practices in land and water management in southern Africa, 27-30 May, 2008, Lusaka, Zambia. (to be published)

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., 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. Vol 126, p24–35.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 11. Regional Climate Projections. [Solomon, S., D. Quin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Eds)]. Cambridge University Press, Cambridge, UK. 996pp

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. European J. Agron. 18:267-288.

Ncube, B. 2007. Understanding cropping systems in semi-arid environments of Zimbabwe: options for soil fertility management. Ph.D. Thesis, Wageningen University, Wangeningen, The Netherlands. 155pp.

Scholes, B. 2008. IPCC findings and implications for Southern Africa. Proceedings 3rd SADC-EU International Scientific Symposium – Towards Meeting the Challenges of Climate Change: Institutional structures and best practices in land and water management in southern Africa, 27-30 May, 2008, Lusaka, Zambia. (to be published)