Evans School of Public Affairs
UNIVERSITY OF WASHINGTON

Evans School Policy Analysis and Research (EPAR)
Professor Leigh Anderson, PI and Lead Faculty
Associate Professor Mary Kay Gugerty, Lead Faculty

Crops & Climate Change: Wheat

EPAR Brief No. 114

Cecily Stokes-Prindle, Stephen Po-Chedley, Brian Smoliak and
Professors Alison Cullen & Leigh Anderson

Prepared for the Policy & Statistics Team
of the Bill & Melinda Gates Foundation

December 14, 2010

Summary

Climate change is projected to adversely affect agriculture in most developing countries. In particular, researchers expect that agriculture in Sub-Saharan Africa (SSA) will experience major impacts from climate change, leaving the already food-insecure region subject to large contractions of agricultural incomes and food availability. [1,2] As part of the Crops & Climate Change series, this brief is presented in three parts:

- Pillar 1: An evaluation of the importance of wheat in SSA, based on production, net exports, and caloric need
- Pillar 2: A novel analysis of historical and projected climate conditions in wheat-growing regions, followed by a summary of the agronomic and physiological vulnerability of wheat crops
- Pillar 3: A summary of current resources dedicated to wheat, based on research and development investments and National Adaptation Programmes of Action

This three-pillared approach will identify potential gaps among resources dedicated to wheat productivity in SSA relative to its resilience to projected climate changes and its role in the region's food security. A similar analysis for maize, rice, sorghum, and millet (EPAR briefs 62, 71 and 115), allows the foundation to compare relative importance, resilience, and resources across five crops.

Overall, this analysis indicates that the importance of wheat as an imported product remains high throughout SSA, though food crop production and dependence is concentrated in a relatively small area. Wheat-growing regions throughout SSA are likely to face yield decreases as a result of predicted rises in temperatures and possible changes in precipitation. Resources intended to aid adaptation to climate change flow primarily from public sector research and development efforts,[3] though country-level adaptation strategies have not prioritized wheat.[4]

Pillar 1: The Importance of Wheat in SSA

Wheat is an important food crop in some areas of Sub-Saharan Africa (SSA). While only a small portion of SSA is highly dependent on wheat in the daily diet, every country reporting trade information shows a negative net trade balance for wheat, indicating that demand exceeds local supply.[5]

Table 1: Wheat in Sub-Saharan Africa At-A-Glance

Total Production (metric tons)	5.79 Million (5.4% of total cereal production)
Total Net Trade (metric tons)	-22.02 million
Countries Very Highly or Highly Dependent, Based on Per Capita Caloric Consumption	Mauritius, Mauritania, Djibouti
Agronomic Requirements	20-25ºC optimum, 35 ºC maximum; 450 to 650 mm annually
Nutritional Information	Protein 11.6% Fat 2.0% Carbohydrate 71.0%
Dedicated CGIAR Research Center	CIMMYT
Total FTE Wheat Researchers*	161 (5% of all SSA crop researchers; 18% of SSA cereal reserachers)
Countries including a wheat-specific strategy in their NAPA**	None
Summary of Use	Staple crop, less commonly cultivated, grown for subsistence and trade.

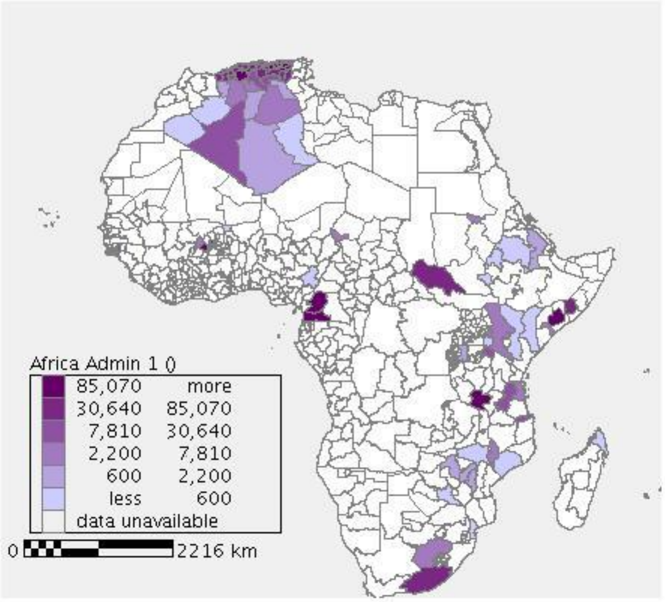
Sources: FAOSTAT, Author's Calculations, *ASTI (2001), **UNFCCC NAPA database

Wheat Production in Sub-Saharan Africa

Wheat is grown predominantly on the Eastern coast of SSA, with some additional production along the Gulf of Guinea (Figure 1). In 2008, SSA produced less than 6 million tonnes of wheat, of which over 1 million tonnes were from South Africa. (For detailed production information by country, see Appendix I.) For comparison, SSA produced nearly 50 million metric tonnes of maize during the same time period. South Africa, Kenya, Ethiopia, Zimbabwe and the Sudan together accounted for 93% of SSA wheat production in 2007.

The predominant farming system for wheat is the highland-temperate mixed system, covering 2% of SSA and contributing 4% of SSA agricultural production.[6] The highland-temperate mixed system supports a high population density, with an average farm size below two hectares. It is typically a single-season system. Other crops grown in the highland-temperate mixed system include teff, peas, lentils, broadbeans, rape, and potatoes. Livestock cultivation includes sheep, goats, cattle, and poultry.

Figure 1. Wheat production in Africa by administrative district



Source: FAO Agro-Maps

Wheat yield levels in much of SSA are lower than yield levels worldwide.[7] Average yield in most of SSA is approximately 1.7 mT/ha, though the average yield in South Africa is notably higher at 3 mT/ha. This compares to 4.8 mT/ha in Europe, 2.7 mT/ha in the United States, and 2.8 mT/ha worldwide.[8] The yield gap is due in part to agro-ecological constraints. Neumann et al. (2010) suggest that most of Africa is already producing wheat at levels close to the regional efficiency frontier, which is determined by variables including temperature, precipitation, and soil quality.[9]

Wheat Consumption in Sub-Saharan Africa

Table2. Dependency on Wheat for Caloric Intake

Level of Dependency	Countries	Population
Very Highly Dependent >800 kcal/person/day	Mauritius, Mauritania	4,288,220 (0.5% of SSA)
Highly Dependent 500-799 kcal/person/day	Djibouti	496,374 (0.1%)
Moderately Dependent 300-499 kcal/person/day	Cape Verde, Lesotho, Sudan, Seychelles, Congo, Swaziland, Gabon, Sao Tome and Principe, South Africa	95,468,932 (12.0%)
Less Dependent <300 kcal/person/day	Remaining SSA countries	695,469,004 (87.4%)

Source: FAOSTAT; CIA World Factbook; Authors' calculations

Countries defined as highly dependent on wheat have a per capita caloric intake from wheat at or above 500 kcal/day (between 25-50% of the recommended daily caloric intake for adults).[10,11] Only three countries in SSA are classified as highly wheat-dependent, and those countries make up 0.6% of the entire population of SSA.

The average per capita protein consumption from wheat in SSA is 6.7 grams per day,[12] but in the small portion of SSA that is highly dependent on wheat for caloric needs, it provides approximately half the 46-56 grams of protein recommended per day.[13]

The nutritional profile of wheat is similar to that of other staple grains. Wheat does have a high protein level (comparable to pearl millet) and more iron than rice or maize (see Table 3). As with other cereals, the bioavailability of iron from wheat is potentially low, but can be improved by processing techniques such as removal of the phytate-rich hull or by combining wheat with foods containing vitamin C.[14] Wheat is most often consumed as bread or porridge.[15]

Wheat is used primarily for food consumption in SSA; the average balance by country is appproximately 90% food use, with small quantities used for seed, wasted in transport or storage, or other uses.[16] South Africa and Nigeria are the only countries reported wheat use for livestock feed, but even in those countries feed use makes up a small portion of total wheat use. In countries such as South Africa or Ethiopia that produce wheat as a significant portion of grain production but do not report high per-capita consumption, wheat may be relevant to nutrition as an income source supporting other food purchases rather than through direct consumption.

Table 3: Average Nutritional Composition of Common Cereals ***(per 100 g edible portion; 12 percent moisture)***

Food	Protein[a] (g)	Fat (g)	Carhohydrate (g)	Energy (kcal)	Ca (mg)	Fe (mg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)
Rice (brown)	7.9	2.7	76.0	362	33	1.8	0.41	0.04	4.3
Wheat	11.6	2	71.0	348	30	3.5	0.41	0.1	5.1
Maize	9.2	4.6	73.0	358	26	2.7	0.38	0.2	3.6
Sorghum	10.4	3.1	70.7	329	25	5.4	0.38	0.15	4.3
Pearl millet	11.8	4.8	67.0	363	42	11	0.38	0.21	2.8
Finger millet	7.7	1.5	72.6	336	350	3.9	0.42	0.19	1.1

Source: Adapted from FAO 1995

Pillar 2: Vulnerability Analysis of Wheat-Growing Regions in SSA

Climate change will affect agriculture through a variety of physiological, environmental, and behavioral pathways. Impacts related to plant physiology tend to be direct responses to changes in temperature and precipitation (e.g. plant fitness and the regions suitable for growing particular crops), but also include indirect responses to external stressors like pests and weeds. The combination of climate factors and plant physiological responses will affect wheat cultivation in complex ways, both positive and negative.[17] The first portion of this analysis will use historical data and climate model projections to provide novel regional estimates of climate conditions, variability, and projected climate change in SSA.[1] The second portion of the analysis will review the literature to provide an overview of wheat's agronomic and physiological vulnerability to climate change.

Climate Analysis: Background

Under an emissions scenario consistent with current development trends, Intergovernmental Panel on Climate Change (IPCC)-coordinated climate model results project a high likelihood of warming across SSA during the twenty-first century. Annual mean surface temperature is expected to increase approximately 0.5–1.0°C by 2029 and 3–4ºC by 2100. Elevated areas in southern Africa may see increases of up to 7ºC by 2100.[18,19,20] The overlap between current growing season temperature and future conditions is projected to be less than 20% by 2050.[21] *Figure 5* illustrates this analysis showing two sets of hypothetical temperature distributions. The left panel shows distributions with some degree of overlap. In the right panel, the distributions do not overlap. Regions characterized by a change such as that shown in the right panel are said to encounter a "novel" climate beyond the observed twentieth century climate.

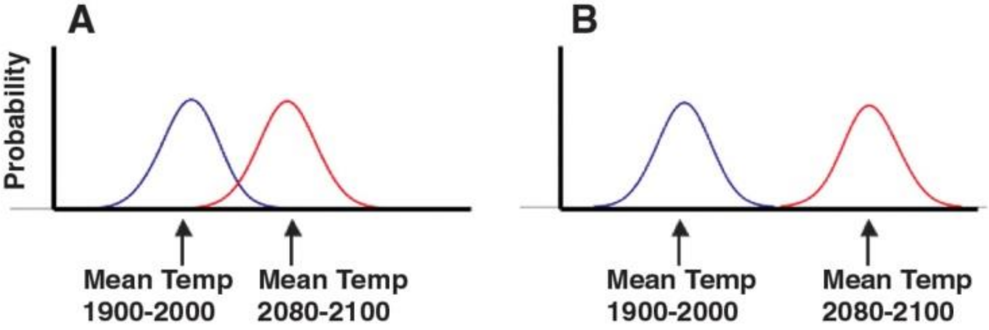


Figure 5. Hypothetical distributions of growing season average temperature for the 20th century (blue) and late 21st century (red). A: some overlap; future mean growing season average temperature is equal to hottest 20th century mean. B: no overlap; distribution of late 21st century growing season temperature exceeds historical distribution completely.

Source: Battisti & Nayor, 2009

Projected changes in precipitation are generally less robust than their temperature counterparts.[22] The factors affecting precipitation are considerably more complicated than those affecting temperature, and involve small-scale phenomena such as thunderstorms. Estimates vary widely by model, region, and emissions scenario. This is a particular issue in arid or semi-arid regions where small absolute changes can be of a high relative magnitude and importance. Across Africa changes in precipitation will occur in both directions; some areas will become wetter and some will become drier. These projections are consistent with previous, independent assessments of African climate change and the robust changes in precipitation projected by IPCC.[23] Future regional assessments will be necessary to isolate changes in the meteorological phenomena that contribute to precipitation and its variability over SSA, for example, the timing of afternoon thunderstorms or the position of the Inter-tropical Convergence Zone, a region of persistent intense thunderstorm activity.

For this analysis, global crop distribution data and twentieth century climate data were used to define four representative categories of growing season climates in SSA: Sahel, Southern Africa, Northern East Africa, and Southern East Africa.[24,25] *Figure 2* illustrates the geographic domains of each region. The regions have unique annual variations of growing season temperature

---

[1] This analysis is the product of a Program on Climate Change capstone project by Stephen Po-Chedley and Brian Smoliak, PhD Candidate, Department of Atmospheric Sciences, College of the Environment, University of Washington. For permission to disseminate results, please contact thecontact the authors.

and precipitation, which strongly influence agriculture through their effect on plant biology and environmental conditions. The representative regions have experienced varying degrees of prolonged climate change over the twentieth century apart from year-to-year variability. Considering future change in the context of this historical variability may yield a comprehensive interpretation of climate change.

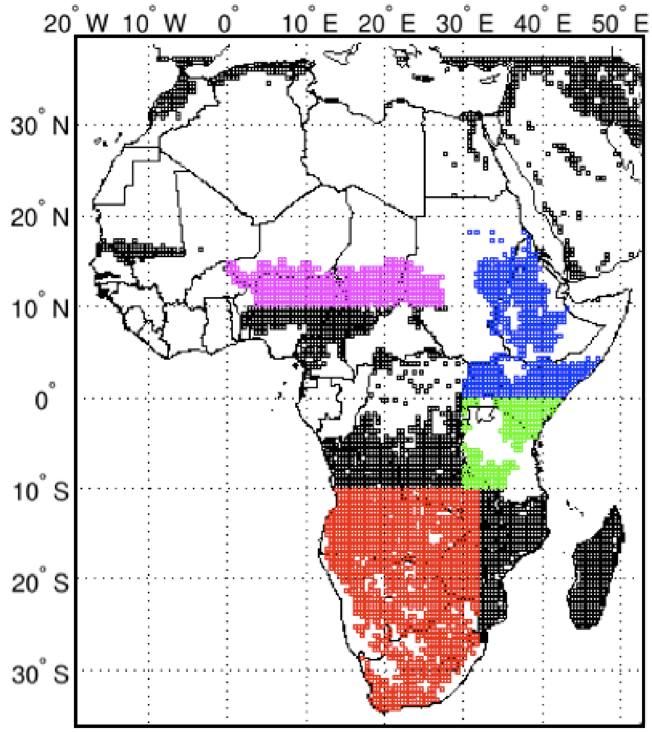


Figure 2: Wheat-growing regions in SSA, including: Sahel (purple), Southern Africa (red), Northern East Africa (blue), Southern East Africa (green), and wheat-growing regions not included in the regional analysis (black)
Source: Crop distribution data from Monfreda et al., 2008

Data and Methodology

The historical temperature and precipitation data for the climatological analyses in Pillar 2 come from the University of East Anglia (UEA) Climate Research Unit (CRU) time-series (TS) 3.0 dataset. The future projections are based on model output from 23 models used for the most recent IPCC assessment report, published in 2007. Additional details on the historical observations and modeling systems are presented in *Appendix 2*.

The analysis of projected climate change uses a methodology similar to previous studies,[26] quantifying the percentage of overlap between historical and projected distributions of two climatological variables: growing-season average temperature and accumulated precipitation. Projected future distributions of temperature and precipitation are presented at three years: 2020, 2050, and 2090, corresponding to near, intermediate, and long time horizons. The distributions are defined by two averages: the same area-average as in the historical distribution and an ensemble average of output from 23 climate models included in the IPCC AR4, each having one or more simulations totaling over 50 realizations of future climate.

The mean future distributions are determined by adding a shift to the 1976–2006 mean calculated from historical observations. These shifts are calculated as the difference between two twenty year averages: 1) means centered at 2020, 2050, or 2090 in simulations driven by emissions consistent with current development trends (SRES A1B) and 2) a mean centered at 1990 in each model's Climate of the 20th Century simulation (20C3M).

Results

Current and Historical Climate Conditions of Wheat-growing Regions

Table 4 presents area-averaged mean and standard deviation for growing season average temperature and growing season total precipitation over the four SSA sub-regions (shown in *Figure 2*). The maximum and minimum average growing season temperature and cumulated rainfall total are also presented as an indication of the extreme climates in each region. The variability of climates within each region is represented by the inter-region standard deviation. Temperature and precipitation differ markedly between the four regions. The Sahel is characterized by a comparatively hot growing season and is relatively dry compared to other crop climates; Coastal West Africa and Madagascar, for example, receive more than 125 cm of precipitation during their respective rice growing seasons.[27] Northern East Africa is similarly dry because of its proximity to the Sahara Desert, but has more moderate temperatures because it a region of increased elevation due to the rifting of East Africa and Ethiopia. Southern Africa has the driest and coolest growing climate, but this is because the principle growing season is during the southern hemisphere winter and winter wheat varieties are utilized in this region. During the Southern East Africa wheat-growing season the inter-tropical convergence zone is further south than during other months of the year, which brings increased rainfall to the region. Southern East Africa, like Northern East Africa, is a highland region, which helps moderate its temperature.

Table 4. Mean (ºC, cm) and standard deviation (ºC, cm) for growing season average temperature and growing season accumulated precipitation over five wheat growing regions in SSA. Intra-region range and standard deviation of the mean are given in the column after the mean. Statistics are calculated from historical monthly-mean data for growing season months only (For relevance, means based on recent period, 1976-2006; for more degrees of freedom, standard deviation based on entire period of record, 1901-2006).

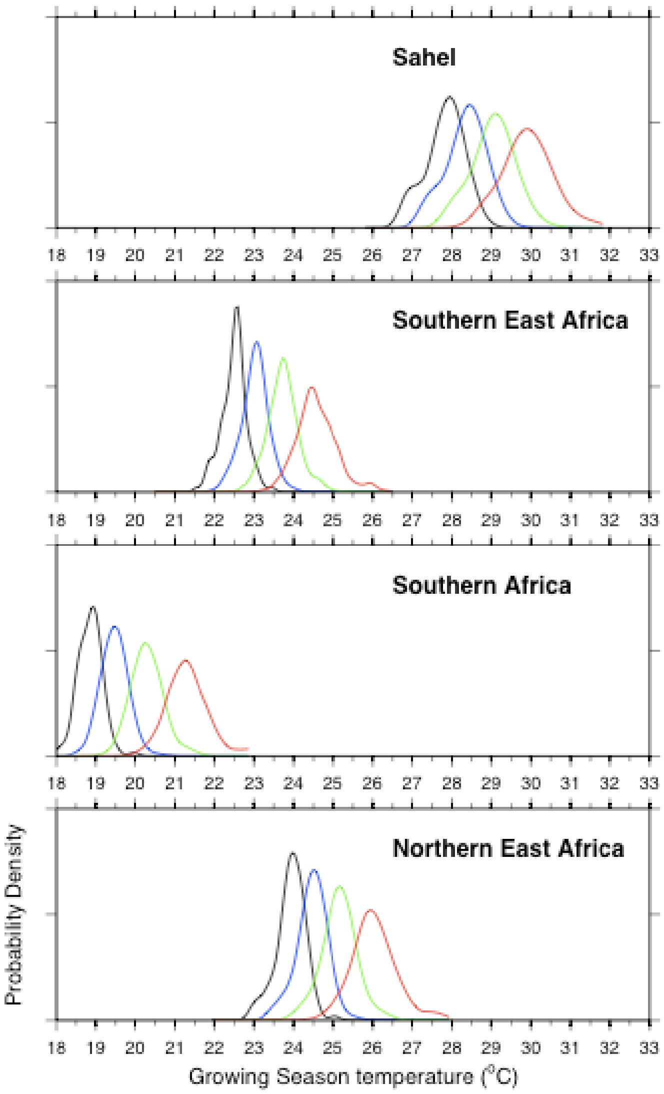
		Growing season average temperature			Growing season accumulated precipitation		
Region	**Growing season**	**Mean**	**Intra-region range & std. dev.**	**Std. dev.**	**Mean**	**Intra-region range & std. dev.**	**Std. dev.**
Sahel	June – November	27.8	22-32, 1.6	0.49	53.6	0-96, 25.1	8.58
Northern East Africa	June – November	23.9	11-34, 4.1	0.36	48.9	0-125, 30.8	9.35
Southern East Africa	January – June	22.5	14-29, 2.8	0.32	56.4	19-136, 23.2	2.29
Southern Africa	May – November	18.9	7-24, 3.0	0.30	14.7	0-79, 10.7	6.30

Source: University of East Anglia (UEA) CRU TS 3.0 dataset

Projected Twenty-First Century Climate Change in Wheat-growing Regions

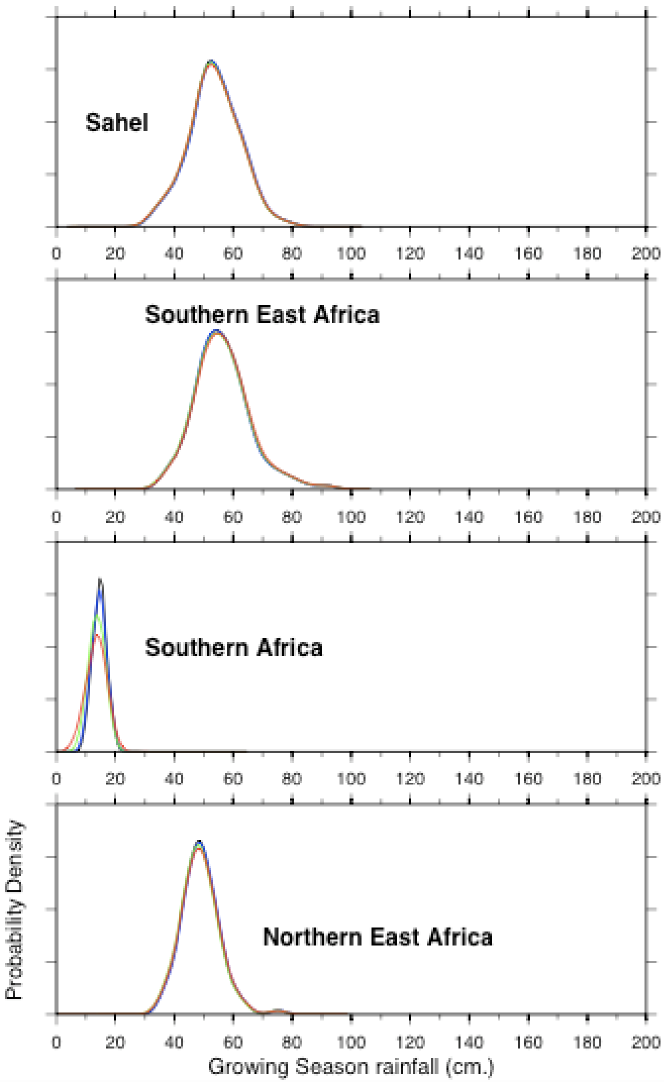
Temperature shift predictions are robust among the 23 models included in our analysis. *Figure 6* shows historical distributions of growing season average temperature for the four regions and three future distributions corresponding to climate at 2020, 2050, and 2090. The magnitude of the shifts themselves is similar, but the percentage of overlap varies spatially according to the degree of natural variability observed across each area. For example, over the Sahel where large temperature variability is observed, the percentage of overlap is larger than the others at 2020, 2050, and 2090. In other words, an equivalent shift in the mean climate at a location with low variability (e.g., Southern Africa) will mean less overlap than for one with high variability (e.g., the Sahel). Notwithstanding this nuance, by 2090, each of the four regions is projected to move into a completely novel warmed climate, distinct from the observed 20th century climate there. *Table 5* illustrates this numerically, depicting the percentage of overlap between the historical and projected future distributions by 2020, 2050, and 2090.

Figure 6. Shifts in average growing season temperature over four wheat-growing regions in SSA. Distributions are shown for 1976-2006 (black), 2020 (blue), 2050 (green), and 2090 (red).



Source: UEA CRU TS 3.0 (historical data), Coupled Model Intercomparison Project database (future projections).

Figure 7. Shifts in total growing season rainfall over four wheat-growing regions in SSA. Distributions are shown for 1976-2006 (black), 2020 (blue), 2050 (green), and 2090 (red).



Source: UEA CRU TS 3.0 (historical data), Coupled Model Intercomparison Project database (future projections).

The shifts are less pronounced for precipitation than for temperature, reflecting a larger degree of disagreement in the size of the shift among the models in time and space (*Figure 7*). In other words, the models disagree over how large and of what sign precipitation changes will be across Africa.[28,29] Thus, the distributions of precipitation shift only slightly over the course of the twenty-first century. Future improvements in the models' ability to project the physical and dynamic factors that contribute to precipitation will likely increase confidence in future changes and allow a better characterization of shifts over these representative regions.

Table 5: Percentage of climate overlap between recent (1976-2006) observations and future projections based on a business-as-usual development scenario used by IPCC climate models. Percentages indicated for temperature (T) and precipitation (P) at 2020, 2050, and 2090.

Region	**Variable**	**2020**	**2050**	**2090**
Sahel	T	71%	26%	3%
	P	96%	96%	96%
Northern East Africa	T	56%	9%	0%
	P	97%	96%	96%
Southern East Africa	T	51%	5%	0%
	P	95%	95%	96%
Southern Africa	T	43%	1%	0%
	P	95%	88%	82%

Source: UEA CRU TS 3.0 (historical data), Coupled Model Intercomparison Project database (future projections).

Discussion

The results presented are consistent with previous studies, which find significant shifts in temperature and uncertain changes in precipitation.[30] This analysis indicates that relative changes in temperature will be much larger than relative changes in precipitation for each region. Temperature shifts are a well-understood response to rising greenhouse gas concentrations and associated radiation and circulation changes. As noted earlier, precipitation trends were small over the twentieth century and set among large year-to-year variability. Thus, despite pronounced uncertainty in the direction of precipitation changes, year-to-year changes will almost certainly overwhelm trends that do occur. Farmers in SSA, drawing from a strong set of experiences of previous precipitation variability, may already have adaptation methods in place to mitigate the impact of extreme short-term climate variability (i.e., prolonged drought or flood). On the other hand, persistent temperature increases constantly change the baseline from which wheat farmers in SSA must judge the present conditions.

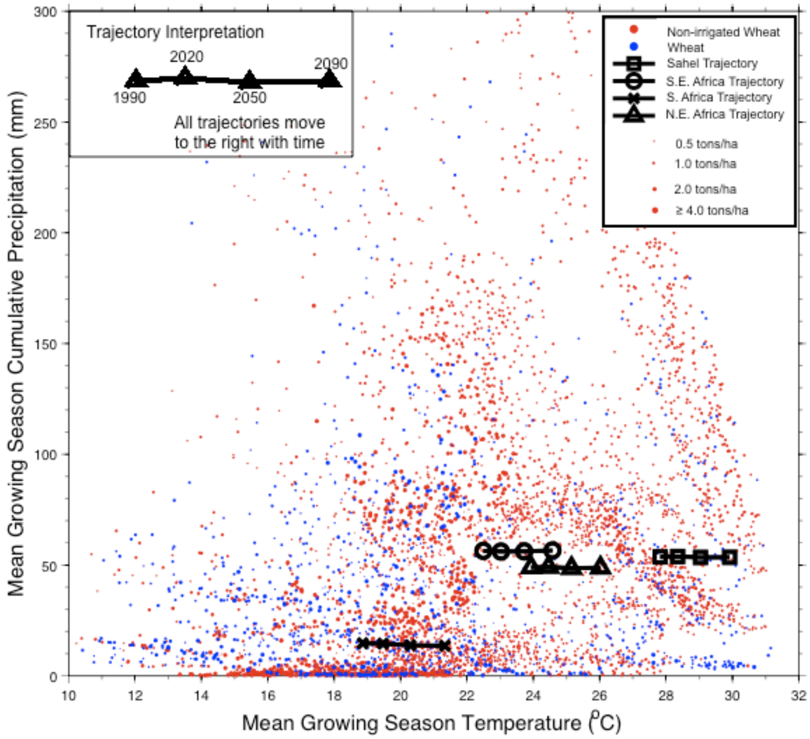


Figure 8. Observed climate range for wheat growing regions in SSA. Each point represents the mean (1976-2006) growing season temperature and accumulated rainfall at a 0.5° × 0.5° grid cell where any wheat is grown. Red circles indicate areas without irrigation infrastructure; blue circles indicate areas with irrigation infrastructure. Larger circles indicate higher yields. Observed 1976-2006 climatologies for each of the five regions used in this analysis are plotted and projected forward into the future using the aforementioned ensemble of IPCC climate models. Note that the growing areas are derived from estimated growing regions circa 2000, but the climatological information is relative to 1990.

Source: UEA CRU TS 3.0 (historical data), Coupled Model Intercomparison Project database (future projections), Monfreda et al., 2008 (crop yield estimates and planting areas), Sacks et al., in press (temporal planting and harvesting data), Siebert et al., 2007 (irrigation)

Throughout Africa, wheat is planted in a wide range of climates (*Figure 8*). Wheat is grown in a wide range of temperatures and can be grown in areas of both low and high cumulative growing season rainfall. Data indicates that at least some of the regions with relatively low rainfall totals and high yields have regional irrigation infrastructure.[31] Irrigation infrastructure is in place across the climatological growing season range (ie 10 – 30°C and 0 – 300 cm per growing season), but it is unclear when this infrastructure is used for wheat crops.

Superimposed on *Figure 8* are climate "trajectories" in precipitation (relatively small changes) and temperature (large increases in each region). In some instances, regions seemingly are projected to leave the most productive climatological zones (South East Africa, for example). In the case of Southern Africa, it appears that there are relatively high yields across the range of temperatures expected over the next century. It will be important to understand the role of irrigation in affecting yields, as increased temperatures will likely decrease soil moisture. Although the trajectories represent large changes in the next century, culminating in novel climates for each region, there is a large degree of overlap in the climatologies between regions. For example, South Eastern Africa in 2050 is very similar to North Eastern Africa today. Further, variability within regions (*Table 4*) suggests that adaptation in planting practices may be possible if technology and information transfer takes place.

Agronomic and Physiological Vulnerability

Estimations of wheat responses are necessarily uncertain, due to the variation in emissions scenarios as well as the limited precision of crop response models in estimating differing impacts across regions and management techniques.[32] Plant-level productivity impacts are not only the result of single climate factors, but also of the interactions between those factors. Temperature, precipitation, CO_2 levels, radiation, and changes in weed or pest populations can all work singly or in tandem to affect the environment and physiological state of the wheat plant. Wheat cultivars have varying responses to temperature and possibly to CO_2 levels;[33] the following discussion provides an overview of expected responses, but individual cultivars may demonstrate slightly different outcomes.

Temperature, Precipitation, and CO_2

The optimum temperature for wheat varies according to the plant stage; the optimum range is generally between 20-25°C, but temperatures up to 35°C are possible.[34] The optimum precipitation range is 450 to 650 mm annually, but much of current wheat-growing SSA is already outside optimum temperature and precipitation thresholds.[35]

Photosynthesis in wheat is low at low temperatures (25% of maximum at 5°C) and increases up to approximately 25°C before slowing and finally ceasing entirely at approximately 40°C. Higher CO_2 levels may raise the optimum temperature threshold. Higher temperatures also accelerate leaf maturation, shortening the active photosynthetic period and plant life cycle. This shortening also reduces the grain-filling period, reducing mass per grain and therefore overall yield.[36] A 1°C increase in temperature during grain fill shortens the grain fill period by approximately 5%, with corresponding decreases in grain mass and yield.[37] In one study of spring wheat, each degree Celsius of temperature increase during the growing season was linked to a 6% decline in grain yield.[38] High temperatures during flowering (above 30°C) can also reduce yield by damaging pollen formation.[39] Slow-developing varieties may be less susceptible to the grain-fill reduction effect in non-drought environments, as the duration of their grain-fill period is generally longer.[40]

The interaction of water limitations and elevated CO_2 is not wholly clear. One review suggests that water use for wheat may decrease under elevated CO_2 and wet conditions, but increase under elevated CO_2 and dry conditions; the same review suggests that yield increases from CO_2 may be greater under well-watered conditions.[41] This conclusion is supported by research finding that wheat grown under a water deficit requires optimal irrigation management to fully benefit from CO_2 fertilization.[42]

The effects of CO_2 increases on wheat are highly sensitive to changes in temperature and nitrogen availability and there is debate within the literature about the magnitude and direction of those effects in the field setting.[43] Higher soil nitrogen levels may increase the positive effects of CO_2; one study found that the yield increase under elevated CO_2 nearly doubled in high- versus low-nitrogen conditions (16% vs. 9%).[44] In addition, elevated CO_2 levels in a low-nitrogen setting may exacerbate the negative effects of nitrogen scarcity, further reducing grain quality.[45]

Elevated CO_2 also reduces stomatal conductance, reducing transpiration and improving water use efficiency.[46] However, temperature increases within the range of some climate scenarios would counteract those water use benefits.[47] Overall, the effect of elevated CO_2 on photosynthesis rates in wheat is difficult to generalize due to the complex and dynamic processes balancing carbon and nitrogen within the plant system.[48] There is some evidence that wheat plants may respond over time to higher CO_2 levels by lowering photosynthesis rates, reducing the CO_2 fertilization effect.[49]

Changes in plant physiology

Reduction of leaf canopy

Establishing a leaf canopy reduces evaporation significantly, but wheat seedlings under drought and temperature stress are likely to have a longer lag time between seeding and leaf growth, increasing the period of vulnerability to high rates of evaporation. Wheat varieties with rapidly-developing large leaf areas are less vulnerable to evaporation, but increased leaf production can reduce harvest index and overall yield.[50]

Changes in water use efficiency

Transpiration efficiency (TE) is the ratio of water assimilated to water transpired (lost from foliage). Higher TE translates to increased water use efficiency). TE decreases in drier air. Decreases in precipitation may therefore reduce wheat water use efficiency. Water stress can also reduce TE by inducing closure of the stomata, but the mechanism is not well understood. TE increases as the proportion of diffuse radiation (relative to direct radiation) increases; drying- and wind-related increases in atmospheric dust could potentially increase TE in wheat and other plants.[51]

Timing of flowering

Timing of flowering has an important effect on the yield and harvest index in wheat and other plants. Plants that flower late may have used too large a portion of groundwater in the vegetative stage, leaving them more vulnerable to temperature or water stresses during post-flowering photosynthesis and grain filling.[52] High temperatures usually result in earlier flowering, but increased seasonal variability may make it more difficult for farmers to select the most appropriate cultivars. An early-flowering variety may do well in one season, while a late-flowering variety may be best adapted in the next.

Changes in Agricultural Conditions

Increased soil water evaporation

The majority of crop water loss is caused by evaporation, particularly in winter-rainfall regions. High temperatures—such as those projected throughout SSA—increase evaporation rates, reducing soil moisture levels and increasing crop water stress.[53,54]

Decreased fallow efficiency

Efficient fallow periods allow water to accumulate deep in the soil. Wheat and other crops access this deep water in the flowering and grain-filling periods; an efficient fallow ensures adequate water access during those crucial periods. Climate change can reduce fallow efficiency in four ways: (1) higher temperatures contribute to increased soil water evaporation; (2) decreases in precipitation can decrease low-profile water storage; (3) extreme precipitation events may inundate the soil beyond its water-holding capacity, resulting in water and nutrient loss through deep drainage; and (4) increased CO_2 can contribute to deep-root weed growth, which leaches water from the soil.[55]

Changes in timing of water stress

Water deficits during floral development can reduce floral fertility and prematurely abort grain filling, leading to severe—sometimes complete—loss of yield in wheat and other crops. Water stresses during grain filling can result in increased vegetative growth but reduced grain biomass and lowered harvest index. Yield losses can occur by these pathways even in the presence of adequate rainfall throughout the rest of the season.[56] Increases in climate variability may increase susceptibility to these timing-based losses.

Increased weed and pest stress

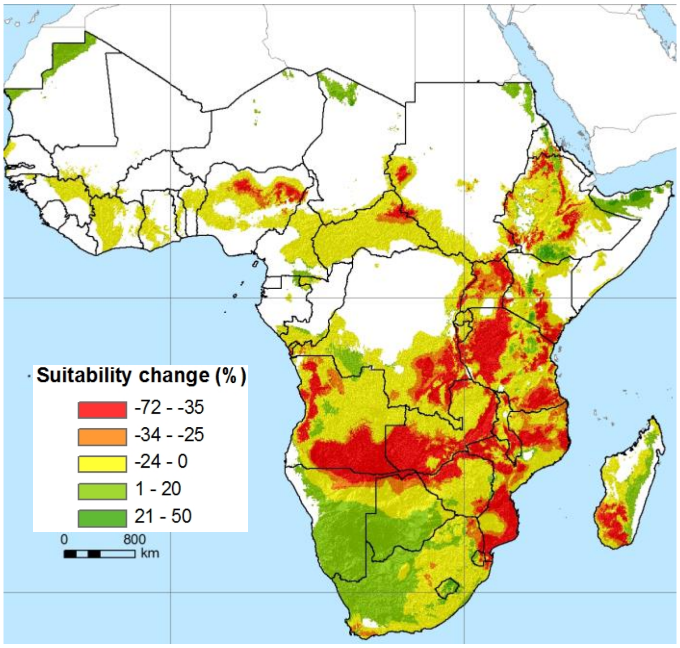
Patterns in the effect of climate change on wheat disease are difficult to characterize, but there are examples of effects in the field. High temperatures may reduce the effectiveness of resistance genes for diseases such as wheat leaf rust.[57] Changes in rainfall patterns have been associated with the spread of wheat stripe rust in South Africa,[58] while increased CO_2 levels have reduced powdery mildew infection in the lab setting.[59]

Damage from insect pests may increase under climate change, both pre- and post-harvest. Higher temperatures may expand the range of several pests. They also increase the insect population by shortening the time span between insect generations and reducing the number of insects killed during the colder season.[60,61]

Overall Impact of Climate Change on Wheat Yields

The global impact of climate change on wheat yields is uncertain, and there is incomplete information on the effects in SSA in particular. Ongoing research at the CGIAR centers projects a global loss of 15.1% in suitable area for wheat production,[62] but some simulations of warming up to 3°C result in slight yield increases in temperate regions.[63] In SSA, suitable wheat-growing areas are projected to decrease in much of mainland Southern Africa, with the exception of some areas in South Africa, Lesotho, Botswana, and Namibia (Figure 8).[64] Under any scenario, impacts will vary regionally. Many wheat-growing regions in SSA are already near the limit of maximum temperature tolerance; the likely impact in SSA is therefore negative.[65] Fisher et al. (2005) project that the land area suitable for wheat production in SSA will virtually disappear by 2080.

Figure 7. Projected changes in suitable wheat production area, 2050.



Source: Jarvis et al., forthcoming

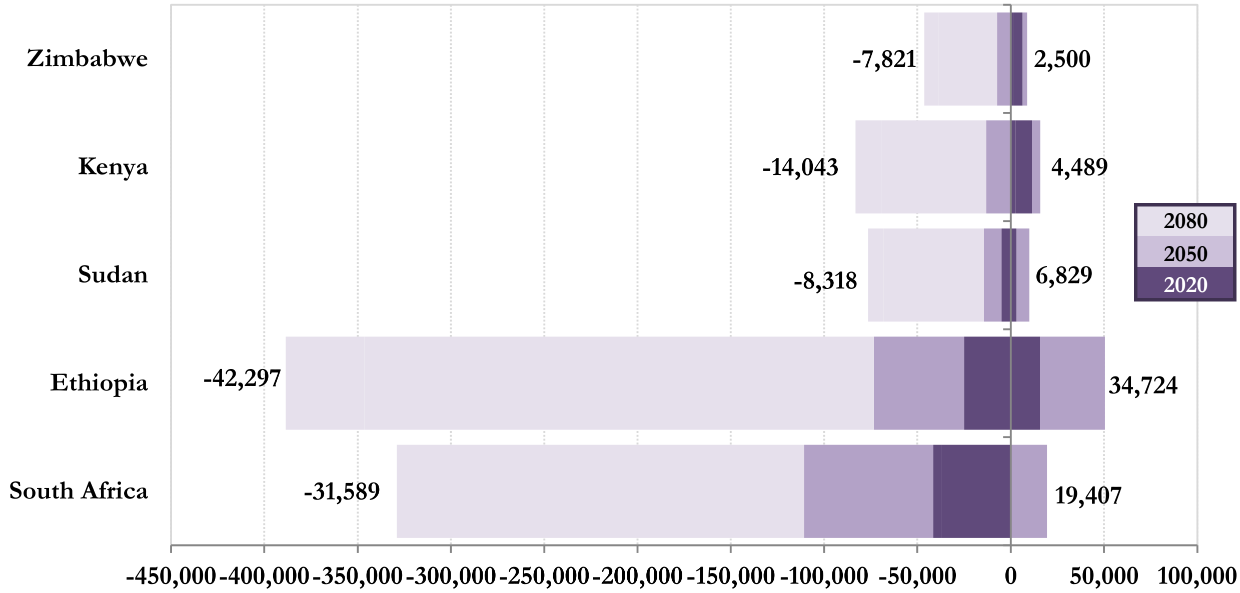
Reliable crop-growing days will be reduced in some areas. Transitional zones (areas in which reliable crop growing days fall below 90 by 2050) are identified mainly in rain-fed mixed crop-livestock systems. These zones are found in a band across West Africa between latitudes 10-12º N, mid-altitude zones in eastern Africa, parts of coastal eastern and southeastern Africa, and some mid-altitude areas running through central Tanzania, Zambia, Zimbabwe and South Africa.[66]

Liu at el. (2008) predict wheat yield decreases of 16-18% across SSA by 2030; in their analysis, yield of other staple crops remained steady or increased slightly.[67] This projection can be compared to a meta-analysis of 16 climate change models by country to 2050, in which the authors found average projected yield losses of 8-22% for non-wheat staple crops (sorghum, millet, groundnut, maize and cassava).[68]

There are few small-scale and country-level studies of SSA wheat productivity under various climate change scenarios. White et al. (2001) do not specifically estimate yield decreases, but their characterization of wheat-growing regions in Ethiopia shows that production is mainly constrained by temperature. This conclusion is supported by Neumann et al.'s (2010) analysis of yield frontiers for wheat in SSA; wheat production in SSA may be close to the limits set by current agronomic constraints.[69] Warming in the Ethiopian system is therefore likely to reduce wheat production. A simulation of the economic effects of climate change in South Africa (SSA's largest wheat producer) predicts reduction wheat yield, offset economically by a switch to soybean and sunflower production in the newly warmer regions.[70]

Iglesias et al. (2009) estimate ranges of country-level wheat production changes under seven SERES scenarios. Their analysis suggests a decline in wheat production in SSA overall, with over 90% of production losses occurring in the top five wheat-producing countries (Figure 9). Their model explicitly incorporates adaptation behaviors in addition to agronomic factors, and some portion of the reduced production is the result of predicted substitution to other crops. The economic impact of these changes is not modeled in their analysis.

Figure 9. Range of predicted 2020, 2050, and 2080 wheat production changes for top five wheat-producing countries in SSA (tonnes)



Source: Iglesies et al.; author's calculations

Pillar 3: Current Resources Dedicated to Wheat in SSA

Climate change impacts will be determined not only by the susceptibility of crops to changing conditions, but also by the ability of people and institutions to adapt to those changes. Wheat crop responses in a given area can fall into any of three categories: (1) the crop benefits from climate change; (2) crop yields decrease, but to an extent that can be countered with improvements in breeding and farming practices; (3) crop yields decline to an extent that will require major changes to the agricultural systems and perhaps the human population. The mechanisms that shift an area from one category to the next will be both ecological and institutional.

Nelson et al (2009) estimate costs of climate change adaptation in SSA at nearly three billion dollars. Their cost estimate is not differentiated by crop. The costs of wheat adaptation alone would be significantly smaller, though certain adaptations (such as infrastructure investments) cannot be assigned to a specific crop or sector.

Research and Development

The Agricultural Science and Technology Indicators initiative surveyed government agencies, NGOs, and private sector researchers in 26 countries in SSA. They identified 3570 full-time equivalent crops researchers, of which 161 (5%) were focused on wheat.[71] Wheat is the third most-researched cereal crop in that analysis, behind maize (with 8% of identified FTEs) and rice, with 7% of all FTEs identified. Sorghum also receives 5% of identified FTEs.

The Consultative Group for International Agricultural Research (CGIAR) research centers are drivers behind a large portion of crop development research. Of the 15 CGIAR centers (not including the Bill & Melinda Gates Foundation) the International Maize and Wheat Improvement Center (CIMMYT) is the main agency for wheat research. Other CGIAR centers conducting wheat research include Bioversity, the International Center for Agricultural Research in the Dry Areas (ICARDA) and the International Food Policy Research Institute (IFPRI). The CGIAR also funds some wheat research through the Generation Challenge Programme, a multi-crop and multi-center plant breeding and improvement effort.

National Adaptation Plans of Action

As part of the Least Developed Countries Work Programme, 31 countries in SSA have submitted National Adaptation Plans of Action (NAPAs) proposing climate change adaptation projects to address urgent national needs.[72] While the priority projects and specific aims vary by country, there are common themes, such as (1) promoting small-scale irrigation; (2) breeding and disseminating improved or local varieties, particularly short-cycle or drought-tolerant varieties of staple crops; (3) improving crop management and (4) crop or livelihood diversification. While the above activities are mentioned in almost every NAPA, none of the 31 NAPAs propose those activities specifically in the context of wheat production.

The relevance of wheat-specific proposals is limited by some countries facing financial or political obstacles to action, and many countries lack the capacity to implement and monitor new policies outlined in their NAPAs. Specific obstacles include: weak involvement of local communities; weak coordination amongst stakeholder involved; delays in allocating funds; weak network of extension services and technologies; lack of access to infrastructure and markets; and insufficient research and development capacity.[73]

Conclusion

Wheat is produced as an important food crop in some areas of SSA, and is a net import throughout the region. Projected increases in temperature and possible changes in precipitation are likely to reduce wheat production and yield in SSA, particularly given that SSA wheat production is already on the margins of wheat-suitable temperatures. Wheat receives significant levels of R&D funding, but country-level economic and infrastructure adaptation efforts have not targeted wheat production specifically.

Please direct comments or questions about this research to Leigh Anderson, at eparx@u.washington.edu

Appendix 1. Wheat Production & Trade in Tonnes, Compared to All Cereal Production

	Wheat Production	**Net Trade (Exports – Imports)**	**Wheat Production as % of Total Cereal Production**
Angola	4800	-25000	0.68%
Benin		-21909	0.00%
Botswana	600	-51024	1.51%
Burkina Faso		-53500	0.00%
Burundi	7987	-4763	2.74%
Cameroon	400	-291380	0.02%
Cape Verde		-23670	0.00%
Central African Republic		-56	0.00%
Chad	8393	-17690	0.43%
Comoros		0	0.00%
Congo		-122286	0.00%
Côte d'Ivoire		-270552	0.00%
Democratic Republic of the Congo	8690	-329373	0.57%
Djibouti		-99867	0.00%
Equatorial Guinea		-5911040	0.00%
Eritrea	20702	-87400	4.48%
Ethiopia	2219095	-600237	18.73%
Gabon		-80551	0.00%
Gambia		0	0.00%
Ghana		-357700	0.00%
Guinea		-36382	0.00%
Guinea-Bissau		0	0.00%
Kenya	322320	-665869	8.92%
Lesotho	3956	-80000	5.44%
Liberia		-30797	0.00%
Madagascar	11000	-119297	0.33%
Malawi	4605	-83089	0.13%
Mali	8585	-61253	0.22%
Mauritania	2000	-289349	1.09%
Mauritius		-157563	0.00%
Mozambique	2500	-347650	0.17%
Namibia	13000	-46748	9.09%
Niger	9000	-16167	0.23%
Nigeria	44000	-7795018	0.16%
Rwanda	20000	-5255	5.68%
Sao Tome and Principe		0	0.00%

Senegal		-389694	0.00%
Seychelles		-453	0.00%
Sierra Leone		-14527	0.00%
Somalia	970	-21199	0.49%
South Africa	1905000	-1042990	20.02%
Sudan	803000	-1176370	12.00%
Swaziland	325	-47677	1.19%
Togo		-69713	0.00%
Uganda	19000	-335633	0.72%
United Republic of Tanzania	82800	-723834	1.33%
Zambia	115843	-19581	7.54%
Zimbabwe	149110	-92999	11.71%

Source: FAOSTAT (2007 data)

Appendix 2. Climatological analysis: Data and methodology

The historical temperature and precipitation data for this analysis come from the University of East Anglia Climate Research Unit (CRU) time-series (TS) 3.0 dataset. The CRU TS 3.0 dataset incorporates land-based daily temperature and precipitation observations for the period 1901 to 2006, gridded to a uniform 0.5º latitude by 0.5º longitude grid (approximately 50 by 50 kilometers across most of SSA) at a monthly-mean resolution (i.e. one value of temperature or precipitation per month for each grid point). This spatial resolution is 100 times greater than that of previously available datasets with resolutions of 5º latitude by 5º longitude. It incorporates monthly-mean observations of six climate variables including temperature and precipitation for stations around the world. Only observations for sub-Saharan Africa are used in the following analyses. Although there is a paucity of data over SSA compared to developed countries, nearly complete spatial coverage is available.[74] Furthermore, strong statistics may be obtained for the complete twentieth century and the most recent two or three decades.

The future projections are based on model output from 23 models used for the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC AR4). These models originate from independent modeling centers around the world. Each is a unique representation of Earth's climate system, including the land surface, the atmosphere, the ocean, and the cryosphere, Earth's frozen water. While all of the models share the same governing equations, they differ in their treatment of phenomena that cannot be fully resolved because the phenomena operate on spatial scales smaller than the models grid spacing. Examples are thunderstorms, small-scale turbulence, and atmospheric aerosols. Averaging the results of these models, some having more than one run (i.e., a single model simulation of the future climate), is a best practice of current studies on future climate. This "ensemble mean" has many statistical degrees of freedom, and expresses the common features between the various models.

Four representative wheat-growing regions were defined based on an objective assessment of SSA areas where wheat is grown and a subjective grouping of grid cells into four macro-regions with similar growing season climates. Growing season is defined for each region based on digitization and geo-referencing of observed crop planting and harvesting dates.[75] Historical distributions of temperature and precipitation are defined by an area-average of grid points within wheat-growing regions with a 1976–2006 mean and variability based on the entire twentieth century record (see *Table 3*). Mean and standard deviation are calculated only for those grid cells in which wheat is grown using only the calendar months corresponding to their respective growing season. To provide relevance for current agronomic conditions, this analysis considers average conditions over the last thirty years, but variability over the entire twentieth century.

The analysis of projected climate change uses a methodology similar to previous studies,[76] quantifying the percentage of overlap between various projected climate variable distributions and historical observations. Our analysis is performed for growing season average temperature and extended to growing season total precipitation. Projected future distributions of temperature and precipitation are presented at three years: 2020, 2050, and 2090, corresponding to near, intermediate, and long time horizons. The distributions are defined by two averages: the same area-average as in the historical distribution and an ensemble average of output from 23 climate models included in the IPCC AR4, each having one or more simulations totaling over 50 realizations of future climate.

The mean future distributions are determined by adding a shift to the 1976–2006 mean calculated from historical observations. These shifts are calculated as the difference between two twenty year averages: 1) means centered at 2020, 2050, or 2090 in simulations driven by emissions consistent with current development trends (SRES A1B) and 2) a mean centered at 1990 in each model's Climate of the 20th Century simulation (20C3M). The historical distribution of variance constrains the corresponding variance of future distributions, based on the assumption that variability has not changed significantly over the 20th century and that climate models do a poor job of representing historical variability. In other words, while climate models can reproduce the climatological mean of temperature and precipitation to a modest degree, they are less able to depict the proper amplitude of their historical variability. The analysis is based on growing seasons as defined in *Table 3*, and assumes no shift in growing season or changes in farming strategies (such as double cropping or altering spatial distributions of crop planting).

Appendix 3. Climatological Analysis: Background and historical context

Temperature

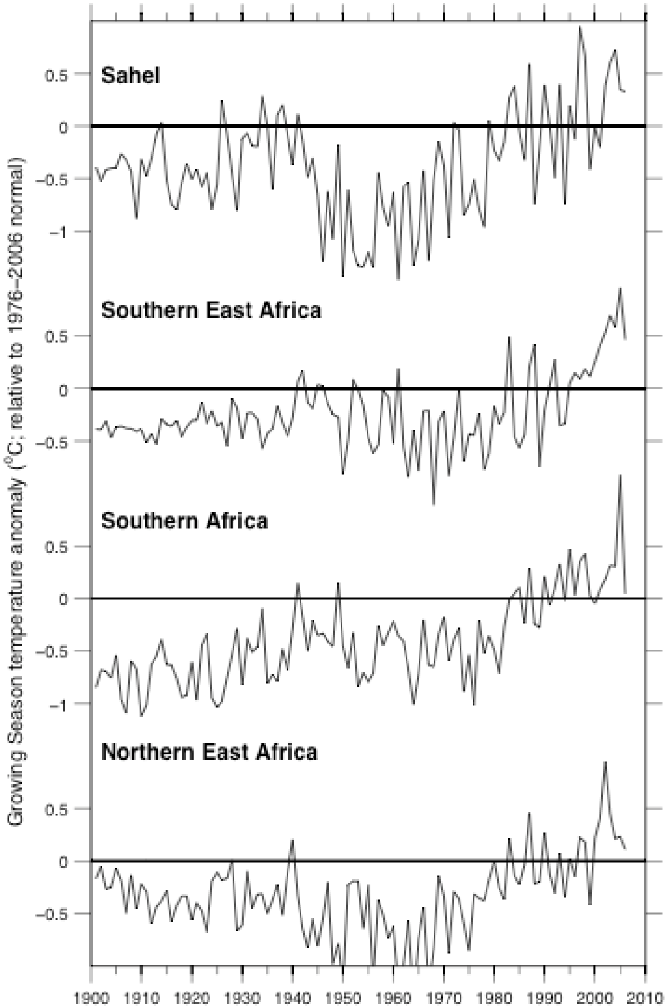
Consistent with the larger climate system, Africa's average growing season temperature is warmer today than it was 100 years ago. While farmers on the ground must cope with the reality of a warmer climate, agronomists analyze the unique trajectories of temperature and precipitation. For example, growing season average temperature in the Sahel has warmed by nearly 1ºC over the twentieth century, with most of the warming realized in the last 40 to 50 years. Temperature has strong multi-decadal variability over the Sahel, with some decades such as the 1930s and 1990s experiencing much higher temperatures than others, such as the 1950s. The growing regions outside the Sahel also show multi-decadal variability, though it is a less prominent feature. Growing season average temperature over Southern Africa and Southern East Africa was relatively constant in the first half of the twentieth century; in contrast, there is a pronounced positive trend characterizing the second half of the twentieth century. Northern East Africa shows cooling until the 1970s. However, as in the other three regions, a warming trend has been recorded over the past thirty years, beginning in the 1970s.

Precipitation

With the exception of the Sahel, precipitation variations over the twentieth century are far less dramatic over Africa than elsewhere around the globe. None of the regions have experienced a precipitation trend detectable outside of year-to-year variability. The Sahel has been experiencing obvious multi-decadal oscillations marked by a large decrease in precipitation from the 1950s to the 1970s, which has been rebounding since (precipitation is now above the 1976 – 2006 average).

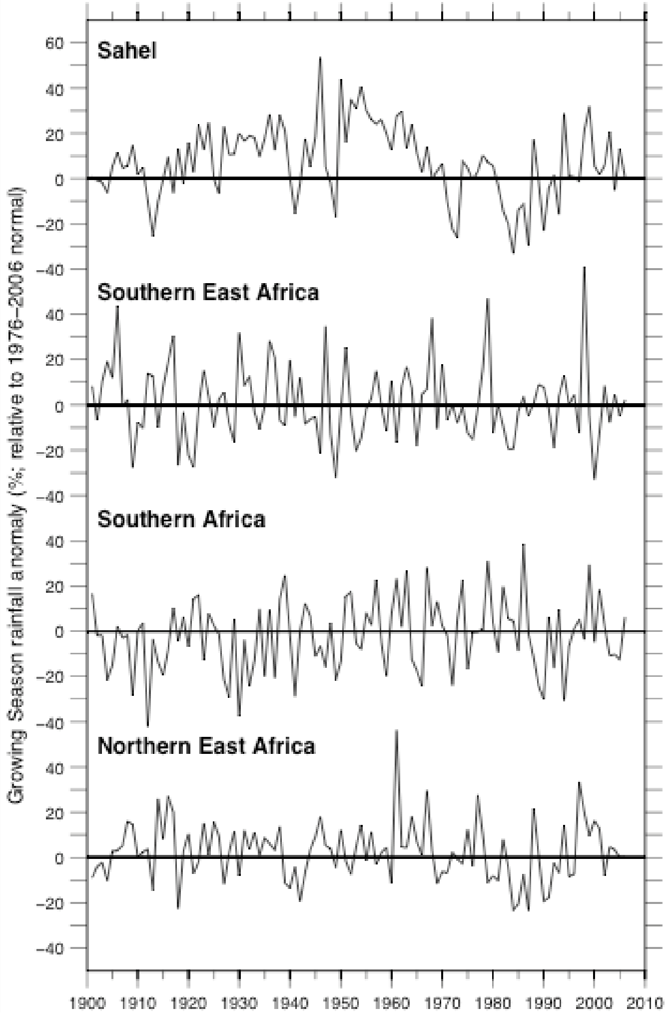
Figure 3 presents four time series of growing season temperature anomalies relative to temperatures observed in the recent period from 1976–2006. *Figure 4* is a similar time series showing total growing season precipitation. There is a time series for each of the four regions to illustrate the distinct character of temperature and precipitation variations during the twentieth century.

Figure 3: Growing season average temperature anomalies relative to recently (1976-2006) observed temperatures. Four wheat-growing regions shown, corresponding to Figure 2 and Table 3.



Source: UEA CRU TS 3.0

Figure 4: Growing season total rainfall anomalies expressed as a percentage relative to recently observed precipitation. Four wheat-growing regions shown, as in Figure 3.



Source: UEA CRU TS 3.0

References

Adejuwon, J.O. (2005). Food crop production in Nigeria: Present effects of climate variability. *Climate Research, 30*: 53-60.

Adger, W. N. (2001). Scales of governance and environmental justice for adaptation and mitigation of climate change. *Journal of International Development*, *13*(7), 921-931. doi: 10.1002/jid.833.

Africa Partnership Forum. (2009). Climate challenges to Africa: from Bali to Copenhagen. *12th Meeting of the Africa Partnership Forum* (Rome, Italy). Retrieved from http://www.africapartnershipforum.org/dataoecd/32/42/42949261.pdf

Agricultural Science & Technology Indicators (2001). Data provided through private correspondence.

Banziger, M. & Araus, J. (2007). Recent Advances in Breeding maize for Drought and Salinity Stress Tolerance. In: Jenks, M. (Ed.) Advances in Molecular Breeding Toward Drought and Salt Tolerant Crops. Dordrecht, the Netherlands: Springer: 587-601.

Battisti & Nayor (2009). Historical warnings of future food insecurity with unprecedented seasonal heat. *Science*, *323*, 240-244.

Bender, J., Hertstein, U. & Black, C.R. (1999). Growth and yield responses of spring wheat to increasing carbon dioxide, ozone and physiological stresses: a statistical analysis of 'ESPACE-wheat' results. *European Journal of Agronomy, 10*(3-4):185-195. doi:10.1016/S1161-0301(99)00009-X

Boshoff, W.H.P., Pretorius, Z.A., van Niekerk, B.D. (2002). Establishment, distribution, and pathogenicity of *Puccinia striiformis* f. sp. *tritici* in South Africa. *Plant Disease, 86*:485–92

Burke, M., Lobell, D. B., & Guarino, L. (2009). Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. *Global Environmental Change*, *19*(3), 317-325. doi: 10.1016/j.gloenvcha.2009.04.003.

Cammell, M.E. & Knight, J.D. (1992). Effects of climatic change on the population dynamics of crop pests. *Advances in Ecological Research, 2*: 117-162.

Central Intelligence Agency. World Factbook. Retrieved from https://www.cia.gov/library/publications/the-world-factbook/

Chakraborty, S., Tiedemann, a. V., & Teng, P. S. (2000). Climate change: potential impact on plant diseases. *Environmental pollution 108*(3), 317-26. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15092926

Challinor, A. J., Ewert, F., Arnold, S., Simelton, E., & Fraser, E. (2009). Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. *Journal of experimental botany*, *60*(10), 2775-89. doi: 10.1093/jxb/erp062.

Challinor, A., Wheeler, T., Garforth, C., Craufurd, P., & Kassam, A. (2007). Assessing the vulnerability of food crop systems in Africa to climate change. *Climatic Change*, *83*(3), 381-399. doi: 10.1007/s10584-007-9249-0.

Chipanshi, A.C., Chanda, R., & Totolo, O. (2003). Vulnerability assessment of the maize and sorghum crops to climate change in Botswana. *Climatic Change,61*(3):339-360.

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, R., Jones, R., Kolli, R. K., Kwon, W. K., Laprise, R., Magana Rueda, V., Mearns, L., Menendez, C. G., Räisänen, J., Rinke, A., Sarr, A., Whetton, P., Arritt, R., Benestad, R., Beniston, M., Bromwich, D., Caya, D., Comiso, J., de Elia, R., Dethloff, K. et al. (2007). *Regional climate projections, Climate Change, 2007: The Physical Science Basis. Contribution of Working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Chapter 11). Cambridge: University Press, 847-940.

Davidson, L. (2003). Approaches to Improve Iron Bioavailability from Complementary Foods. *Journal of Nutrition, 133*(5): 1560S-1562S

Dixon, J., Gulliver, A., & Gibbon, D. (2001). *Farming systems and poverty: Improving farmers' livelihoods in a changing world.* Food and Agriculture Organization of the United Nations (FAO). Retrieved from ftp://ftp.fao.org/docrep/fao/003/y1860e/y1860e00.pdf

Easterling, W., Aggarwal, P., Batima, P., Brander, K., Erda, L., Howden, S., et al. (2007). Food, fibre and forest products. In P. V. M.L. Parry, O.F. Canziani, J.P. Palutikof, *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 273-313). Cambridge, UK: Cambridge University Press.

FAO. (2003). *World agriculture: towards 2015/2030*. Retrieved from http://www.fao.org/docrep/004/Y3557E/ Y3557E00.HTM

FAO. (2009) *Food and Agriculture Organization of the United Nations (FAO)* FAO Statistical Databases

Garrett, K.A., Dendy, S.P., Frank, E.E., Rouse, M.N. and Travers, S.E. (2006). Climate change effects on plant disease: Genomes to Ecosystems. *Annual Review of Phytopathology, 44*: 489-509

Gbetibouo, G.A. and Hassan, R.M. (2005). Measuring the economic impact of climate change on major South African field crops: a Ricardian approach. *Global and Planetary Change, 47*(2-4):143-152

Gitay, H., Brown, S., Easterling, W., & Jallow, B. (2001). Chapter 5: Ecosystems and Their Goods and Services In Climate Change in 2001: Impacts, Adaptation, and Vulnerability. Retrieved from http://www.grida.no/publications/other/ ipcc_tar/?src=/climate/ipcc_tar/wg2/index.html

Government of Guinea-Bissau. (2006). *Republic of Guinea-Bissau National Programme of Action of Adaptation to Climate Changes*. Available from http://unfccc.int/cooperation_support/least_developed_countries_portal/submitted_napas/ items/4585.php

Government of Liberia. (2008). *Liberia National Adaptation Programme of Action (NAPA)*. Available from http://unfccc.int/ cooperation_support/least_developed_countries_portal/submitted_napas/items/4585.php

Government of The Gambia. (2007). *Gambia National Adaptation Programme fo Action (NAPA) on Climate Change*. Available from http://unfccc.int/cooperation_support/least_developed_countries_portal/submitted_napas/items/4585.php

Guinean Ministry of Agriculture, Livestock, Environment, Water and Forests. (2007). *Plan d'action national d'adaptation aux changements climatiques (PANA) de la république de Guinee*. Available from http://unfccc.int/cooperation_support/ least_developed_countries_portal/submitted_napas/ items/4585.php

Hewitson, B.C. & Crane, R.G. (2006). Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa. *International Journal of Climatology 26*(10), 1315–1337.

Hope, K. (2009). Climate change and poverty in Africa. *International Journal of Sustainable Development & World Ecology*, *16*(6), 451-461. doi: 10.1080/13504500903354424.

Hulme, M., Doherty, R., Ngara, T., New, M., & Lister, D. (2001). African climate change : 1900 – 2100. *Climate Research*, *17*, 145-168.

Iglesias, A. & Rosenzweig,C. (2009). Effects of Climate Change on Global Food Production under Special Report on Emissions Scenarios (SRES) Emissions and Socioeconomic Scenarios: Data from a Crop Modeling Study. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. Available at http://sedac.ciesin.columbia.edu/mva/cropclimate/. (December 11, 2010)

Jarvis, A., Ramirez, J. & Bonilla-Findji, O. (Forthcoming). Analysis of suitability for wheat production under climate change. Correspondence with the author, December 14, 2010.

Jones, P.G. & Thornton, P.K. (2003). The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change, 13*(1): 51-69. doi: 10.1016/S0959-3780(02)00090-0

Kimball, B. A. and Bernacchi, C.J. (2001). Evapotranspiration, canopy temperature, and plant-water relations. *Ecological Studies, 187*(C): 311-324. doi: 10.1007/3-540-31237-4_17

Kimball, B.A., Morris, C.F., Pinter Jr., P.J., Wall, G.W., Hunsaker, D.J., Adamsen, F.J., LaMorte, R.L., Leavitt, S.W., Thompson, T.L., Matthias, A.D. and Brooks, T.J. 2001. Elevated CO2, drought and soil nitrogen effects on wheat grain quality. *New Phytologist, 150*(2):295-303.

Latham, M.C. (1997). Human Nutrition in the Developing World. Food and Nutrition Series No. 29. Rome, Italy: FAO.

Leff, B., N. Ramankutty, & Foley, J.A. (2004). Geographic distribution of major crops across the world. *Global Biogeochemical Cycles, 18, GB1009.*

Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., Naylor, R. L., et al. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science, 319*(5863), 607-10. doi: 10.1126/science.1152339.

Lobell, D.B., Burke, M. B., (2008). Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. *Environmental Research Letters, 3*(3). doi: 10.1088/1748-9326/3/3/034007.

Magorokosho, C., Banziger, M. & Betran, F.J. (2005). Characterization of local maize landraces from Zimbabwe, Zambia, and Malawi. In Jarvis, D., Mar, I. & Sears, L. (Eds.) Enhancing the Use of Crop Genetic Diversity to Manage Abiotic Stress in Agricultural Production Systems. Rome, Italy: International Plant Genetic Resources Institute: 25-30.

Mati, B. (2000). The influence of climate change on maize production in the semi-humid semi-arid areas of Kenya. *Journal of Arid Environments, 46*(4):333-344. doi: 10.1006/jare.2000.0699

Mitchell, T. D. and Jones, P. D. (2005). An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology, 25,* 693-712.

National Research Council. (1995). *Lost crops of Africa: Volume 1, Grains.* Washington, D.C.: National Academy of Science.

Nelson, G.C., Rosegrant, M.W., Koo, J., Robertson, R., Sulser, T., Zhu, T. et al, Eds. (2009). Climate Change: Impact on Agriculture and Costs of Adaptation. Washington, D.C.: International Food Policy Research Institute.

Neumann, K., Verburg, P.H., Stehfest, E., & Muller, C. (2010). The yield gap of global grain production: A spatial analysis. Agricultural Systems, 103(5): 316-326. doi: 10.1016/j.agsy.2010.02.004

Osman-Elasha, B. (2008). Incorporating Community-Based Perspectives in Future Agreement. OECD *Adaptation in the post-2012 framework Meeting* (Paris, France). Retrieved from http://www.oecd.org/dataoecd/38/1/40634744.pdf

Osseo-Asare, F. (2005). Food culture in Sub-Saharan Africa. Westport, CT: Greenwood Press.

Passioura, J.B. (2007). The drought environment: Physical, biological, and agricultural perspectives. *Journal of Experimental Botany, 58*(2):113-117.

Passioura, J.B. & Angus, J.F. (2010). Improving productivity of crops in water-limited environments. *Advances in Agronomy, 106*:37-75. doi: 10.1016/S0065-2113(10)06002-5

Pimentel, D., Ed. (2007). Encyclopedia of Pest Management, Volume 2. Boca Raton, FL: CRC Press.

Pingali, P.L., Ed. (2000). *CIMMYT 1999–2000 World Maize Facts and Trends. Meeting World Maize Needs: Technological Opportunities and Priorities for the Public Sector.* Mexico, D.F.: CIMMYT.

Porter, J. & Gawith, M. (1999). Temperatures and the growth and development of wheat: a review. *European Journal of Agronomy*, *10*(1):23-36. doi:10.1016/S1161-0301(98)00047-1

Randall, D.A, Wood, R.A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R.J., Sumi, A., & Taylor, K.E. et al. (2007) *Climate Models and Their Evaluation. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Chapter 8). Cambridge: University Press, 611-612.

Reddy, K. R. & Hodges, H.F., Eds (2000). Climate Change and Global Crop Productivity. Wallingford, U.K.: CAB International, 81-106.

Rosenzweig, C., & Hillel, D. (1998). *Climate Change and the Global Harvest: Potential Impacts of the Greenhouse Effect on Agriculture.* Oxford, U.K.: Oxford University Press.

Ruosteenoja, K, Carter, T.R., Jylhä, K., and Tuomenvirta, H. (2003). *Future Climate in World Regions: And Intercomparison of Model-Based Projections for the New IPCC Emissions Scenarios*. Retrieved from http://unfccc.int/resource/cd_roms/na1/v_and_a/Resoursce_materials/Climate/FEI_FutureClimate.pdf

Sacks, W.J., Deryng, D., Foley, J.A., & Ramankutty, N. (in press). Crop planting dates: An analysis of global patterns. *Global Ecology and Biogeography.*

Schlenker, W. & Lobell, D. B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters, 5*(1):1-14. doi: 10.1088/1748-9326/5/1/014010

Schmidhuber, J., & Tubiello, F. N. (2007). Global food security under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(50), 19703-8. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/18077404

Siebert, S., Döll, P., Feick, S., Hoogeveen, J. & Frenken, K. (2007) *Global Map of Irrigation Areas version 4.0.1.* Johann Wolfgang Goethe University, Frankfurt am Main, Germany / Food and Agriculture Organization of the United Nations, Rome, Italy

Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M. M., et al. (2008). *Climate change 2007: the physical science basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from http://ethree.com/downloads/Climate Change Readings/Climate Science/IPCC Reports/AR4WG1_FrontMatter-v2.pdf

Tester, R.F., et al. (1995). Effects of elevated growth temperature and carbon dioxide levels on some physicochemical properties of wheat starch. *Journal of Cereal Science, 22*(1):63-71. doi:10.1016/S0733-5210(05)80008-6

Thompson, G.B., Brown, J.K., Woodward, F.I. (2006). The effects of host carbon dioxide, nitrogen and water supply on the infection of wheat by powdery mildew and aphids. *Plant, Cell & Environment, 16*(6):687-694.

Thornton, P.K., Jones, P.G., Alagarswamy, G. & Andresen, J. (2009). Spatial variation of crop yield response to climate change in East Africa. *Global Environmental Change, 19*(1):54-65.

United Nations Framework Convention on Climate Change. Submitted NAPAs retrieved from http://unfccc.int/national_reports/napa/items/2719.php

Vivek, B., Banziger, M. & Pixley, K.V. (2005). Characterization of maize germplasm grown in eastern and southern Africa: Results of the 2004 regional trials coordinated by CIMMYT. Mexico, D.F.: CIMMYT.

Walker, N.J. & Schulze, R.E. (2008). Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. *Agriculture, Ecosystems & Environment,124*(1-2):114-124. doi: 10.1016/j.agee.2007.09.001

Wilby, R.L. and Wigley, T.M.L. (1997): Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography,* 21, 530-548.

World Bank. (2009a). IMPLEMENTING AGRICULTURE FOR DEVELOPMENT World Bank Group Agriculture Action Plan: FY2010–2012.

World Bank. (2009b). The Costs to Developing Countries of Adapting to Climate Change New Methods and Estimates The Global Report of the Economics of Adaptation to Climate Change Study Consultation Draft.

---

[1] Nelson, 2009
[2] Solomon et al., 2008
[3] Pingali, 2000
[4] Nelson, 2009
[5] FAO, 2009
[6] Dixon et al., 2001
[7] Lawlor & Mitchell, 2000
[8] FAOSTAT, 2007
[9] Neumann et al., 2010, Figure 3
[10] FAOSTAT; CIA; authors' calculations
[11] Lathem, 1997
[12] FAOSTAT, 2007
[13] Lathem, 1997
[14] Davidson, 2003.
[15] Osseo-Asare, 2005, p. 109
[16] FAOSTAT Commodity Balance Sheet, 2007 data
[17] FAO, 2003, p. 78
[18] Christensen, 2007
[19] Ruosteenoja, 2003
[20] Randall et al., 2007, p.611
[21] Burke et al., 2009
[22] Solomon et al., 2008
[23] Burke et al. 2009
[24] Monfreda et at., 2008, Global Biogeochemical Cycles, Vol. 22
[25] Mitchell & Jones, 2005
[26] Burke et al., 2009
[27] Crops and Climate: Rice. EPAR Brief.
[28] IPCC AR4, Figure SPM.7
[29] Christensen et al., 2007
[30] Lobell & Burke, 2008
[31] Siebert et al., 2007
[32] Hodson & White, 2009, p. 52; Lawlor & Mitchell, 2000, p 59
[33] Lawlor & Mitchell, 2000, p. 71
[34] Porter & Gawith, 1999, Table 3
[35] Liu et al., 2007, p. 227
[36] Lawlor & Mitchell, 2000, p. 64; Hodson & White, 2009, p. 53; Tester et al., 1995
[37] Lawlor & Mitchell, 2000, p. 68
[38] Bender et al., 1999, cited in Lawlor & Mitchell, 2000, p.68
[39] Hodson & White, 2009, p. 53
[40] Lawlor & Mitchell, 2000, p. 71

---

[41] Lawlor & Mitchell, 2000, p.69
[42] Hodson & White, 2009, p. 54
[43] Hodson & White, 2009, p. 53
[44] Hodson & White, 2009, p. 53, citing Kimball et al., 2001; Lawlor & Mitchell, 2000, p.63
[45] Hodson & White, 2009, p. 54
[46] Lawlor & Mitchell, 2000, p. 64;Hodson & White, 2009, p. 54
[47] Hodson & White, 2009, p. 54; Kimball & Bernacchi, 2006
[48] Lawlor & Mitchell, 2000, p. 64
[49] Lawlor & Mitchell, 2000.
[50] Passioura, 2010
[51] Passioura, 2010
[52] Passioura, 2010
[53] Passioura, 2010
[54] Reddy & Hodges, 2000
[55] Passioura, 2010
[56] Passioura, 2010
[57] Garrett et al., 2006, p. 494
[58] Boshoff et al., 2002, cited in Garrett et al., 2006, p. 496
[59] Thompson et al., 1993
[60] Cammell & Knight, 1992
[61] Pimentel, 2007
[62] Jarvis et al., forthcoming.
[63] Hodson & White, 2009, p. 54
[64] Jarvis et al., forthcoming
[65] Hodson & White, 2009, p. 54
[66] Jones & Thornton, 2003
[67] Liu et al., 2008, p. 228
[68] Schlenker & Lobell, 2010
[69] Neumann et al., 2010, Figure 3
[70] Gbetibuou & Hassan, 2005
[71] ASTI data; authors' calculations
[72] Africa Partnership Forum, 2009
[73] Africa Partnership Forum, 2009; United Nations Framework Convention on Climate Change
[74] Mitchell & Jones, 2005, p.706
[75] Sacks et al., 2010
[76] Burke et al., 2009