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Farming with current and future climate risk: Advancing a 'Hypothesis of Hope' for rainfed agriculture in the semi-arid tropics

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Abstract

Climate change predictions point to a warmer world within the next 50 years, a trend that is increasingly being supported by 'on-the-ground' measurements. However, the impact of rising temperatures on rainfall distribution patterns in the semi-arid tropics (SAT) of Africa and Asia remains far less certain.

During 2008, ICRISAT's crop modelers, GIS experts, crop physiologists and plant breeders met in Hyderabad, India for one week. Using a range of weather data driven tools, they initiated research to test the hypothesis that *"in the medium term (2010–2050), ICRISAT is well placed to help farmers mitigate the challenges and exploit the opportunities that are posed by climate change through: (i) the application of existing knowledge on crop, soil and water management innovations, and (ii) the re-deployment and re-targeting of the existing germplasm of its mandate crops."* Rather than selecting specific climate change scenarios, we chose to undertake a 'sensitivity-based' analysis in which we looked at the impact of a factorial combination of climate change of 5 different temperature increases (1, 2, 3, 4 and 5°C) and 3 different percentage changes in seasonal rainfall (0%, +10% and −10%) and compared the outputs with a 'control' of the current climate at each location for which the analyses was undertaken. We undertook three types of analyses. Firstly, we looked at the implication of these climate change combinations for changes in the length of growing period (LGP) and how they might effect the global distribution and extent of the SAT. Secondly, we examined in some detail how these scenarios would impact on crop production (millet, sorghum, groundnut and pigeonpea) in eastern, southern and western Africa and in India. We also looked, albeit to a lesser extent, at the potential 'fertilizer effect' of enhanced CO_2 levels on crop production. Finally, we examined the potential of improved production practices and better adapted germplasm to mitigate the impact of climate change.

The key points that emerged from this *ex ante* analyses are:

- Climate change will reduce the LGP across the SAT and their geographical distribution, but this could in large part be mitigated by improved water management innovations and the re-targeting and re-deployment of existing germplasm.
- Predicted temperature increases, through their effect of increasing the rate of crop development, have greater negative impacts on crop production than relatively small (+/− 10%) changes in rainfall.
- The impact of temperature increases alone on the yields under current low input agricultural practice is likely to be relatively small as other factors will continue to provide the overriding constraints to crop growth and yield. Significant reductions in rainfall amounts however, would modify this conclusion.
- The adoption of existing recommendations for improved crop, soil and water management practices, *even under climate change*, will result in substantially higher yields than farmers are currently obtaining in their low input systems.
- The development and adoption of better 'temperature-adapted' varieties, together with improved management practices, could result in the almost complete mitigation of the negative impact of temperature increases.

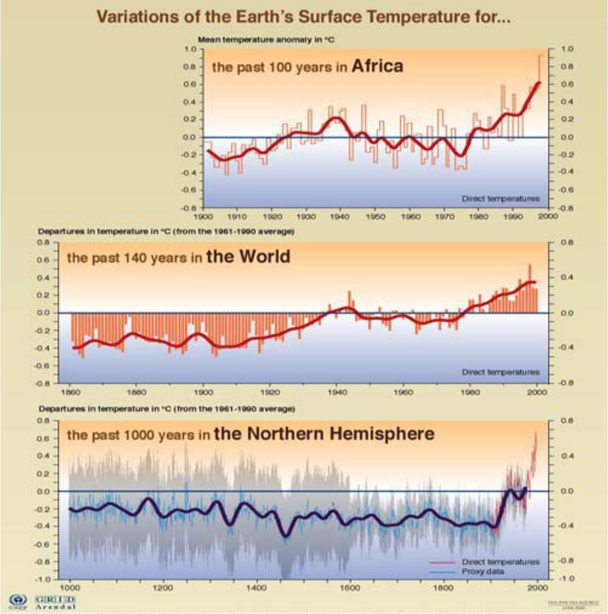
Recognizing that these analyses are preliminary in nature, we end by suggesting key areas of future research that are required to translate our ‘Hypothesis of Hope’ into reality on the ground.

Climate change: A global concern

The impact of escalating human activity on greenhouse gas emission, global warming and changes in global climate patterns is almost certainly the most discussed issue of the first decade of the 21st century. And it is being discussed worldwide at all levels of society – from global, regional and national institutions through to development agencies and down to private citizens and to farmers in the developing world.

In 2002, The Intergovernmental Panel for Climate Change (IPCC) provided strong evidence of accelerated global warming (Fig. 1). In Paris in February 2007, they released their most recent assessment which dispersed beyond any reasonable doubt the link between human activity and global warming, although the final outcome and impact of climate change still remains uncertain (IPCC 2007a).

In the intervening period many key investors and stakeholders in agricultural development in the Third World have recognized that, whilst 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 semi-arid tropics (SAT) of Africa and Asia and who rely largely or totally on rainfed agriculture for their livelihoods. It is they who are currently most vulnerable to existing rainfall variability and climatic shocks. Whatever happens to future greenhouse gas emissions, the world is now locked into inevitable changes to climate patterns and however uncertain those changes might currently be, farmers and farming practice will eventually need to adapt to them. In this context, the quotation of IISD (2003) deserves emphasis: *“Adaptation to climate change is therefore no longer a secondary and long-term response option only to be considered as a last resort. It is now prevalent and imperative, and for those communities already vulnerable to the impacts of present-day climatic hazards, an urgent imperative.”*



Sources: World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), *Climate Change 2001, Impacts, Adaptation, and Vulnerability, and Synthesis Report.*

Figure 1. Temperature changes in Africa, the world and the Northern hemisphere.

ICRISAT’s operational research plan. Recognizing this, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has developed an Operational Research Plan (2008–2015) entitled “Adaptations to Climate Change in the Semi-Arid Tropics” (ICRISAT 2008). This plan addresses key climate change adaptation challenges that span two time scales, namely, (i) the *short to medium term*; and (ii) the *medium to longer term*.

Short to medium term: **Helping farmers and stakeholders to cope better with current rainfall variability as a prerequisite to adapting to future climate change.** Season-to-season variability in rainfall amounts and distribution is an important consideration for ICRISAT given its mandate for the improvement of rainfed farming systems in the SAT of the developing world. Many factors contribute to the current low levels of investment in these systems, but production uncertainty associated with between and within season rainfall variability remains a fundamental constraint to many investors and vulnerable communities who often overestimate the negative impact of current climate induced uncertainty. Climate change is likely to make matters worse with increases in rainfall variability in the SAT being predicted.

In common with major players in the field of climate change adaptation (DFID 2005, World Bank 2006), *ICRISAT believes that for agricultural communities and agricultural stakeholders to adapt to climate change and the predicted future increases in climate variability, their ability to cope better with the constraints and opportunities of current rainfall variability must first be enhanced* (Cooper et al. 2008).

Building on this conviction, ICRISAT has successfully partnered with a range of organizations in

Sub-Saharan Africa and Asia in the development and initiation of a range of projects which address the core of our short- to medium-term strategy, namely, enhancing the management of current climate risk.

Medium to longer term: **Adapting and managing our mandate crops to grow in a warmer world.** ICRISAT has identified medium to longer term (20–30 years) priorities that will result in crop varieties and cropping systems that are adapted to a changed environment. Key factors considered are:

- Higher temperature tolerance to extreme events and modified crop duration due to temperature increases.
- Moisture extremes – both increased moisture stress and risk of temporary flooding.
- Changed distribution and severity of pests and diseases.
- The 'migration' of our mandate crops into geographical areas already marginal for other crops currently being grown there.

Because of their evolutionary advantage, ICRISAT mandate crops are better adapted than other major food crops [rice (*Oryza sativa*), maize (*Zea mays*), wheat (*Triticum aestivum*)] to such stresses. Our current breeding strategies have therefore already had to take into account existing high temperatures and low and variable rainfall and hence variable moisture stress. Because of this, in prioritizing ICRISAT's crop adaptation activities for addressing climate change, we are able to draw heavily on current research products and lessons learned as we shape the way forward (ICRISAT 2008).

The focus of this report: ICRISAT's medium to longer term adaptation plans. During 2008, ICRISAT used a range of computer-based programs and models to undertake a series of *ex ante* analyses designed to assess, in the medium to longer term, the potential of improved crop, soil and water management innovations coupled with better adapted germplasm to mitigate the negative aspects of predicted climate change. This was an extensive piece of work and a great deal of information has been generated and many lessons learned with regard to the suitability of different approaches. It is not the intention of this article to present the full scope of the results, but rather to highlight example outputs that illustrate the key findings and which point to the way forward.

Choosing climate change scenarios for our *ex ante* analyses

One of our first tasks was to decide what climate change scenarios we should use as the basis of our *ex ante* analyses. In doing this, we referred to the latest IPCC predictions that were derived from 21 General Circulation Models (GCMs) which were presented in their 2007 report (IPCC 2007b). We have summarized these climate change predictions for Africa and Asia in Table 1 where maximum and minimum predictions of change for temperature and rainfall are given together with the 25, 50 and 75 quartile values from the 21 GCMs.

Table 1 illustrates the variability in model prediction and hence the difficulty (especially with rainfall changes in Africa) of identifying a single climate change scenario as the basis for our analysis. It is made more complicated since the range of model predictions of climate change in Table 1 are derived from a single Greenhouse Gas Emission Scenario - Storyline A1B.

Many other Storylines exist, all of which suggest different rates and patterns of greenhouse gas increases in concentration over time and hence different GCM

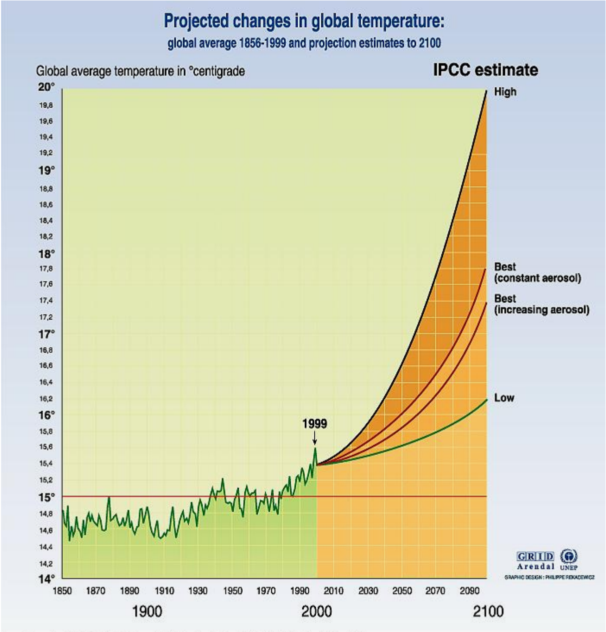
Table 1. Regional predictions for climate change in Africa and Asia by the end of the 21st century.

		Temp. response (°C)					Rainfall response[1] (%)				
Region	Season	Min	25	50	75	Max	Min	25	50	75	Max
Africa											
West Africa	Annual	1.8	2.7	3.3	3.6	4.7	–9	–2	2	7	13
East Africa	Annual	1.8	2.5	3.2	3.4	4.3	–3	**2**	**7**	**11**	25
Southern Africa	Annual	1.9	2.9	3.4	3.7	4.8	–12	–9	–4	2	6
Asia											
East Asia	Annual	2.3	2.8	3.3	4.1	4.9	2	**4**	**9**	**14**	20
Southern Asia	Annual	2.0	2.7	3.3	3.6	4.7	–15	**4**	**11**	**15**	20
Southeast Asia	Annual	1.5	2.2	2.5	3.0	3.7	–2	**3**	**7**	**8**	15

1. Values of the same sign for regions in which the middle half (25–75%) of the model prediction distribution for rainfall change are in bold.

predictions of temperature increases and rainfall changes. This is illustrated in Figure 2. However, it is clear that all scenarios predict a steady increase in temperature.

As a result of this uncertainty we decided not to choose any particular scenario, but rather to undertake a 'sensitivity-based' analysis in which we looked at a *factorial combination* of climate change of 5 different temperature increases (1, 2, 3, 4 and 5°C) and 3 different percentage changes in seasonal rainfall (0%, +10% and −10%) and compared the outputs with a 'control' of the current climate at each location for which the analysis was undertaken. In such a sensitivity analyses, no specific timelines are assumed in the simulations but broadly, a 1°C increase in temperature reflects a 'worst case scenario' of change to 2030 while 5°C scenario will reflect a 'worst case scenario' of change by the end of the century (Fig. 2). Based on this, we undertook three types of analyses. Firstly, we looked at the implication of these climate change combinations for changes in the length of growing period (LGP) and how they might effect the global distribution and extent of the SAT. Secondly, we examined in some detail how these scenarios would impact on crop production [millet, sorghum (*Sorghum bicolor*), groundnut (*Arachis hypogaea*) and pigeonpea (*Cajanus cajan*)] in eastern, southern and western Africa and in India. We also looked, albeit to a lesser extent, at the potential 'fertilizer effect' of enhanced CO_2 levels on crop production. Finally, we examined the potential of improved production practices and better adapted germplasm to mitigate the impact of climate change.



Source : Temperatures 1856 - 1999: Climatic Research Unit, University at East Anglia, Norwich UK. Projections: IPCC report 95.

Figure 2. Global increases in temperature across time and Greenhouse Gas Emission Scenarios until 2100.

Impacts of climate change on LGP and SAT distribution

The length of growing period (LGP). LGP at any location is an important indicator of the yield potential of that location and determines the suitability of contrasting management practices and maturity length crop types and cultivars. The LGP is defined as the number of days in any given rainfall season when there is sufficient water stored in the soil profile to support crop growth. It can be calculated from knowledge of incoming daily rainfall, daily soil evaporative and crop transpiration demand and the ability of the soil to store water within the crop rooting zone. In this context, long-term information of rainfall, temperature, solar radiation, wind speed and relative humidity are needed. Based on such information and using the procedures described by Thornton et al. (2006), the impact of a range of climate change scenarios on the likely percentage change in the average LGP across Africa have already comprehensively mapped as illustrated for East and Central Africa using the climate change scenario produced by the GCM HadCM3.B1 for the period 2000 to 2050 (Fig. 3).

As would be expected, there is substantial variation across the region with this particular climate change

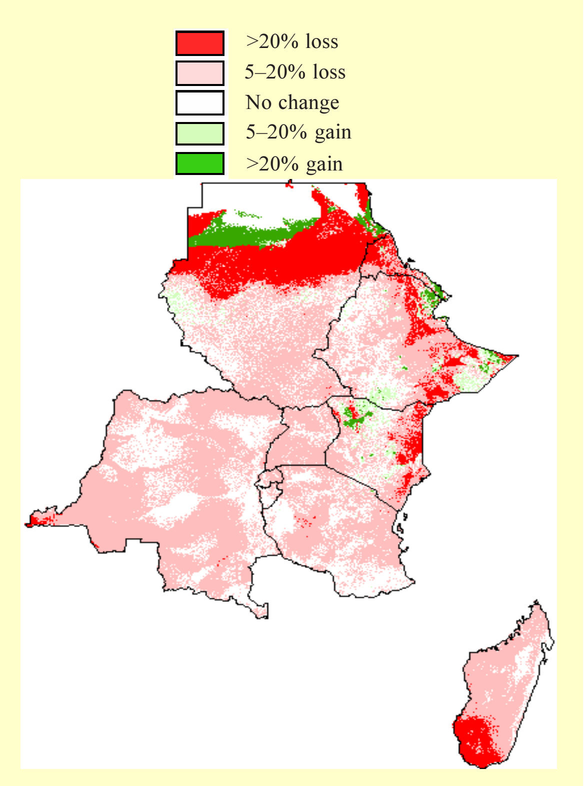


Figure 3. Percentage change in LGP in East and Central Africa to 2050 as predicted by HadCM3.

scenario suggesting that in much of the region there will be little to moderate reduction in the LGP (0–20%), whilst in other parts there will be quite severe losses in LGP (>20%). In a few areas there will be quite substantive gains in LGP (>20%). This kind of information is very valuable in providing a basis for strategic planning and decision making at the regional and country level.

However, it is at the district level that development initiatives are more likely to be planned and implemented. At this scale, we need to look in greater detail at the implications of season-to-season variation in rainfall, rather than rely on just average changes in LGP.

Looking at LGP in more detail: Makindu, Kenya as a case study. To do this, we used the crop/water balance routine of the crop growth simulation model, the Agricultural Production Systems Simulator (APSIM). As a case study, we used 45 seasons (1959–2004) of daily rainfall and temperature data for the short rainy season at Makindu, a SAT location in Kenya, and determined the LGP for *each of those 45 seasons*. We undertook this analysis for a soil profile that was able to store 150 mm of plant available water (PAW). We looked at the range of LGPs under the current climate (control), and also looked at the impact of a 1 and 3°C increase in mean temperature, but retained rainfall levels at their present-day values. The outputs of these analyses for the 45 seasons are presented in Figure 4 in a probability format as the '% chance of exceeding' any given LGP. From Figure 3, the region-wide mapping suggests that in the Makindu area of Kenya, average LGPs might decrease from 5 to 10% by the year 2050, when temperatures might increase between 1 and 2°C. This is reflected in the more detailed analyses in Figure 4.

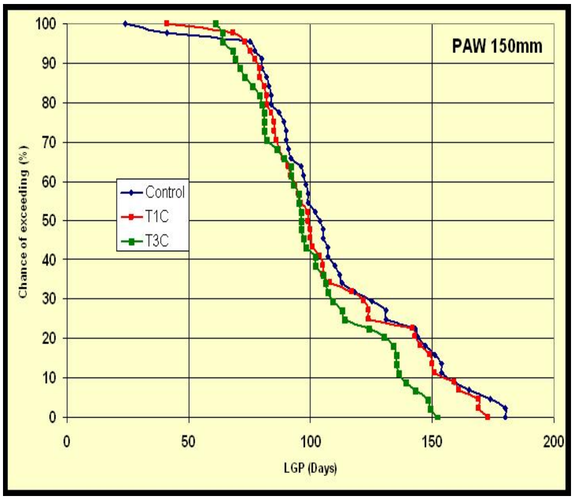


Figure 4. The impact of a 1 and 3°C temperature increase on the LGP for the short rainy season at Makindu, Kenya.

However, the important point here is to recognize that even under the current climate of today, farmers at Makindu experience LGPs ranging from 25 days (crop failure) to over 175 days as shown by the blue 'control' line in Figure 4. *In that light, a 5–10% decrease in the average LGP is unlikely to result in farmers having to cope in the future with a situation that they have not and are not already experiencing*.

This reinforces an important point: innovations that allow farmers to cope better with current season-to-season rainfall variability can do much to help them adapt to future climate change.

This is well illustrated by further consideration of a very variable but key component of the crop/soil water balance that determines the LGP**,** namely surface water runoff. In many parts of the SAT, and Makindu is no exception, intense rainfall events result in frequent surface water runoff and soil erosion (Fig. 5). Under such conditions, water conservation innovations are recommended in order to reduce such runoff losses and increase the amount of water that is stored in the soil profile for subsequent crop use.

APSIM was used to examine the climate induced risk of surface runoff at Makindu under current climatic conditions. In the example that we give here, APSIM was programmed to simulate the impact of two water conservation innovations on surface water runoff under fertilized maize at Makindu, namely, (i) soil ridging on the contour; and (ii) soil mulching with maize crop residues. The output provided simulations of what the impact of these measures would have been for each of the short rainy seasons between 1959 and 2004**.** These 45 sets of results were then plotted in the probability format and are presented in Figure 6.

Figure 5. Rainfall runoff and erosion from a cropped field near Makindu, Kenya.

The simulation results are in close agreement with those of field-based trials which have shown that both types of innovation are effective in water conservation and hence greater storage in the soil profile and confirm that APSIM is well able to simulate such effects (Okwach and Simiyu 1999).

We then evaluated the effect that water conservation innovations could have in mitigating the impact that increased temperatures have in reducing the LGP as shown in Figure 4. In this exercise we simulated the LGP at Makindu under three scenarios, namely, (i) current climate with no water conservation which represents current practice (blue line in Figure 7); (ii) current climate + 3°C with no water conservation which represents recommended practices (green line in Figure 7); and (iii) current climate + 3°C + mulching for water conservation (red line in Figure 7).

The implications of the outputs of this analysis are important. The average LGP at Makindu under current climate and current soil management is 110 days, but this is reduced by 8%, with a 3°C rise in temperature, to 101 days. However, the application of maize residue mulch under the climate change scenario in fact raised the average LGP to 113 days, 3 days longer than under current climate conditions. When the mulch was applied, only in the 30% of the most favorable seasons was the LGP, under a 3°C temperature increase, lower than that experienced today.

In summary, water conservation measures not only can have important beneficial impacts on water storage in the soil profile and hence the LGP under *current* climate conditions (Fig. 6.), but also can play a major role in helping to manage and ameliorate the impact of *future* climate change on the LGP (Fig. 7).

The global distribution of the SAT. The SAT are defined as regions where the average LGP is between 75 and 180 days and the mean monthly temperature of all months, corrected to sea level, is greater than 18°C with daily mean temperatures during the growing period being greater than 20°C (TAC 1992). It is clear from the previous section that climate changes in temperature and rainfall amounts will affect the LGP in many parts of the world. Inevitably, this means that it will also impact on the extent and distribution of regions that are defined and mapped as the SAT.

As a basis of this global analysis, we used MarkSim. MarkSim is a spatially explicit daily weather generator that was developed at CIAT (Jones and Thornton 2000) and was released in 2004. The climate surfaces that are produced use data from 10,000 stations in Latin America, 7000 from Africa and 4500 from Asia. MarkSim relies on climatic data surfaces interpolated from weather stations and generates estimates of long-term daily weather records on a grid basis of 18 × 18 km. We used such data as representative of 'current climate.' We then modified these datasets according to each of 15 factorial combinations of temperature and rainfall changes that we had chosen and assessed the impact that this had on changes in the LGP for each temperature and rainfall change combination.

For each grid, LGPs were classified into 'SAT' and 'non-SAT' according to the definition provided by TAC (1992). The SAT point layer was then interpolated over space to delineate the extent of the SAT for "current" climate and for each of the 15 change scenarios. Spatial differences were computed between "current" climate and each of the 15 scenarios to provide maps of area lost and area gained for the SAT. Corresponding areas were tabulated in km². An example of this mapping exercise is

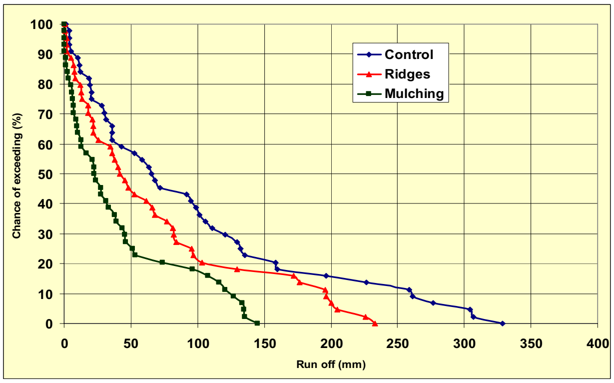


Figure 6. The impact of two water conservation innovations on surface water runoff (mm) at Makindu, Kenya for 45 seasons (1959–2004).

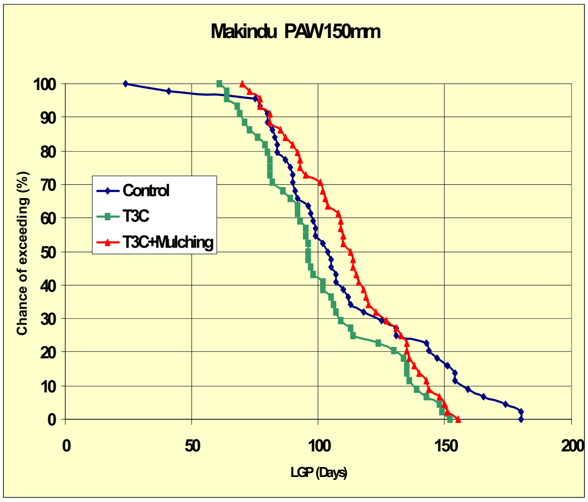


Figure 7. The effect of mulching on ameliorating the impact of climate change on LGP in Makindu, Kenya.

presented in Figure 8 and the 'losses' and 'gains' in land area of all 15 factorial combinations of temperature and rainfall change are summarized in Table 2.

The changes presented will largely occur through: (i) SAT areas being *'lost'* from their driest margins to arid zones through LGPs becoming too short, or (ii) *'gained'* on their wetter margins from sub-humid regions through the reduction in the current LGPs in those zones. As would be expected (Table 2), the greater the degree of aridity and warming in the climate change scenarios, the more pronounced is the impact on changes in the distribution of the SAT. Although both losses and gains in SAT land area were observed for each scenario examined, in 14 out of the 15 cases, the net area that would be defined and mapped as SAT increased.

The implications of this, of course, go far beyond the academic considerations of definitions and mapping. They will directly affect many millions of families worldwide who rely upon rainfed agriculture for their livelihoods. They will affect the choice and suitability of the crops that farmers grow and how they grow them, the extent to which they integrate livestock into their farming system and how they feed them and they will probably find themselves subject to a changed nature of climate-induced production risk and possible climatic shocks. We examine some of these challenges and opportunities in more detail later.

The key points that have emerged from the above analyses are:

- The nature, rate and scope of climate change currently remain uncertain. The choice of what scenarios to consider should be made from a pragmatic perspective. Our approach of undertaking a sensitivity analysis through a factorial combination of temperature and rainfall change scenarios is one such pragmatic approach.

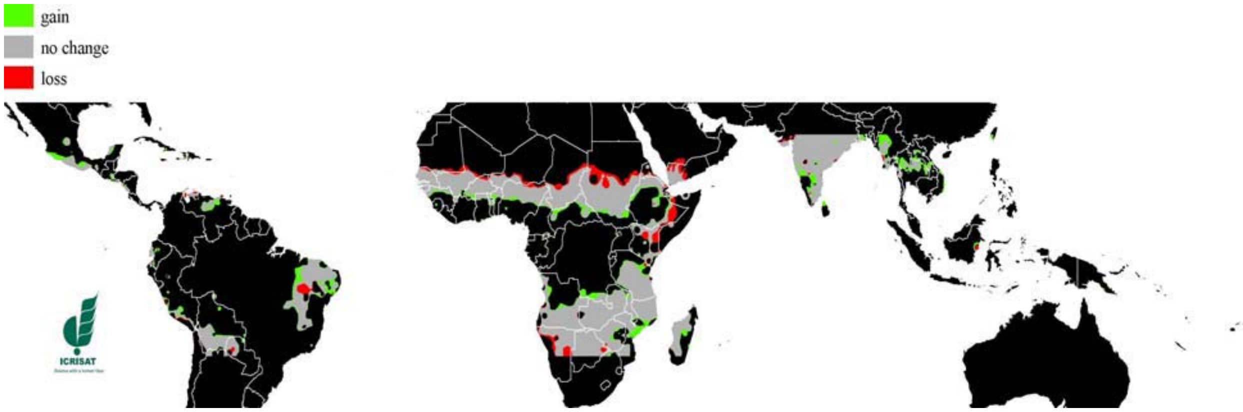


Figure 8. The projected change in the global extent of the SAT resulting from a mean temperature increase of 2°C and an average decline of 10% in rainfall.

Table 2. The effect of a factorial combination of temperature changes (+1, 2, 3, 4 and 5°C) and percentage changes in rainfall (0, +10, –10%) on the global area lost from and gained by the semi-arid tropics (SAT).

Mean rainfall change (%) above current levels	Area ('000 km)^2 at mean temperature increase (°C) above current levels					
	1	2	3	4	5	Average
+10	Loss 308 Gain 250	Loss 134 Gain 394	Loss 243 Gain 674	Loss 426 Gain 1002	Loss 650 Gain 1392	Loss 352 Gain 1237
0	Loss 259 Gain 505	Loss 525 Gain 913	Loss 701 Gain 1275	Loss 1007 Gain 1649	Loss 1273 Gain 2182	Loss 753 Gain 1305
–10	Loss 766 Gain 1221	Loss 1140[1] Gain 1636[1]	Loss 1492 Gain 2223	Loss 1776 Gain 2922	Loss 1901 Gain 3322	Loss 1415 Gain 2265
Average	Loss 444 Gain 659	Loss 600 Gain 981	Loss 812 Gain 1391	Loss 1069 Gain 1858	Loss 1275 Gain 2299	

1. Scenario presented in Figure 8.

- The LGP is an important indicator of the yield potential of a location and determines the suitability of contrasting management practices and maturity length crop types and cultivars. It will be impacted by both changes in rainfall patterns and temperature increase.
- Changes in the LGP can be mapped at a range of scales. Mapping mean changes in LGP at the country and regional scale are useful for strategic decision making at that level, but at the district level, where the planning of development initiatives is more likely to take place, a more detailed consideration of the changes in season-to-season variation of LGP and the associated climate risk is more useful than considering changes in mean values.
- LGPs can be modified through improved water conservation practices that increase the amount of water stored in the soil profile for subsequent crop use. In a case study, our simulations suggest that the negative impacts of climate change on the LGP at Makindu in Kenya can be *more than offset* by the adoption of existing recommendations for improved water conservation.
- Climate change impacts on LGPs will affect the global distribution of the SAT. The changes that are noted will largely occur through: (i) SAT areas being *'lost'* from their driest margins to arid zones through LGPs becoming too short, or (ii) *'gained'* on their wetter margins from sub-humid regions through the reduction in the current LGPs in those zones.

The impact of climate change on crop growth and yield

The scope of the study. As has been already discussed, APSIM can simulate a wide range of soil and water management practices together with the growth and yield of a range of crops amongst which maize, sorghum, pearl millet (*Pennisetum glaucum*), chickpea (*Cicer arietinum*), pigeonpea and groundnut are particularly important in the SAT. Another crop growth simulation model, the Decision Support System for Agro-technology Transfer (DSSAT) has very similar attributes to APSIM and was used for the simulations undertaken for Indian locations. When properly calibrated for these crops, APSIM and DSSAT provide an accurate simulation of actual crop yields across a range of soil types and seasons. Given that they are driven by daily weather data, they can also be satisfactorily used to evaluate the impacts of temperature and rainfall change scenarios.

We undertook an extensive analysis which investigated the impact of the 15 chosen climate change scenarios on the growth and yield of sorghum, millet, groundnut and pigeonpea across a range of locations in western, eastern and southern Africa and in India for which long-term daily climate data was available (Table 3).

Table 3. Summary information of locations where APSIM and DSSAT were used to evaluate the impact of temperature and rainfall changes on the growth and yield of sorghum (S), millet (M), pigeonpea (PP) and groundnut (GN).

	Mean climate within growing season				
Location	Max temp	Min temp	Mean rainfall	Period of record	Crops simulated
Kenya					
Makindu	28.6	18.0	337 (short rains)	1959–2004	S, PP
Katumani	25.2	14.0	293 (short rains)	1957–2004	S, PP
Zimbabwe					
Bulawayo	27.2	16.4	548	1951–2001	S, PP, GN
Masvingo	28.3	16.7	596	1951–2001	S, GN
Malawi					
Kasungu	28.2	18.1	788	1927–1999	GN
Niger					
Sadore	37.5	24.1	525	1983–2007	M
India					
Parbhani	32.5	22.3	790	1969–2007	S
Dharwad	29.6	20.4	410	1975–2003	S
Patancheru	32.8	23.3	678	1975–2007	S
Aurangabad	33.3	21.9	538	1955–1983	S
Bijapur	31.5	22.1	410	1983–2007	M
Hisar	35.4	24.9	350	1970–2007	M
Anantapur	33.5	23.7	343	1965–2006	GN
Junagadh	32.9	25.0	720	1985–1998	GN

In undertaking this first analysis, we made the following assumptions:

- Soil nutrients, weeds, pests and diseases would not be limiting factors. This allowed us to initially focus purely on the impact of climate change on *potential* crop yield.
- Temperature increases would be equally reflected in changes in both the maximum and minimum air temperatures.
- Changes in rainfall would be equally reflected in each rainfall event and that there would not be a change in the number of rain events or their distribution from that typical of current climates.

We recognize that such simplifying assumptions must place a need for caution on too detailed an interpretation of the results, but we felt that they were justified in enabling us to rapidly identify the main effects of climate change in the scenarios that we were using.

We also initially intended to look at the impact of enhanced CO_2 levels as part of our investigation but found that the APSIM modules for sorghum and millet, unlike the legume modules, are yet to include the capability to respond to varying levels of atmospheric CO_2. As a result, we did not pursue this as a major part of our simulation. Nevertheless, before we present the main body of the work, we present example results which illustrate the CO_2 fertilization effect on groundnuts in Zimbabwe.

The disaggregated impacts of climate change: A case study of groundnuts. Using 50 years (1951–2001) of daily climate data from Bulawayo in Zimbabwe as a basis, we simulated the disaggregated impact of changes in the three key components of climate change. Carbon dioxide levels were raised from 350 to 700 ppm, mean temperatures during the growing season were raised by 3°C and mean rainfall amounts were decreased by 10% as described above. These values were chosen from IPCC predictions for southern Africa by the end of this century (Table 1). We compared these disaggregated impacts with: (i) the combined impact of climate change; and (ii) with growth and yield under current climatic conditions which we called the 'baseline'. The outputs from the 50 seasons of simulations are summarized in Table 4 and Figure 9.

The results indicate that APSIM provides a realistic estimate of the CO_2 fertilization effect on groundnut yields. In the 25% poorest seasons, the effect was very marginal, largely due to the moisture stress that groundnut would experience in such years. However, in the 60% most favorable seasons, higher levels of CO_2 resulted in a yield increase of 7 to 13%, averaging 8% across all seasons. This is in broad agreement with the results of other field-based and simulation studies (Muchow and Sinclair 1991, Abraha and Savage 2006). Decreasing the rainfall by 10% had predictable impacts on groundnut yield with an average reduction in yield of 7% across all seasons. As would be expected, such decreases in yield were more pronounced in the 25% poorest seasons and far less serious in the 25% most favorable seasons when rainfall was abundant and well distributed.

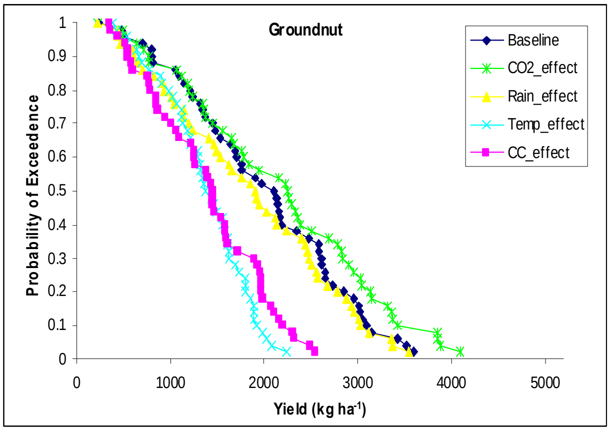


Figure 9. Disaggregated impacts of climate change on groundnut production at Bulawayo.

Table 4. The impacts of disaggregated climate change components on groundnut yield at Bulawayo, Zimbabwe.

Yield value distribution	Yield under current climate (kg ha^{-1})	% change due to CO_2 increase (350→700 ppm)	% change due to 10% decrease in rainfall	% change due to temperature increase of 3°C	% change due to combined effects of climate change
Minimum	244	0	–12.7	+27.1	+33.8
25% quartile	1311	+2.4	–20.9	–16.4	–34.8
50% quartile	2104	+7.3	–8.7	–34.8	–31.1
75% quartile	2653	+12.7	–3.4	–32.2	–26.4
Maximum	3583	+13.3	–1.3	–37.9	–29.3

The impact of increased temperatures was negative and far more pronounced than the impacts of either CO_2 or rainfall changes and was relatively constant, averaging –31% across all seasons. What explains the large impact of increased temperatures in yield? As will be illustrated in the next section, it is primarily related to a shortening of crop development phases with increased temperatures and the consequent reduction in the time available for the plant to effectively use available resources, namely, solar radiation and soil water and nutrients for dry matter accumulation and yield production. This has been analyzed and discussed in greater detail elsewhere, not only for groundnuts, but also for similar simulations undertaken on pigeonpea, sorghum and maize (Dimes et al. 2008).

Similar outputs from other early simulations also pointed to the overriding importance of the negative impact of increased temperatures on crop yield. They were important in guiding and focusing the analyses of the larger study described in the sections reported below.

The impact of temperature increase on rates of crop growth and yield. As illustrated in the groundnut case study above, whilst the impacts of changes in the CO_2 and rainfall amounts are generally relatively small and as expected in the SAT, increases in mean air temperatures have a more pronounced impact on the rate of crop development (time to maturity in days) and subsequent crop yield. This general picture was also reflected in the main body of the work as illustrated for a grain legume (pigeonpea) and a cereal (sorghum) in Tables 5 and 6.

Focusing on the impact of temperature changes, we illustrate this further and in more detail by selecting and summarizing typical datasets from the large number of simulations that were undertaken (Table 3). These are presented for: (i) short-duration pigeonpea at Katumani, Kenya (Table 7); (ii) sorghum at Aurangabad, India (Table 8); (iii) pearl millet at Hisar, India (Table 9); and (iv) groundnut at Bulawayo, Zimbabwe (Table 10). In addition we present similar data for maize (at Makindu, Kenya) as it is such a widely grown and important crop in Africa and Asia (Table 11) and is also known to be sensitive to ambient temperatures with regard to its rate of development and yield formation (eg, Cooper 1979).

In all cases illustrated, the picture is similar, namely increasing temperatures enhance the rate of crop development and result in corresponding declines in crop yield. We must emphasize again and as explained earlier, the simulations presented in Tables 7 to 11 assume no changes in rainfall amounts or distribution.

Table 5. The simulated effect of a factorial combination of temperature and rainfall changes on mean short-duration pigeonpea yields at Katumani, Kenya[1].

Mean rainfall change (%) from current levels	Yield (kg ha^{-1}) at mean temperature increase above current levels (°C)					
	1	2	3	4	5	Average
+10	1796	1667	1557	1454	1361	1567
0	1612	1503	1406	1322	1238	1416
–10	1399	1318	1233	1166	1091	1241
Average	1602	1496	1398	1314	1230	

1. Mean yield under current climate = 1736 kg ha^{-1}.

Table 6. The simulated effect of a factorial combination of temperature and rainfall changes on mean sorghum (variety CSV 15) yields at Parbhani, India[1].

Mean rainfall change (%) from current levels	Yield (kg ha^{-1}) at mean temperature increase above current levels (°C)					
	1	2	3	4	5	Average
+10	3972	3644	3318	3025	2733	3338
0	3915	3597	3252	2952	2673	3277
–10	3788	3457	3118	2822	2547	3146
Average	3891	3566	3229	2933	2651	

1. Mean yield under current climate = 4221 kg ha^{-1}.

Factors that will affect temperature response functions. Whilst the general impact of raised temperatures are clear, there are more detailed points that need to be highlighted with regard to how crops respond to temperature increases. A typical response function, describing how the rate of plant development (ie, time to maturity) changes with regard to the ambient temperature it is experiencing, will show a near linear phase of reduction in time to maturity as temperature increases. However, the gradient of this near linear phase gradually declines until an "optimum" temperature is reached. Beyond that optimum temperature, the gradient of response will become reversed with further increases in temperature actually resulting in a slower rate of development and hence increases in the time to maturity (see Figure 10).

The shape of this temperature : rate of development response function will depend upon: (i) the plant species; (ii) varietal differences within species; (iii) to some extent the degree of moisture stress that the plant is experiencing; and (iv) in some instances, for example, landrace pearl millets in West Africa, plants will demonstrate a photoperiodic response to changing daylength which interacts with temperature as a driver of rate of development. Furthermore, which "part" of the response curve that governs what actually happens to any particular crop in the field will be determined by the contrasting ambient seasonal temperature patterns of different locations. For example, current mean seasonal temperatures in the locations used to illustrate temperature responses (Tables 7 to 11) range from 19.1°C at Katumani, Kenya to 30.1°C at Hisar, India.

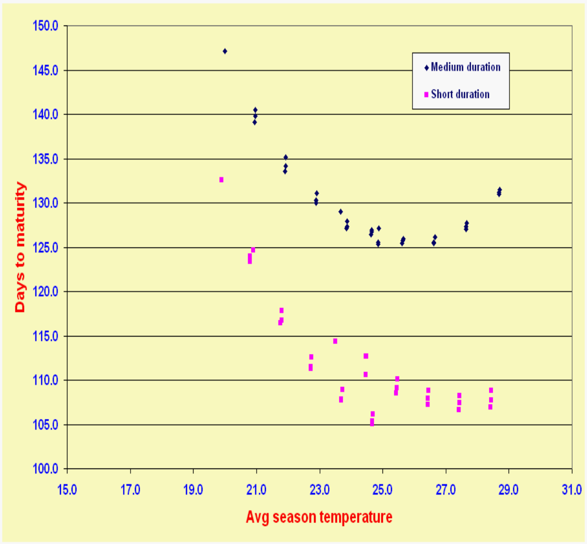


Figure 10. The simulated relationship (APSIM) between the rate of development (time to maturity in days) and mean seasonal temperature of medium- and short-duration pigeonpea at Katumani and Makindu, Kenya.

Table 7. The simulated impact of temperature increases on the mean rate of development and yield of short-duration pigeonpea at Katumani, Kenya based on historical daily climatic data (1957–2004).

Climate scenario	Mean seasonal temperature (°C)	Time to maturity (days)	% reduction from current maturity time	Crop yield (kg ha^{-1})	% reduction from current yield
Current	19.6	133	–	1736	–
Current + 1°C	20.6	124	6.5	1612	7.1
Current + 2°C	21.6	117	12.0	1503	13.4
Current + 3°C	22.6	111	15.9	1406	19.0
Current + 4°C	23.6	108	18.7	1322	23.8
Current + 5°C	24.6	105	20.5	1238	28.7

Table 8. The simulated impact of temperature increases on the mean rate of development and yield of sorghum (variety CSV 15) at Aurangabad, India based on historical daily climatic data (1955–1983).

Climate scenario	Mean seasonal temperature (°C)	Time to maturity (days)	% reduction from current maturity time	Crop yield (kg ha^{-1})	% reduction from current yield
Current	27.6	105	–	2941	–
Current + 1°C	28.6	100	4.8	2628	10.6
Current + 2°C	29.6	95	9.5	2264	23.0
Current + 3°C	30.6	91	13.3	1913	34.9
Current + 4°C	31.6	88	16.1	1608	45.3
Current + 5°C	32.6	85	19.0	1285	56.3

These points are illustrated by looking at the contrasting temperature response functions of short-duration pigeonpea and medium-duration pigeonpea derived from simulations undertaken at Katumani and Makindu in Kenya (Fig. 10). Combining data from two locations provides a wide range of mean seasonal temperature ranges comprised of Katumani and Makindu. Within this range, medium-duration pigeonpea (blue points) shows a near linear decrease in time to maturity (days) within the simulations undertaken at Katumani (19.6 to 24.6°C), but at the warmer location Makindu (23.2 to 28.3°C), it reaches an optimum temperature at around 26°C, whereafter the gradient is reversed and time to maturity (days) increases with temperature. Short-duration pigeonpea (pink points) shows a similar but greater rate of decrease in time to maturity (days) at Katumani and appears to reach its optimum value around 28°C at the warmer location Makindu.

In addition, Figure 10 also illustrates that for short-duration pigeonpea at Makindu (temperatures 23.3 to 28.3°C), for any given temperature, the number of days to maturity is greater than simulated for a similar temperature at Katumani. In this instance, it is probable that the greater moisture stress that occurs at Makindu has modified the temperature response function by delaying time to maturity.

These results provided added confidence in APSIM in that they closely reflect phenological observations obtained through field trials on short- and medium-duration pigeonpea (Silim and Omanga. 2001, Silim et al. 2006). These results illustrate that, when properly calibrated, APSIM is a tool well able to simulate the rate of crop development, crop growth and yield under current and climate change scenarios.

Table 9. The simulated impact of temperature increases on the mean rate of development and yield of pearl millet (variety ICTP 8203) at Hisar, India based on historical daily climatic data (1970–2007).

Climate scenario	Mean seasonal temperature (°C)	Time to maturity (days)	% reduction from current maturity time	Crop yield (kg ha^{-1})	% reduction from current yield
Current	30.1	73	–	1678	–
Current + 1°C	31.1	71	2.7	1405	16.2
Current + 2°C	32.1	68	6.8	1184	29.4
Current + 3°C	33.1	67	8.2	1026	38.8
Current + 4°C	34.1	65	10.9	909	45.8
Current + 5°C	35.1	64	12.3	822	51.0

Table 10. The simulated impact of temperature increases on the mean rate of development and yield of groundnut (variety Chalimbana) at Bulawayo, Zimbabwe based on historical daily climatic data (1951–2001).

Climate scenario	Mean seasonal temperature (°C)	Time to maturity (days)	% reduction from current maturity time	Crop yield (kg ha^{-1})	% reduction from current yield
Current	21.8	119	–	1426	–
Current + 1°C	22.8	110	7.5	1237	13.2
Current + 2°C	23.8	104	12.6	1078	24.4
Current + 3°C	24.8	100	16.0	950	33.3
Current + 4°C	25.8	98	17.6	871	38.9
Current + 5°C	26.8	98	17.6	822	42.3

Table 11. The simulated impact of temperature increases on the mean rate of development and yield of maize (variety Katumani Composite B) at Makindu, Kenya based on historical daily climatic data (1959–2004).

Climate scenario	Mean seasonal temperature (°C)	Time to maturity (days)	% reduction from current maturity time	Crop yield (kg ha^{-1})	% reduction from current yield
Current	23.3	87	–	3214	–
Current + 1°C	24.3	82	5.7	3083	4.1
Current + 2°C	25.3	77	11.4	2924	9.0
Current + 3°C	26.3	73	16.1	2759	14.2
Current + 4°C	27.3	70	19.5	2591	18.8
Current + 5°C	28.3	67	22.9	2406	25.1

The key points that have emerged from the analyses undertaken and presented in the above section are:

- We investigated the impact of a factorial combination of 15 climate change scenarios (3 rainfall regimes and 5 temperature regimes) under 'non-limiting' conditions with regard to soil nutrients, weeds, pests and diseases.
- Responses to increased CO_2 levels and changes in rainfall totals were largely as expected and less important than the negative impact of temperature increase.
- Temperature increases enhanced the rate of plant development of both cereal and legume crops as reflected by a reduction in time to maturity and corresponding reductions in grain yield. This observation will, to some extent, offset the negative impacts that increased temperatures have on reducing the LGP.
- Reduced time to maturity means that crops have less potential to intercept incoming solar radiation and use available soil water and nutrients for dry matter production and grain yield formation.
- More detailed differences in how different crops at different locations respond to temperature increase will be governed by: (i) the plant species; (ii) varietal difference within species; (iii) the degree of moisture stress that the plant is experiencing; (iv) the contrasting seasonal temperature patterns of different locations; and (v) the interaction of temperature and photoperiod with genotypes and sensitivity to photoperiod.
- The above points have an almost *'counter intuitive'* implication. In the light of the impact that increased temperature has in reducing time (days) to maturity and subsequent lower crop yields, in a warmer world, there will be a need to re-deploy germplasm that would, *under current climatic conditions,* be considered to be too long a maturity type for any given location. For example, in a warmer world, a currently defined 'medium-duration type' will become a 'short-duration type'.

Mitigating the impacts of climate change through natural resources management and crop adaptation

Comparing the impacts of temperature increase under low input and improved management. In the previous section, we undertook our simulations under soil and crop management conditions that allowed the impact of climate changes in rainfall and temperature to show their maximum effect within the 15 scenarios that we chose with soil nutrients, weeds, pests and diseases being kept 'non-limiting'. However, that does not reflect neither current 'low input' farmer practice nor the relatively modest and affordable 'improved practices' that are current recommendations advocated for farmers.

Under current farmer 'low input' practices, it is likely that many factors such as nutrient deficiency, weed competition, inappropriate water management, low-yielding varieties, pests and diseases will *still* provide major limiting constraints to crop growth and yield, even under possible climate change scenarios. This can be well illustrated by an example which examined the impacts of climate change in southern Africa (+3°C temperature and –10% rainfall) on current typical low nitrogen (N) fertilizer input versus high N input on maize at Bulawayo in Zimbabwe (Fig. 11). The yield distributions show that in the poorest 15% of years under the *current climate*, maize yields at low N (green line) are higher than under N non-limiting conditions (blue line), illustrating the strong interaction of N supply and water supply in determining grain yields in these environments. Also evident is the fact that for N-constrained crops under *climate change* (red line) yields in the driest 30% of seasons will be adversely affected, but there will be little negative impact on yield for the majority of seasons. *In other words, if farmers in the SAT maintain their current low level management practices, climate change will be largely inconsequential due to, in this instance, the overriding constraint of fertility on crop yield.* Conversely, under high N-input levels, climate change (pink line) substantially reduces maize yield below those obtained under high N-input under current climates (blue line).

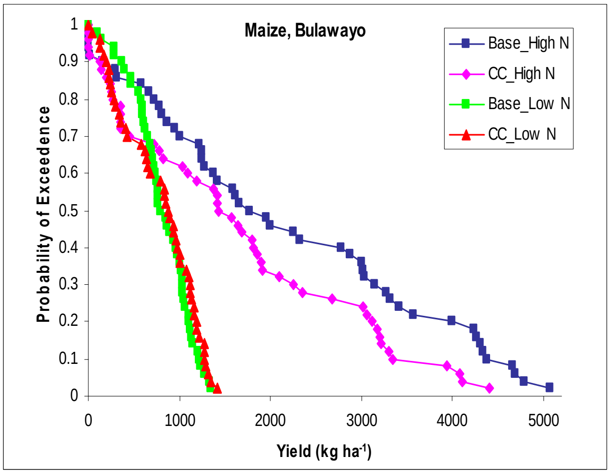


Figure 11. Probability distributions of maize grain yield under current (Base) and climate change scenario (CC) for high and low levels of nitrogen (N) at Bulawayo, Zimbabwe.

However, for the 70% better seasons the potential yield under climate change still exceeds the distribution of current farmer practice (low N) by a much larger margin than the reduction in potential yield due to climate change. This highlights not only the large yield gap that smallholder farmers in these rainfed farming systems are foregoing in the better seasons, but also points to the potential that exists for mitigating the impacts of future climate change on food production through greater adoption of currently recommended innovations, in this case the application of N fertilizer.

This is further illustrated by examining the impact of temperature increases (1, 2 and 3°C) on the yield of sorghum at four locations in India under contrasting fertilizer application, namely, current farmer practice and recommended practice. Whilst farmers' management of fertilizer obviously varies across locations, an average "*farmer's nutrient application*" was assumed for this analysis, namely, 18 kg N + 20 kg phosphorus (P) ha^{-1} as diammonium phosphate (DAP) at sowing and 15 kg N ha^{-1} as urea at 40 days after sowing. In the case of improved management the recommended practice is the application of 40 kg N + 40 kg P ha^{-1} as DAP at sowing and 40 kg N ha^{-1} as urea at 40 days after sowing. The summarized output of this set of simulations is presented in Table 12.

A similar picture to that found for maize in Zimbabwe emerges for sorghum in India. Under current farmer fertilizer management practices, temperature increase has very little, if any, impact on grain yield reduction in sorghum due to the overriding constraint of nutrient limitation to crop yield.

Furthermore, the data confirm that *even under a temperature increase of 2°C* which corresponds to a "worst case scenario" for 2050, the simple adoption of improved fertilizer recommendations will still result in far higher yields under such 'climate change' than farmers are achieving under the current climatic situation. This is particularly evident at the two wetter locations Parbhani and Patancheru (Table 12).

Such potential is by no means limited to improved fertilizer practice. For example, we have earlier illustrated the impact of improved water conservation on mitigating the impact of climate change on the LGP at Makindu in Kenya (Fig. 6) together with the implications that such improved soil water availability will have on crop growth and yield.

Seeking extrapolation domains for ICRISAT's climate risk and adaptation research. Because we have utilized crop growth simulation models for the bulk of our *ex ante* analyses of the impacts of climate change, we have had to use 'point source' long-term daily climatic data as the basis of such analyses. Since both rainfall and temperature vary to such an extent from location to location, reliance on 'point source' data is in fact a partial limitation to such work since the resulting simulations only strictly apply to the location at which the climate information was collected.

One obvious question is therefore, "*Where else would the major current and future climate-induced risks and opportunities identified for any given location be relevant?*"

CLIMEX software can help us start to answer that question. CLIMEX, amongst other functions, is able to identify areas with climates that 'match' the climate at any given location at which detailed climate risk analyses research has been undertaken. It then maps areas which have different degrees of 'climatic match' to the chosen location in the context of rainfall total amounts and their distribution within the growing season together with seasonal maximum and minimum temperature patterns. In other words, it can map *extrapolation domains* for climate risk-related research undertaken using point source data.

We provide an example of such a map for the extrapolation domains in Africa of climate risk management research undertaken at Makindu, Kenya (Fig. 12). In interpreting such maps, a degree of caution is required

Table 12. The impact of increasing temperatures on the grain yield of sorghum (variety CSV 15) under low fertilizer (LF) input (farmer practice) and recommended fertilizer (RF) input at four locations in India.

	Parbhani (790 mm)[1]		Patancheru (678 mm)		Aurangabad (538 mm)		Dharwad (410 mm)	
Climate scenario	LF	RF	LF	RF	LF	RF	LF	RF
Current	1338	2624	1458	2710	1365	2163	1317	2386
+ 1°C	1376	2566	1503	2671	1372	2008	1336	2100
+ 2°C	1382	2465	1516	2562	1322	1779	1321	1756
+ 3°C	1377	2332	1506	2442	1220	1522	1197	1433

1. Figures in parentheses are mean seasonal rainfall totals.

and extrapolation domains should be limited to mapped areas with a *'composite fit index'* (see inset color code in Fig. 12) of 0.92 to <1, the two brightest shades of red in the map shown.

Advancing and testing a 'Hypothesis of Hope'. If we consider the results highlighted earlier that increase in temperature reduces time to maturity resulting in crop yield reduction, we feel that there is a sound basis for advancing a 'Hypothesis of Hope' that states:

"In the medium term (2010–2050), ICRISAT is well placed to help farmers mitigate the challenges and exploit the opportunities that are posed by climate change through: (i) the application of existing knowledge on crop, soil and water management innovations; and (ii) developing better adapted cultivars and the re-deployment and re-targeting of the already available germplasm of its mandate crops."

Such a hypothesis, if proven true, would suggest two climate change adaptation imperatives with regard to advocacy:

1. Targeting research managers and policy makers: *Better formulated and targeted policies that facilitate and support the adoption of agricultural innovation today assume even greater urgency in the light of future climate change. Not only will they immediately improve the welfare of rural populations but also will do a great deal on mitigating the impacts of future climate change.*
2. Targeting ICRISAT's agricultural research: *Given the lead time required, ICRISAT must embark on an intensive characterization of its existing germplasm without delay in order to be well placed to advise policy makers and agricultural support agents on the re-targeting and re-deployment of its germplasm resources for a future warmer world and developing cultivars better adapted to a warmer world.*

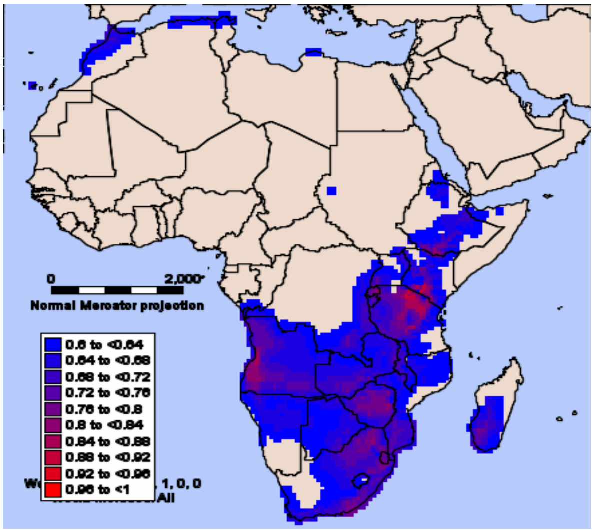


Figure 12. Mapped areas that have different degrees of climatic match with the long-term mean climate at Makindu, Kenya.

Whilst there remains much to be done in fully testing such a hypothesis, we present a framework within which we believe such a hypothesis could be tested and two case studies where we have simulated possible innovations that appear to support our hypothesis.

The schematic framework for testing our hypothesis. We present the schematic framework in Figure 13. The framework identifies three yield gaps that ICRISAT needs to address in seeking solutions to both current and future climate-induced production risk.

The Current Yield Gap: Column 1 in the schematic framework represents yields that farmers are getting under their current and relatively low input management. Column 5 represents the yields that farmers could get through the adoption of current simple and affordable recommendations for improvements in variety choice and crop, and soil and water management practices. This is the yield gap that ICRISAT is currently addressing.

Yield Gap 1 under Climate Change: Column 2 represents the marginally decreased yields that farmers would get under climate change if they were to continue using the same low input system. We have shown earlier that under such low input systems, other factors continue to provide the overriding constraint. Column 3 represents the yields that farmers could get, even under climate change, if they adopted current improved practice recommendations. This is the yield gap that ICRISAT is and will continue to address through our work to develop, scale-up and scale-out enhanced crop, soil and water management options for farmers in the SAT.

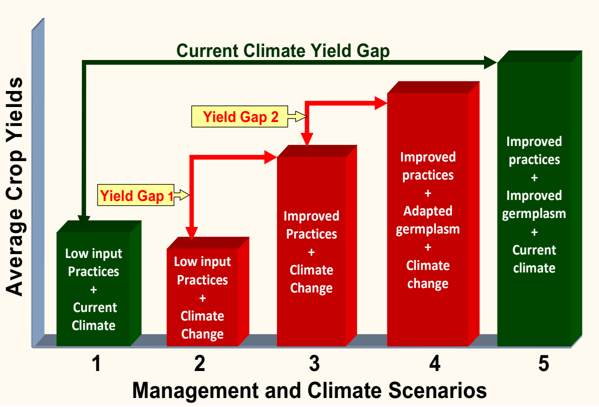


Figure 13. 'Hypothesis of Hope' schematic framework.

Yield Gap 2 under Climate Change: Column 4 represents the yields that farmers could get under climate change if they were to adopt current improved practice recommendations *together with* germplasm better adapted to a warmer world. Within the scope of the *ex ante* analyses that we have done so far, we consider better adaptation to solely constitute varieties whose maturity length is better suited towards growing in a warmer world. We recognize that other factors such as possible changes in rainfall patterns and in the distribution of pests and diseases will also have to be considered. This is the yield gap that ICRISAT will be addressing through our work to develop and deliver improved crop varieties with enhanced performance under high CO_2 concentrations, high temperatures and erratic rainfall conditions for farmers in the SAT.

The schematic framework re-highlights three important points that have already been made earlier:

1. The impact of temperature increases on the yields of low input agriculture is likely to be relatively small as other factors will continue to provide the overriding constraints to crop growth and yield.
2. The adoption of currently recommended improved practices, even under climate change, will result in substantially higher yields than farmers are currently getting.
3. The adaptation of better 'temperature adapted' varieties could result in the almost complete mitigation of the negative climate change effects that result from temperature increases.

In the following sections, we have illustrated two sets of simulations that provide an *ex ante* testing of our 'Hypothesis of Hope'.

Groundnut production in Malawi: a case study for legumes. Groundnuts are grown by many small-scale producers in Malawi in rotation with tobacco (*Nicotiana tabacum*) and maize. During the planting season, farmers plant tobacco first as their principal cash crop followed by maize as their dominant food crop and groundnut third as a 'dual purpose' food/income generation crop. The most widely grown groundnut variety is 'Chalimbana' that matures in 150 days. In addition, both maize and groundnut are planted on ridges that are spaced to suit the tobacco crop, namely, 1.2 m apart, rather than at the recommended row spacing of 0.75 m. This results in groundnut being planted late and at too low a plant population density. Based on this the following scenarios were simulated:

- Column 1: Chalimbana planted late (mid December to mid January) at a row spacing of 1.2 m. This represents current low input farming.
- Column 2: Low input agriculture as above but under a climate change scenario of an increase in temperature of 3°C.
- Column 5: Improved practice under current climate comprised a shorter-duration variety (121 days to maturity) planted early (mid November to mid December 15th) at a row spacing of 0.75 m.
- Column 3: Improved practice as above under an increased temperature of +3°C.
- Column 4: Improved practice under climate change as above**,** but with an adapted longer duration cultivar that matures in *138 days under current conditions*, but which matures in *119 days under the warmer climate change scenario* simulated.

These scenarios were simulated using 72 seasons of long-term daily climatic data from Kasungu in Malawi. The results are presented in Figure 14.

The simulation outputs support our hypothesis in the following respects. Firstly, the yield decline of the low input system from current levels (column 1), due to temperature increases (column 2), was negligible amounting to 138 kg ha^{-1}. Secondly, even under the climate change scenario, improved production practices (column 3) resulted in yields 28% above those being currently obtained under low input systems. Lastly, again under climate change, growing an adapted cultivar, better suited to a warmer world together with improved practices (column 4), resulted in yields that were 880 kg ha^{-1} higher than those currently obtained by farmers under low input practices and only 245 kg ha^{-1} lower than those that could be achieved with improved practices under today's climate (column 5).

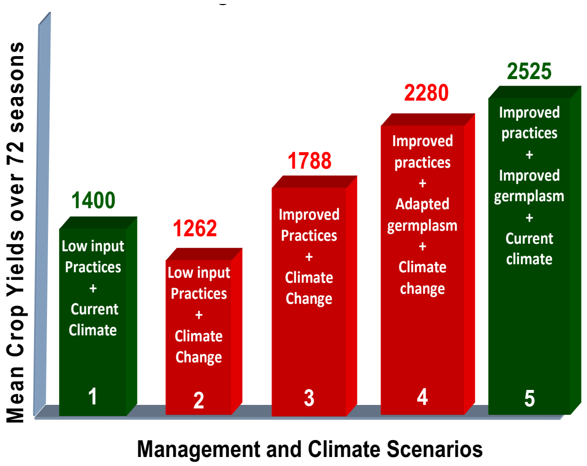


Figure 14. Groundnut yield (kg ha^{-1}) simulations (APSIM) at Kasungu, Malawi, 1927–1999.

Sorghum production in India: a case study for cereals. Sorghum is a very widely grown crop in the SAT of India but currently yields remain low due to lower than recommended use of N and P fertilizer. Sorghum (variety CSV 15) is widely grown and at Aurangabad reaches maturity 105 days after emergence. Based on the above, the following scenarios were simulated using DSSAT and long-term daily climate data from Aurangabad.

- Column 1: Sorghum (variety CSV 15) planted between June 1st and July 20th with 18 kg N + 20 kg P ha^{-1} as DAP at sowing and 15 kg N ha^{-1} as urea at 40 days after sowing. This represents current low input farming.
- Column 2: Low input agriculture as above but under a climate change scenario of an increase in temperature of 3°C.
- Column 5: Improved practice under current climate comprised sowing CSV 15 within the same planting window, but with the recommended application of fertilizer, namely, 40 kg N + 40 kg P ha^{-1} as DAP at sowing and 40 kg N ha^{-1} as urea at 40 days after sowing.
- Column 3: Improved practice as above under an increased temperature of +3°C.
- Column 4: Improved practice under climate change as above, but with an adapted longer duration sorghum variety that matures in *119 days under current conditions* at Aurangabad (such as Brandes, taken from the DSSAT sorghum data base), but which matures in *103 days under the warmer climate change scenario* simulated.

The outputs of these simulations are presented in Figure 15. Again encouraging results were obtained. A temperature increase of +3°C had very little impact (145 kg ha^{-1} reduction) on the sorghum yield under low input fertilizer use as nutrient limitation remained a strongly limiting factor. Even under climate change, the adoption of improved fertilizer use (column 3) resulted in yield gains of 357 kg ha^{-1} over what farmers are currently getting under low input practices and today's climatic conditions (column 1). Perhaps the most notable result in this case is that growing a longer duration variety (Brandes), better suited to grow in a warmer world (column 4) resulted in farmers being able to achieve yields 5% higher than they could under "improved practices" with today's climate (column 5).

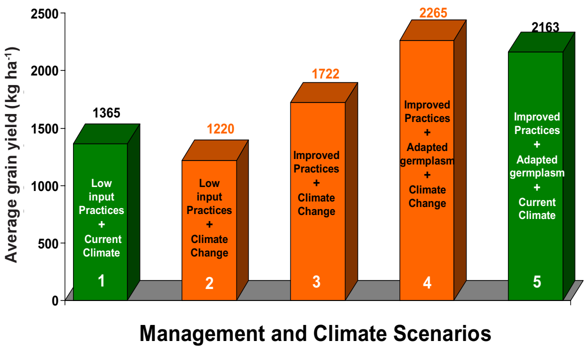


Figure 15. Sorghum yield simulations (DSSAT) at Aurangabad, India, 1955 to 1983.

We recognize that these two simulated tests of our hypothesis hardly scratch the surface of the work that remains to be done, both in our simulation work and the more pragmatic testing of our hypothesis in the field.

From the analyses undertaken and presented in the above section, the following important points have emerged:

- The impact of temperature increases on the yields of low input agriculture is likely to be minimal as other factors will continue to provide the overriding constraints to crop growth and yield. Significant changes in rainfall amounts due to climate change, however, would modify this conclusion.
- The adoption of currently recommended improved practices, even under climate change, will result in substantially higher yields than farmers are currently getting.
- The adaptation of better 'temperature adapted' varieties could result in the almost complete mitigation of climate change effects.
- Much of our current and future work in this field will depend on crop growth simulation models and hence point source climate data. We recognize the need to be able to identify extrapolation domains for our climate risk and adaptation work and are beginning to seek solutions to this challenge.
- Based on these results, we advanced the 'Hypothesis of Hope', stated earlier.
- Such a hypothesis, if proven true, would suggest two climate risk management and adaptation imperatives with regard to advocacy, namely: (1) Targeting research managers and policy makers; and (2) Targeting ICRISAT's agricultural research.
- Two *ex ante* case studies for groundnut and sorghum suggest that our hypothesis has merit and is worth further investigation.

Conclusions and the way forward

Current climate-induced production risk and future climate change will impact on all of ICRISAT's crop improvement and natural resource management endeavors in the SAT. These *ex ante* analyses illustrate both the challenges that current and future climate risk poses as well as the opportunities that it can offer. They also suggest that in spite of the certainty of climate change, research and development organizations can look ahead with a degree of optimism for the future of rainfed farming communities in the SAT. However, a great deal remains to be done if we are to play our part in translating this 'Hypothesis of Hope' into reality on the ground and in farmers' fields. Four key areas of future research are essential:

1. We need to enhance and expand the value of our crop growth simulation work with APSIM and DSSAT through undertaking an extensive field-based exercise that results in the proper phenological and physiological characterization of sub-sets of our germplasm so that we can fully exploit the genetic diversity we have at hand through the development of new and the re-deployment of existing cultivars, both in our simulations and in our field research.
2. The above 'genetic-based' field research should be complimented by an equally extensive calibration of DSSAT and APSIM for the wide range of soil, fertility, water and crop management practices that we believe hold hope both now and for the future.
3. We need to expand the scope of our climate change research beyond that reported in this article to include more in-depth investigation into the impact of weather extremes (both temperature and moisture) on crop growth and yield as well as to start investigating the impact of changed climates on the potential distribution of pests and diseases of our mandate crops.
4. We should initiate further field studies that test our hypothesis through field studies at 'analogue' locations whose *current* climate mimics climate change scenarios that we anticipate for the SAT in the *future*.

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