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Crops & Climate Change: Sorghum and Millet

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Summary

In most developing countries, climate warming and changes to precipitation patterns are already affecting crop production, and climate change is projected to continue to adversely affect agriculture.[1,2] In particular, climate change is expected to have major impacts on agriculture in Sub-Saharan Africa (SSA), leaving the already food-insecure region subject to large contractions of agricultural incomes and food availability.[3] As part of the *Crops & Climate Change* series, this brief is presented in three parts to assess any imbalances among the relative importance of the crops, their predicted responses to climate change, and current resources devoted to the crops:

- Pillar 1: An evaluation of the importance of sorghum and millet in SSA, based on production, net exports, and caloric need
- Pillar 2: A novel analysis of historical and projected climate conditions in sorghum and millet-growing regions, followed by a summary of the agronomic and physiological vulnerability of sorghum and millet crops
- Pillar 3: A summary of current resources dedicated to sorghum and millet, based on full-time researchers, Bill and Melinda Gates Foundation Funding, and National Adaptation Programmes of Action

This three-pillared approach serves to identify potential gaps in resources dedicated to sorghum and millet productivity in SSA relative to the crops' resilience to projected climate changes and the crops' role in the region's food security. A similar analysis for maize, rice, and wheat (EPAR briefs 62, 71, and 114), allows the foundation to compare relative importance, resilience, and resources across five crops.

Our analysis indicates that sorghum and millets may become increasingly important in those areas of SSA predicted to become hotter and subject to more variable precipitation as a result of climate change. Although sorghum and millet are currently grown on marginal agricultural lands and consumed for subsistence by poorer population segments, climate change could render these drought- and heat-tolerant crops the most viable future cereal production option in some areas where other cereals are currently grown. Fewer international development resources are currently devoted to sorghum and millet than are devoted to other cereal grains, and current resource allocation may not reflect the increased reliance on these grains necessitated by projected climactic changes.

Pillar 1: The Importance of Sorghum and Millet in SSA

Sorghum and millets are important cereal crops in dry climates where many other cereals cannot be easily grown.[4] They are generally considered less-desirable cereal crops, primarily consumed by poor and marginalized populations.[5] The geographic regions in which sorghum and millet are grown are among the most susceptible to climate change.[6]

Because of their tolerance for heat and drought, sorghum and millets could take on an increasingly important role in the regions of SSA which, as a consequence of climate change, are forecast to become too hot and dry to support continued production of consumer-preferred cereals such as maize.[7]

Table 1: Sorghum and Millet in Sub-Saharan Africa At-A-Glance

Total Production (metric tons)	Sorghum 24.3 Million (15.7% of total cereal production) Millet 17.3 Million (10.8%)
Total Net Trade (metric tons)	Sorghum -456,869 Millet -51,060
Countries Very Highly or Highly Dependent	Sorghum (Burkina Faso) Millet (Niger, Burkina Faso, Mali)
Agronomic Requirements (temperature, precipitation)	Sorghum(27.5ºC, 400mm) Millet (30ºC, 150mm)
Nutritional Information: (protein, fat, carbohydrate content, % of total grain weight)	Sorghum (10.4%, 3.1%,70.7%) Pearl Millet (11.8%, 4.8%, 67.0%) Finger Millet (7.7% 1.5%, 72.6%)
Dedicated CGIAR Research Centers	ICRISAT
Total FTE Researchers*	Sorghum 188.9 (5.2% of all SSA crop researchers; 17.9% of all cereal researchers) Millet 100.1 (2.8%; 9.5%)
Countries including a sorghum or millet strategy in their NAPA**	Eritria, Burkina Faso, Mali, Burundi, Lethoso, Guinea, Mozambique, Tanzania, Guinea-Bissau
Summary	Inferior cereals frequently grown for subsistence, drought and heat tolerant, receiving increasing resources

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

All 49 SSA countries consume at least some sorghum and millet, although consumption levels vary widely from country to country for both crops.[8] Sorghum and millet production has increased overall in SSA and especially in West Africa over the past several decades, although per-capita consumption has been relatively stagnant.[9,10,11] Sorghum and millets tend to be economically inferior goods, with national consumption declining when per-capita income rises.[12] Consumer preference for other grains also results in a high proportion of subsistence-based production and consumption, and creates unreliable crop markets for farmers.[13]

Sorghum and Millet Production

Sorghum and millet plants are typically grown in areas of SSA where other grains do not grow well because of high temperatures or restricted water resources.[14] Sorghum tends to be grown in locations too hot or dry to successfully grow maize, while pearl millet tends to be grown where it is too hot, dry and sandy to successfully grow sorghum.[15,16] Similarly, sorghum is grown where the growing season is too short to support maize production, while pearl millet is grown where the growing season is too short to support sorghum cultivation.[17] However, international research and investments improving maize yield and plant hardiness, coupled with a reduction in sorghum price support by governments as a consequence of market deregulation, has allowed maize production to become price-competitive in SSA. As a result, maize production has replaced sorghum in some traditional sorghum producing areas.[18] Even in semi-arid climates where sorghum currently outperforms maize grain yields, producers may choose to continue growing maize because of consumer preferences or government policies.[19]

38 SSA countries produce sorghum and 36 countries produce millet, with the highest production levels for both crops forming a horizontal belt across the Sahel from Burkina Faso to Ethiopia (See Figures 1 & 2). Within this zone, millets tend to be grown on sandy upland soils, while sorghum is grown in more fertile alluvial soils in river valleys.[20] The top five sorghum producing countries (Nigeria, Sudan, Ethiopia, Burkina Faso and Niger) produce 77% of SSA's sorghum supply, while the top 5 millet producing countries (Nigeria, Niger, Mali, Burkina Faso and Sudan) produce 80% of SSA's millet supply.[21] Sorghum production quantity nearly tripled in Eastern and Western Africa between 1961 and 2009, while sorghum production in Southern Africa declined during that period.[22] Millet production in Western Africa also more than tripled during the same time period, while other SSA regions saw more moderate millet production increases.[23]

Figure 1: Sorghum Production in Africa (Metric Tonnes)

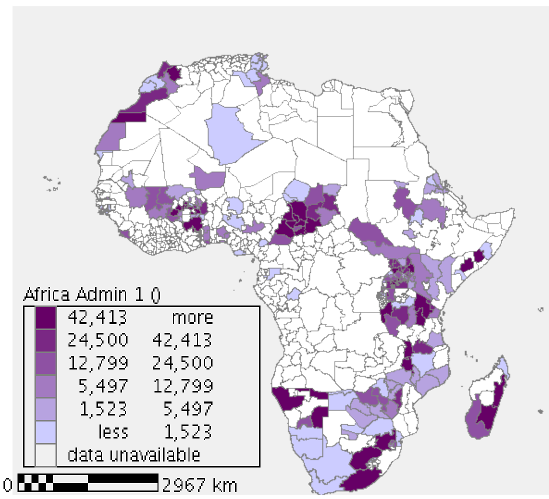
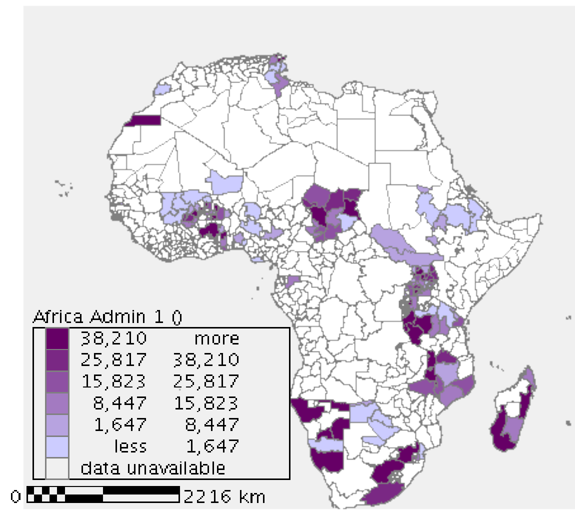


Figure 2: Millet Production in Africa (Metric Tonnes)



Source: FAO Agromaps[24]

Because so much sorghum and millet is consumed for subsistence by extremely poor populations, or is traded unrecorded in local markets, production and trade volumes are difficult to estimate. [25,26] In addition, FAOSTAT did not report sorghum or millet import or export data for many SSA countries (See Appendix 2). Therefore, the production and trade statistics included in this report should be interpreted with some caution.

There were higher reported volumes of sorghum production than millet production in SSA in 2007; sorghum production totaled 24.3 million metric tons and millet production totaled 17.3 million metric tons. Sorghum accounted for 15.7% of the total volume of cereals produced in SSA, while millet accounted for 10.8% (See Appendix 1).[27] This somewhat greater reliance on sorghum than millet is also reflected by the larger area of land devoted to sorghum production: sorghum accounts for 18.4% of total cereal area harvested on average in SSA countries, while the millet area harvested accounts for 14.7%.[28]

Production in SSA is limited by consumer preferences for other cereals and farmer's lack of investment in and adoption of improved sorghum and millet varieties.[29] Grain molds and mildews, bird predation, insect pests such as stem borers, head bugs and midges, and parasitic weeds such as Striga (witchweed), which inhibits plant water and nutrient uptake by attaching itself to roots, also reduce sorghum and millet yields in SSA.[30]

<u>Sorghum and Millet Consumption</u>

The geographic consumption of sorghum and millet in SSA matches geographic production distribution more closely than for other grains because of high levels of subsistence farming of these crops.[31] The highest levels of recorded international sorghum and millet trade occurs outside of SSA in India, the U.S. and China, reflecting a demand for animal feed more than trade for human consumption.[32] More sorghum and millet were imported than exported from SSA in 2007, with a net import volume of 456,869 tons of sorghum and 51,060 metric tons of millet.[33] Kenya imported the most millet among SSA countries, and Chad imported the most sorghum.[34]

Nutrition & Caloric Intake

Sorghum and millet are important calorie sources for millions of Sub Saharan Africans, especially in the Sahel region of West Africa. As Tables 2 and 3 demonstrate, in 2005, over 236 million people, or about 30% of SSA's population, depended on sorghum for more than 300 kilocalories of their daily food intake, and over 58 million people, or 8% of SSA's population, depended on millet for more than 300 daily kilocalories.[35]

Table 2: Dependency on Sorghum for Caloric Intake

Level of Sorghum in Local Food Supply	Countries	Population
Very Highly Dependent >800 kcal/person/day		
Highly Dependent 500-799 kcal/person/day	Burkina Faso	16,241,811 (2% of total SSA population)
Moderately Dependent 300-499 kcal/person/day	Chad, Mali, Nigeria, Sudan	220,496,757 (27.7%)
Less Dependent <300 kcal/person/day	Remaining SSA countries	558,983,962

Source: FAOSTAT (2005 food supply data); FAOSTAT (2007 production data), CIA World Factbook, Author's Calculations

Table 3: Dependency on Millet for Caloric Intake

Level of Millet in Local Food Supply	Countries	Population
Very Highly Dependent >800 kcal/person/day	Niger	15,878,271 (2% of total SSA population)
Highly Dependent 500-799 kcal/person/day	Burkina Faso, Mali	30,381,165 (4%)
Moderately Dependent 300-499 kcal/person/day	Chad, The Gambia	12,357,622 (1.5%)
Less Dependent <300 kcal/person/day	Remaining SSA countries	737,105,472

Source: FAOSTAT (2005 food supply data); FAOSTAT (2007 production data), CIA World Factbook, Author's Calculations

The population of Burkina Faso is dependent on sorghum for more than 500 kilocalories per person per day, while Niger, Burkina Faso and Mali are all dependent on millet for more than 500 daily kilocalories.[36] Burkina Faso and Niger rely on the combination of sorghum and millet for over 1000 daily kilocalories per-capita, and Chad, The Gambia, Mali, Nigeria and Sudan rely on the combination for between 500 and 1000 daily kilocalories per-capita.[37] By contrast, Burundi, Cote d'Ivoire, Guinea and Malawi all depend on sorghum and millet for less than 20 daily kilocalories per-capita each.

Sorghum and millet, like other cereals, are primarily starchy in composition. Sorghum and pearl millet are also comparable to other cereals in their protein content, which comprises 12.3% and 13.3% of total grain weight, respectively.[38] While sorghum has a slightly higher protein content than maize, the protein is of lower nutritional quality.[39] The protein contained in pearl millet is similarly reported to have a better amino acid profile than that of sorghum.[40] Fat content is around 3% in sorghum, which is higher than the fat content in wheat and rice but lower than that of maize. Pearl millet has a comparable fat content to maize, although other varieties of millet have a fat content more similar to that of sorghum. Whole grains of both crops are important sources of B vitamins niacin, riboflavin and thiamin, which are primarily contained in the outer bran layers of the grain. Sorghum and millet are comparable to maize in B vitamin content. Beer brewed from sorghum, a common preparation of the grain, promotes iron absorption at a rate 12 times higher than from sorghum gruels.[41] Mineral content in both grains is primarily affected by the soil type and environmental conditions.[42] Table 4 compares the average nutritional composition of sorghum and millet with that of other common cereals.

Table 4: 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

Sorghum and Millet Cultivars

Although there is one predominant species of sorghum grown in Africa, *Sorghum bicolor*, Africa features a variety of millet species including pearl millet *Pennisetum glaucum*, finger or African millet *Eleusine coracana*, foxtail millet *Setaria italica*, kodo millet *Paspalum scrobicalatum,* and white fonio millet, *Digitaria exilis*.[43] Of the millet species, pearl millet is the most widely cultivated, and has the highest yield potential under heat and drought stress.[44] As of 2006, pearl millet accounted for 90% of the millet grown in West and Central Africa, the continent's center of millet production.[45]

Certain varieties and hybrids of millet and sorghum species feature truncated growth cycles and other adaptations which help them survive in areas with short rainy seasons.[46] A literature review of improved sorghum and millet varieties by Bidinger et al., (2008) notes that several studies have confirmed that local landrace-based millet varieties perform better under marginal growing conditions than do conventionally bred varieties.[47] However, landrace-based varieties may produce lower yields as compared to improved varieties, and may be unable to capitalize on the availability of water resources by producing greater yields in non-drought years.[48] Short-cycle local varieties of sorghum and millet also may not contain preferred taste characteristics.[49] In addition, varieties adapted to local rainfall and temperature conditions will not necessarily be adapted to variable or more extreme future local climatic conditions.[50,51] Researchers have identified a need for the improvement of early-maturing and short-cycle sorghum and millet varieties that would be better adapted to the changing seasonal temperature and precipitation which is forecasted by climate warming scenarios.[52, 53]

Hybrid breeding programs for sorghum and millet have been somewhat successful at increasing yields. Improved varieties released in West and Central Africa in the early 1990s increased sorghum yields by 4-85% over traditional races during a multi-year period of evaluation.[54] However, hybrid breeding in India and the United States, two centers of agricultural research on these crops, has often focused on maximizing grain yields under favorable conditions instead of ensuring consistent yields in harsh environmental conditions.[55] Because breeding for adaptation to drought and low soil moisture is difficult under conventional phenotypic breeding selection strategies, potentially substantial crop yield improvements could be realized from the devotion of resources to the identification of genes which express drought resistant traits in local landrace varieties for translocation to high-yield varieties.[56] Introduction of modified varieties will continue to face earlier difficulties encountered by modified varieties in the form of disease, pest predation and improper adaptation to local soil stresses.[57] Additional information can be found in EPAR Brief 54: "Adoption of Improved Sorghum and Millet Cultivars in SSA."

Pillar 2: Vulnerability Analysis of Sorghum and Millet-Growing Regions in SSA

Climate change will affect agriculture through a variety of physiological, environmental, and behavioral pathways.[58] 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 sorghum and millet cultivation in complex ways, both positive and negative.[59] The first portion of this analysis utilizes 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 sorghum and millet'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.[60,61,62] The coincidence between current growing season temperature and projected future conditions (overlap) is projected to be less than 20% by 2050.[63] In other words, by 2050 an average of four out of five years will have a projected mean growing season temperature above the warmest observed during the twentieth century. Figure 3 illustrates this analysis showing two sets of hypothetical temperature distributions. The left panel shows distributions with some degree of overlap, however 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.

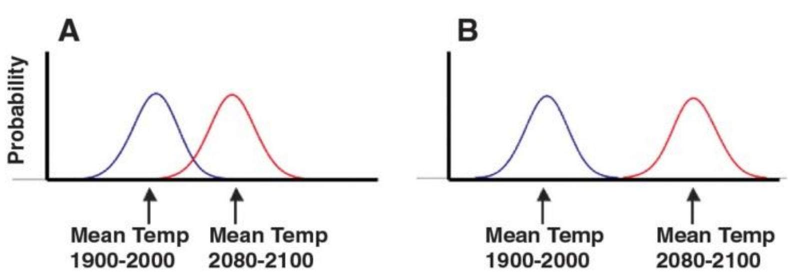


Figure 3. Hypothetical distributions of growing season average temperature for the 20th century (blue) and late 21st century (red). A: some overlap; future mean growing season average temperature is equal to hottest 20th century mean. B: no overlap; distribution of late 21st century growing season temperature exceeds historical distribution completely.

Source: Battisti & Nayor, 2009

Projected changes in precipitation are generally less robust than their temperature counterparts.[64] 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 are likely to 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.[65] 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

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

Convergence Zone, a region of persistent intense thunderstorm activity.

For this analysis, global crop distribution data and 20th century climate data were used to define five representative categories of growing season climates in SSA: Sahel, Coastal West Africa, East Africa, South Central Africa, and Southern Africa.[66,67] *Figure 4* illustrates the geographic domains of each region. The regions have unique annual variations of growing season temperature and precipitation, which strongly influence agriculture through their effect on plant biology and environmental conditions. The representative regions have experienced varying degrees of persistent change over the 20th 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.

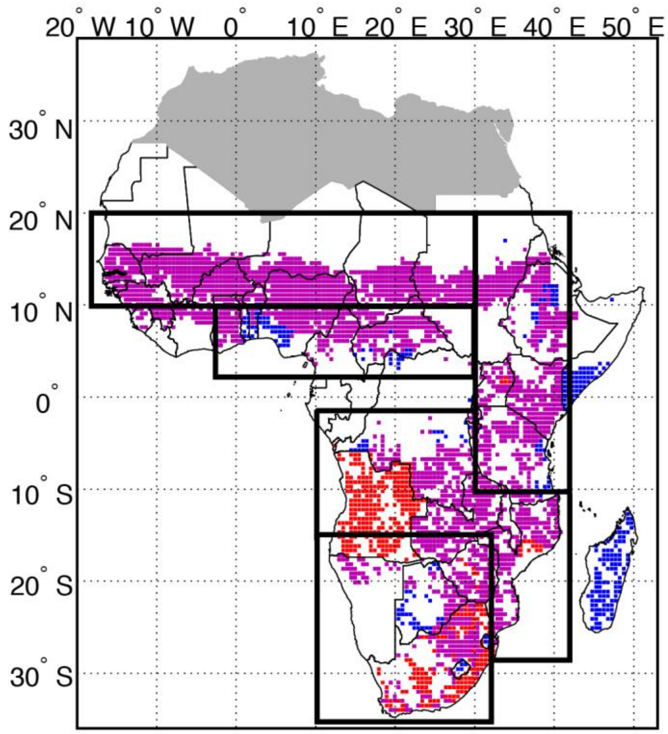


Figure 4: Sorghum and millet growing regions in SSA. Sorghum regions are indicated in blue, millet regions in red, and regions where both are grown in purple. Colored grid cells within the regions bounded with thick black lines denote the representative sorghum and millet growing regions used for climatological analysis: Sahel, Coastal West Africa, East Africa, South Central Africa, and Southern Africa. Grid cells outside of the thick lines were not included in the analyses.

Source: Crop distribution data from Monfreda et al., 2008

Data and methodology

The historical temperature and precipitation data for the following climatological analyses 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 global climate models used for the most recent IPCC assessment report, published in 2007. Additional details on the historical observations and numerical modeling systems are presented in *Appendix 3*.

The analysis of projected climate change uses a methodology similar to previous studies,[68] 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 these variables are presented at three years: 2020, 2050, and 2090, corresponding to near, intermediate, and long time horizons. The mean of the historical distribution is defined by an area-average of observational data 1976 to 2006. The shape of the historical distribution comes from the variance of observational data 1901 to 2006.

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). Additional methodological details are available in *Appendix 3*.

Results

Current and Historical Climate Conditions of Sorghum and Millet Growing Regions

Table 4 presents area-averaged mean and standard deviation for growing-season average temperature and growing-season accumulated precipitation for each of the five SSA sub-regions (shown in Figure 3). Temperature and precipitation differ markedly between the five regions. The Sahel is characterized by a comparatively hot and dry growing season, unsurprising given its proximity to the Sahara desert. Furthermore, the Sahel is characterized by a large difference in mean temperature within the area selected for analysis. Mean temperature ranges from 33ºC near the Sahara to 22ºC closer to the coast. Mean accumulated precipitation varies even more, from 236cm near the coast to 20cm near the Sahara desert. Coastal West Africa has a lower mean growing season temperature due to its proximity to the tropical Atlantic Ocean and the moderating influence of evaporative cooling stemming from moisture in its verdant forests. Both of these influences also tend to bring Coastal West Africa a wetter growing season. Despite being located at similar latitudes to the Sahel and Coastal West Africa, Eastern Africa's average growing season is cooler and drier, owing to its higher elevation and monsoonal winds from the south. It also shows some intra-region variability in the mean, similarly expressing the large gradients in elevation and topographic aspect. South Central Africa has a cooler growing season than the Sahel, characteristic of its elevated position on the South African plateau, as does the portion of Southern Africa selected for analysis.

Table 4: Mean (ºC, cm) and standard deviation (ºC, cm) for growing season average temperature and growing season accumulated precipitation over five sorghum and millet 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 and stable statistics, means based on recent period, 1976-2006; for increased statistical 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 – October	28.4	23-32, 1.7	0.44	59.4	16-206, 28.0	8.6
Coastal West Africa	June – October	25.0	19-27, 1.3	0.31	96.0	56-185, 18.0	6.8
East Africa	March – August	23.7	13-32, 4.1	0.31	49.0	10-123, 23.0	5.2
South Central Africa	December – June	22.8	18-27, 1.8	0.28	88.1	25-143, 14.1	7.2
Southern Africa	December – June	20.6	11-26, 2.5	0.35	43.3	7-112, 16.1	7.5

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

While mean temperature gives one summary picture of the growing season climate of these regions, standard deviation provides a depiction of how much temperature departs from the mean on a year-to-year and decade-to-decade basis. Temperature variability is considerably greater in the Sahel than other regions, with growing season temperatures deviating 0.44ºC from the mean on average for the last century. For precipitation, the Sahel exceeds the other regions, with 8.6 centimeters of deviation from the mean on average. Large variability in growing-season accumulated precipitation is significant in semi-arid regions like the Sahel, the East African highlands and the South African highlands, particularly in the case of warm-season drought. Changes in variability are much harder to determine, especially in data-poor regions such as SSA. Higher-moment statistics such as variance tend to be unstable in short records, making attempts to isolate persistent changes much more difficult. Comparing data for the early and late periods of the 20th century indicates that temperature variance has not changed across SSA and that year-to-year precipitation variability has remained consistent in equatorial Africa, decreased by 10cm across the Sahel and Eastern Africa, and increased by 10cm in Southern Africa. This evidence is only suggestive, and lacks a firm physical basis for causality. Figures A2 and A3 in Appendix 4 present these differences in variability visually through time series of growing-season temperature and accumulated rainfall.

Projected 21st Century Climate Change in Sorghum and Millet Growing Regions

Temperature shift predictions are consistent amongst the 23 models included in our analysis. Figure 5 shows historical distributions of growing season average temperature and three future distributions corresponding to climate at 2020, 2050, and 2090 for each of the five representative regions. 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 for other regions at 2020 and 2050. In other words, an equivalent shift in the mean climate at a location with low variability (e.g., South Central Africa) will mean less overlap than for one with high variability (e.g., the Sahel). Notwithstanding this nuance, by 2090, each of the five regions is projected to move into a completely novel warmed climate, distinct from its observed 20th century climate. Table 5 illustrates this numerically, depicting the percentage of overlap between the historical and projected future distributions by 2020, 2050, and 2090. Despite being unique relative to their own historical distributions, it should be noted that several of the future temperature distributions have analogues in the present climate (e.g., Coastal West Africa in 2090 has a similar temperature range as the Sahel does today).

The shifts are less pronounced for precipitation than for temperature (Figure 6*).* In other words, while the models generally produce a similar warming in the 21st century over SSA, the models disagree over the magnitude and direction of precipitation changes.[69,70] This is expressed visually in Figure 6, wherein the future distributions of growing season accumulated rainfall are essentially identical to their 20th century counterparts. Put differently, the distributions of precipitation shift only slightly and remain the same over the course of the 21st century. Future improvements in the models' ability to project the physical and dynamical factors that contribute to precipitation will likely increase confidence in future projections and allow a better characterization of shifts over these representative regions.

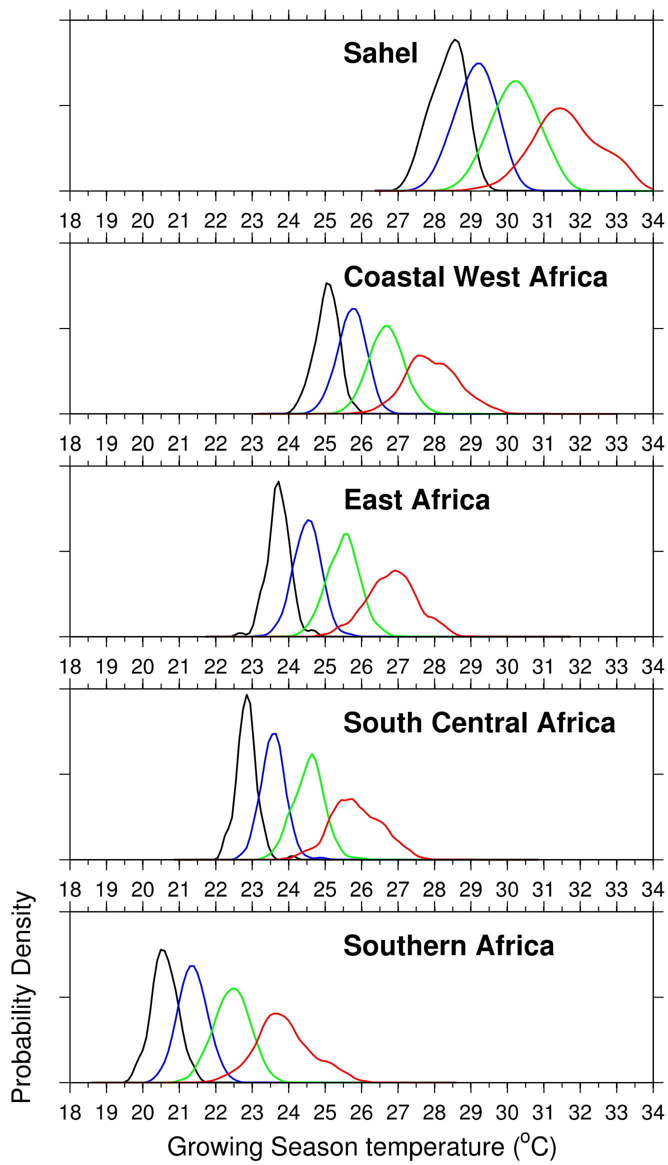
Table 5: Percentage of climate overlap between recent (1976-2006) observations and future projections based on a business-as-usual development scenario used by IPCC climate models. Percentages indicated for temperature (T) and precipitation (P) at 2020, 2050, and 2090.

Region	Variable	2020	2050	2090
Sahel	T	45%	5%	0%
	P	94%	93%	90%
Coastal West Africa	T	35%	1%	0%
	P	93%	91%	80%
East Africa	T	27%	0%	0%
	P	95%	94%	90%
South Central Africa	T	29%	0%	0%
	P	95%	94%	86%
Southern Africa	T	39%	0%	0%
	P	94%	90%	91%

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

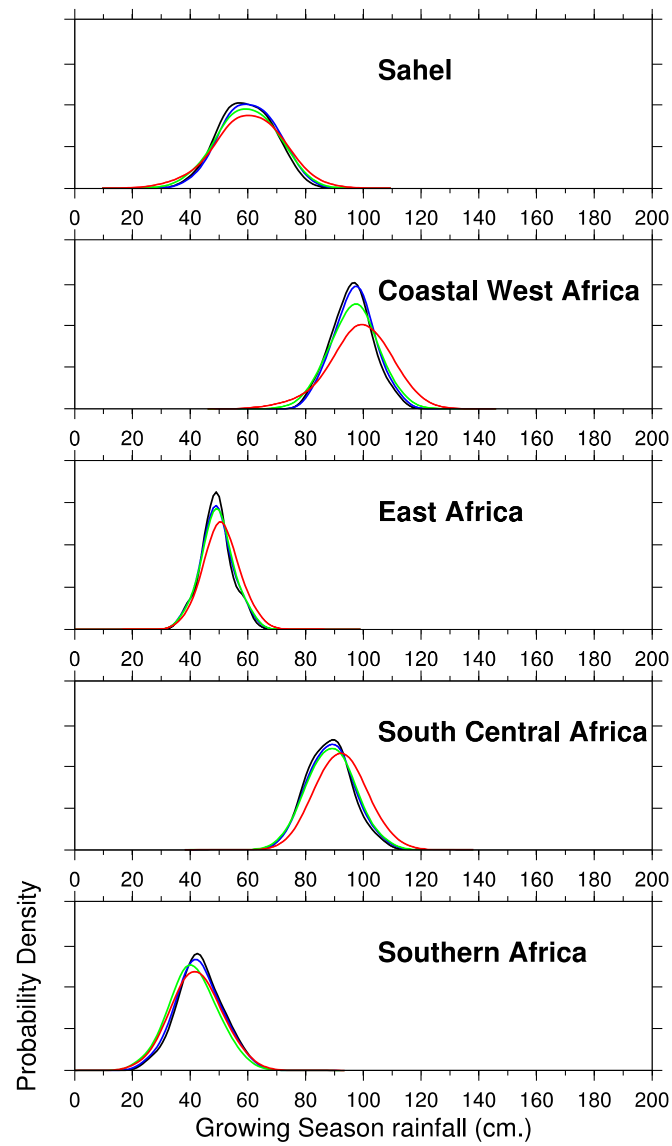
Figure 5. Shifts in average growing season temperature over five sorghum and millet growing regions in SSA. Distributions are shown

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 6. Shifts in total growing season rainfall over five sorghum and millet 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).

Agronomic and Physiological Vulnerability

Sorghum and Millet Climate Requirements

Pearl millet, finger millet and other African millet species each have slightly different ideal growing conditions.[71] For pearl millet, the predominant millet in SSA, the ideal growth climate is around 30ºC, with a 10ºC minimum temperature for meaningful levels of photosynthesis to occur.[72,73] Sorghum's optimum growth temperature is about 27.5ºC.[74] These optimum temperatures determined under controlled experimental conditions vary according to the stage of the plants' life cycle: sorghum germinates well in temperatures of 21-35ºC, maximizes plant growth from 26-34ºC, and maximizes reproductive growth from 25-28ºC.[75] Semi-arid regions of SSA with high sorghum production levels, such as Sudan and Mali, feature temperatures within or near this optimum range during the sorghum growing season.[76] Prasad et al. (2006) found that sorghum seed growth rates decreased at temperatures above 36ºC, and that sorghum seed size decreased when temperatures rose above 32ºC.[77] The authors also found that the negative effects of elevated temperatures on sorghum pollen viability, seed yield, and harvest index were all exacerbated under an elevated CO_2 experimental condition.[78]

Sorghum and millet are relatively drought-tolerant in comparison to other popular SSA cereals, such as maize. While maize requires 50cm annual rainfall, sorghum can tolerate as little as 40cm, and pearl millet can tolerate as little as 12.5cm.[79] As a result of their C_4 photosynthetic processes, sorghum and millet have high water use efficiency; one study found that sorghum was 2.9 times as efficient as wheat (a C_3 crop) in terms of the water transpired during plant assimilation of carbon via photosynthesis.[80] 89% of cereals in SSA get their water from rainfall, and not irrigation, and millet and sorghum are only infrequently supported by irrigation infrastructure.[81, 82] Sudan has some of the most extensive irrigation of sorghum in SSA, include two irrigation schemes covering a total of 22,000 square kilometers.[83]

<u>Current Sorghum and Millet Climatic Range</u>

Consistent with the climate requirements of sorghum and millet, relatively higher yields are reported in sorghum and millet growing areas (*Figure 7 and A1*) with temperatures between 25 and 30ºC.[84]] Furthermore, *Figures 7* and *A1* suggest that both crops are grown in areas with growing-season accumulated rainfall less than 10cm. Data indicates that some of the regions with low rainfall totals and high yields have regional irrigation infrastructure[85] Irrigation infrastructure is in place across the climatological growing season range for sorghum and millet (i.e. 11 – 33ºC and 0 – 300 cm per growing season), though the data are not specific enough to indicate whether the infrastructure is supporting sorghum, millet or other crops within each grid cell.

<u>Changes in Plant Physiology under Climate Change</u>

Photosynthesis & Biomass Production

In general, increased temperatures accelerate plant development; however, high temperatures may decrease grain yield as a consequence of more rapid biomass growth.[86] Increasing CO_2 concentration in the atmosphere has a positive effect on crop biomass production, known as CO_2 fertilization, whereby increased CO_2 stimulates photosynthesis and promotes plant biomass production.[87,88] Elevated CO_2 suppresses photorespiration and increases the ideal temperature for photosynthesis.[89]

For millet, sorghum, maize and other crops that utilize the atypical C_4 photosynthetic process, the growth benefits of elevated CO_2 levels are muted because of their relative photosynthetic efficiency.[90] Climate change models have accordingly shown declining marginal growth benefits to C_4 crops as a result of the predicted rising atmospheric carbon levels.[91] Climate change modeling is corroborated by experimental studies which have not found beneficial effects for sorghum plant growth in elevated atmospheric CO_2.[92] However, C_4 crops also have optimum photosynthetic responses at higher temperatures (30-35ºC) than do C_3 plants, and thus may be able to tolerate the higher temperatures in SSA forecasted under climate change models better than C_3 cereals such as rice.[93] The theoretical and laboratory-observed effects of elevated CO_2 levels on plant growth have not yet been supplemented by any CO_2 enrichment field experiments in tropical croplands that could confirm these predictions.[94]

Evapotranspiration & Water Use Efficiency

While climate change predicts possible increases in precipitation, higher temperatures will also increase evapotranspiration (the evaporation of water emitted by plants as a consequence of photosynthesis) into the atmosphere most drastically in areas where the temperature is already high, such as SSA.[95] Evapotranspiration also increases with lower precipitation, thus subjecting plants to a greater demand for water when there is reduced supply.

Elevated CO_2 causes plant stomata to narrow, decreasing water loss and thereby improving water use efficiency.[96,97] Conversely, increases in temperature decrease water use efficiency by increasing evaporation.[98] Conley et al. (2001) found that elevated atmospheric CO_2 increased water use efficiency and reduced evapotranspiration in sorghum.[99]

Soil Nutrient Uptake

Elevated temperature and drought may reduce grain yield and starch content and increase protein content, while elevated levels of atmospheric CO_2 may reduce protein and micronutrient concentrations.[100] Soil warming could increase nutrient uptake by 100-300% by increasing nutrient diffusion and enlarging root surface area, although these benefits could be counteracted by reduced nutrient uptake due to inadequate levels of soil moisture.[101] In response to the complication of soil nutrient interactions as a result of climate change, St. Clair & Lynch (2010) suggest a three-prong adaptation strategy including (1) judicious application of fertilizers, (2) soil conservation to reduce erosion and maintain organic soil matter and (3) cultivation of crop species, genotypes and systems that make use of soil resources while simultaneously conserving soil fertility and nutrients.[102]

Changes in Agricultural Conditions under Climate Change

Temperature

Generally, where crops are already cultivated in climates near their maximum tolerable temperature, even small amounts of climate change can drastically reduce yields.[103] However, increased global temperatures may allow crops to grow at higher altitudes or in previously climactically sub-optimal conditions.[104]

Increases in temperatures will change and potentially increase the areas where sorghum and millet are grown in SSA. One model of climate change's impact on current crop-growing regions by Burke et al. (2009) indicates that by 2075, 97% of African sorghum-growing areas and 98% of millet-growing areas will experience higher temperatures.[105] Increased temperatures are predicted to increase the area in SSA that provides an optimum 30ºC climatic temperature for growing sorghum and especially millet.[106] Meanwhile, the area of SSA with growing season temperatures of 25ºC, the optimum temperature for corn and rice, is predicted to shrink.[107]

On the other hand, a study of global climate-crop yield relationships using statistical regression by Lobell and Field (2007) found that a 1ºC rise in temperature was associated with an 8% reduction in sorghum yield.[108] While the study was not able to offer results at the regional scale, it indicates that increased temperature has been associated with decreases in sorghum yields. Set in context with the previous discussion, the question becomes whether or not the increases in sorghum cultivation area are enough to offset the losses due to some areas moving above the optimal growing temperature range.

Water Availability

In general, rainfed crops are likely to be worse hit by climate change than irrigated crops because of the limited mechanisms for coping with precipitation scarcity and variability.[109] Declining rainfall generally reduces the soil's capacity to retain moisture, an effect that would be exacerbated in a warmer future climate, where greater evaporation is more likely.[110] Clay-rich soils are less sensitive to rainfall variation than sandy soils because of their better ability to retain moisture.[111] Pearl millet root systems penetrate up to 360cm deep into the soil, which renders the species more drought tolerant than other cereals.[112] Sorghum has a similarly well-branched and extensive root system.[113]

Changes in Timing of Water Stress

The planting schedules of crops are often dependent on the onset of the local rainy season. Farmers may attempt to adapt to changing rainfall patterns by altering crop planting dates and growing season timing, although the efficacy of such adaptations may vary by location.[114]

Rainfall patterns during critical stages of plant growth cycles may be more important than the total rainfall received during the growing season. For example, a study by Adejuwon (2005) of sorghum, millet and other crop yields in Nigeria found that 2/3 of the annual crop yield variability was explained by variability in the timing of rainfall during the growing season.[115] Other studies have found that post-flowering drought stress at the end of the growing season has the strongest influence on crop yields in both sorghum and millet.[116] Consistent with this result, Adejuwon found that crop yields of sorghum and millet were significantly correlated with the presence of September rainfall, likely because low September rainfall indicates an early cessation of the growing season prior to the completion of the plant's final, grain-filling growth cycle phase.[117] Likewise, Sivakumar (1992) examined seventy years of historical precipitation data and noted a positive correlation between pearl millet yields in Niger and August rainfall during pearl millet's reproductive grain-filling growth stage.[118]

Adejuwon concluded that the long growing season of sorghum in Nigeria renders it relatively susceptible to rainfall variability in comparison to other crops, although rice and maize's relatively lower susceptibility to rainfall variability in the study was likely due to existing irrigation infrastructure supporting those crops.[119] Changes in seasonal rainfall variability, paired with a rise in temperature, has been predicted to reduce pearl millet yields in Niger by 13% by 2025.[120]

Extreme Weather Events

A temperature increase of just 2ºC is predicted to increase the intensity and frequency of severe rainfall events, droughts, floods and heat waves.[121] The relationship between temperature and extreme weather events is non-linear. Therefore, even in the case of successful mitigation and subsequently small changes in temperature, extreme weather events will still likely increase substantially.[122]

Weeds, Pests and Pathogens

Sorghum and millet, as C_4 crops, may be at a disadvantage against prevalent C_3 parasitic weeds such as Striga. Because Striga and other C_3 weeds are comparatively inefficient at photosynthesis and carbon fixation, they will benefit more than C_4 crops as a result of the increased temperatures and the CO_2 abundance predicted by climate change scenarios.[123] Because Striga is a prevalent weed in SSA that is estimated to currently infest 2/3 of cereal fields in 17 SSA countries, beneficial growing conditions for Striga could have a large negative impact on crop yields.[124]

Pests and pathogens are also expected to affect crop yields in myriad and not-yet-understood ways. Mold and head bugs are pests which inhibit crop growth in the rainy season and cause physical and chemical changes to grains which reduce milling value and nutritional quality. [125] As climate change alters future seasonal precipitation patterns, the impacts of these pests could correspondingly change. Changes to rainfall patterns in SSA have also been observed to affect the migratory patterns of crop-devastating desert locusts.[126] The potential effects of climate change on plant diseases in SSA have not been as thoroughly studied as the effects of climate change on pests and weeds.[127]

Overall Impact of Climate Change on Sorghum and Millet Yields

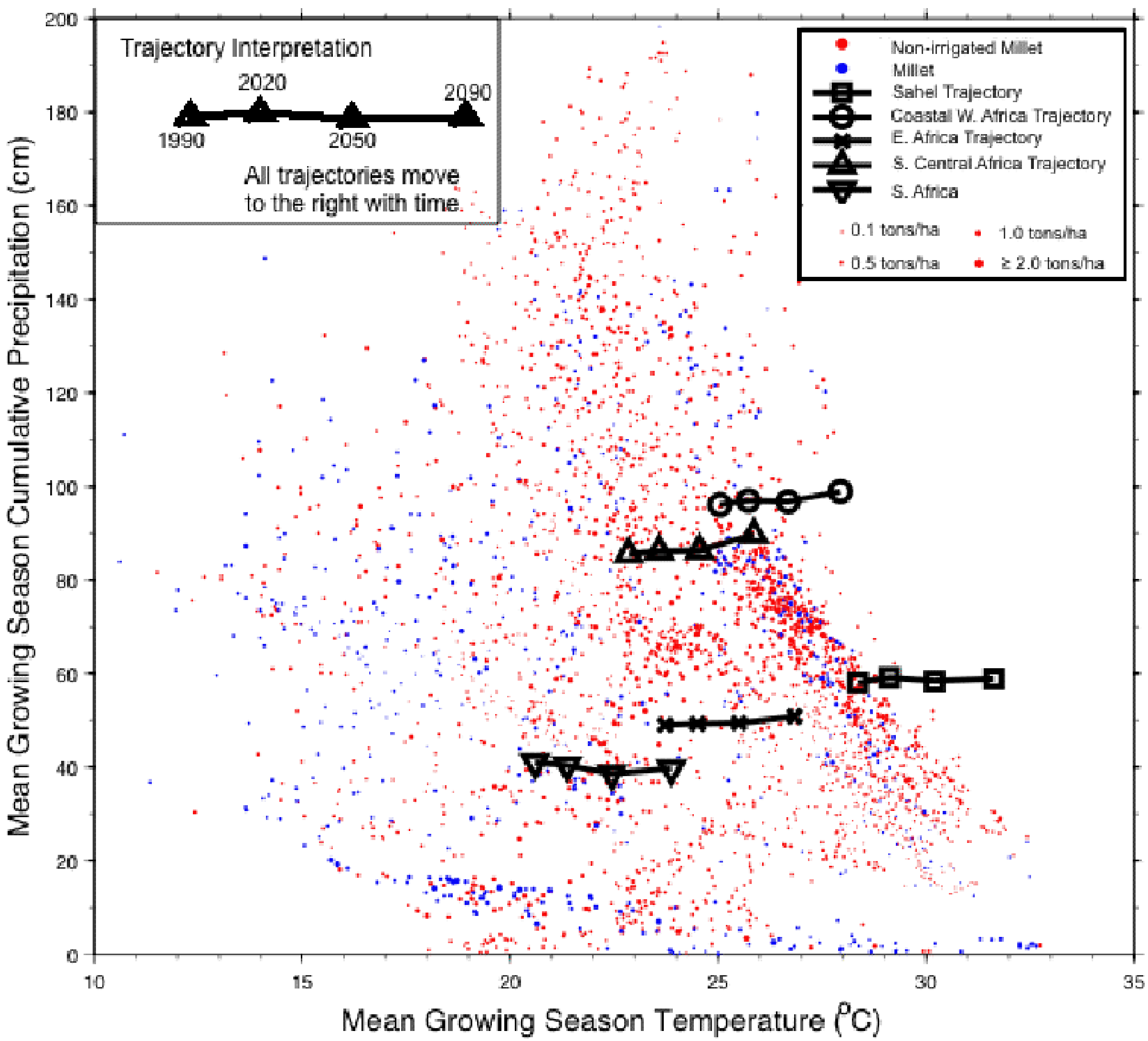
The results of the novel climate analysis we presented are consistent with previous studies, which find significant shifts in temperature and uncertain changes in precipitation.[128] Temperature shifts are a well-understood response to rising greenhouse gas concentrations and associated radiation and circulation changes. As noted earlier, precipitation trends were small over the 20th century and set amongst large year-to-year variability. Thus, despite pronounced uncertainty in the direction of precipitation changes, year-to-year changes will very likely overwhelm trends that do occur. Farmers in SSA are likely to draw from a strong set of experiences of previous precipitation variability and may already have adaptation methods in place to mitigate the impact of extreme short-term climate variability (i.e., prolonged drought). On the other hand, persistent temperature increases constantly change the baseline from which sorghum and millet farmers in SSA have to judge the present conditions. Increasing crop tolerance to drier soils would be a rational response to strong projections of future warming set against uncertainty in the direction and magnitude of precipitation changes.

Furthermore, the novel climate analysis offers some insight into the vulnerability of sorghum and millet. For example, our analysis of current production indicates that sorghum and millet are primarily grown at temperatures at the lower end of their range of optimal growing temperatures. Projected increases in temperature may increase plant fitness and yield in highland regions that are currently cooler than optimal conditions in the growing season. Notwithstanding, warming in the Sahel could decrease crop yields and suitable planting area, particularly during periods when naturally occurring multi-decadal fluctuations in temperature amplify the warming trend due to the radiative effects of human greenhouse gas emissions.

We also analyzed the size of the shift in mean temperature relative to historically observed variability. We have shown that by

2020, most regions will experience average conditions on par with the historically hottest growing-seasons. However, Figures 5 and 7 show that some regions may move into temperature regimes analogous to other portions of the subcontinent. Hence the implications of a completely novel climate will vary from region to region, depending largely on whether the climate is unprecedented across the accumulated record of SSA in its entirety. In many cases, current best practices from one region (e.g. East Africa) may be relevant for another in the future (e.g. Southern Africa). In the case of the Sahel, SSA's center of production of sorghum and millet, the climate is projected to move into territory unprecedented in historical observations over SSA.

Figure 7. Observed climate range for millet growing regions in SSA. Each point represents the mean (1976-2006) growing season temperature and accumulated rainfall at a 0.5° x 0.5° grid cell where any millet 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. Similar results were obtained for sorghum, which are shown in Appendix 4.



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)

The foregoing analysis is based on growing season average temperature, not on the month-to-month or day-to-day changes that drive plant growth on a scale relevant to farmers on the ground. Further research on the influence of temperature and precipitation on specific stages of plant growth would be necessary before attempting a similar analysis with climate projections with daily resolution.

Case Studies

The overall impact of climate change on sorghum and millet yields depends on the complex interplay of changes in plant physiology and agricultural conditions. To the extent that these combined effects have been studied by others, models typically look at average changes and exclude the effects of extreme events, variability, and agricultural pests, all of which are likely to increase.[129] In addition, research investigating the combined impacts of climate changes on weeds, pests and plant diseases is still insufficient.[130]

A number of analyses have examined sorghum and millet productivity in portions of SSA under various climate change scenarios. The overall effect is uncertain. Results presented have varied substantially, with sorghum and millet yield increases predicted in some studies, and yield decreases predicted in others. Certain climate change models have predicted that the Sahel, where the majority of sorghum and millet in SSA are grown, will become wetter, while other models show the Sahel becoming drier.[131] The divergent reported results are a product of variation across the literature as to which climactic forecast models the study utilized, which direct and indirect climactic impacts on plant growth were considered by the models, which grain cultivars were assessed, and which regions of SSA were analyzed.

Liu et al. (2008) modeled the effects of climate change on crop production and food insecurity across SSA. The study's model incorporated forecasted changes in temperature, precipitation and CO_2, but assumed that other variables potentially impacted by climate change would remain unchanged.[132] Their modeling showed predicted increases in millet yields across almost all regions in SSA by 7-27%, while sorghum production was predicted to remain nearly unchanged.[133] These results were best explained by predicted temperature increases across SSA to match millet's optimum growth temperature of 30ºC.[134]

Schlenker & Lobell (2010) also modeled the effects of climate change on sorghum, millet and other crop yields across SSA. Their study simulated crop responses under 16 future climate models by utilizing historical crop yield data matched with historical temperature data. However, the study assumed that no technological or growing-season adaptations to climate change would take place.[135] The study also did not incorporate the impacts of elevated CO_2 and did not assess variations in rainfall distribution patterns.[136] The median results among the 16 utilized climate models predicted a 17% yield reduction for both sorghum and millet by the middle of the 21st century.[137] While the aggregate impact of climate change on sorghum and millet yields across SSA may be negative, the authors showed evidence that changes in yield may still be positive or negative from country-to-country. This distinction is consistent with our own novel climate analysis, as well as the characterization of overall impact offered above.

Adejuwon (2006) modeled the potential effects of climate change in Nigeria, SSA's highest producer of both sorghum and millet.[138] His model considered the potential influences of increased atmospheric carbon dioxide and forecasted changes through 2099 in precipitation, humidity, temperature and solar radiation at six climactically distinct regional sites. He found that sorghum yields were predicted to increase steadily in two locations (including one high-altitude location), peak during the mid-21st century at three other locations, and alternately decline and increase over the next 100 years at the sixth location.[139] For millet, three locations in the more humid locations in the middle of the country were expected to experience consistently increasing yields, while one forested and one semi-arid location were expected to experience yield increases in the first half of the 21st century followed by declines in the second half of the century.[140] Across Nigeria during the first half of the 21st century, droughts were found to pose the greatest risk of an annual crop failure, although this conclusion was not specific to sorghum and millet. By contrast, during the second half of the century the greatest risk to food security was posed by temperatures above the optimum for crop growth.[141]

Butt et al. (2005) examined the impacts of climate change using two separate climate change projection models on crop yields in Mali. [142] Sorghum yields were predicted to decrease by up to 30% in drier and lower productivity regions under the harsher of the two climate projections modeled, and decrease by up to 18% in the more moderate climate projection modeled.[143]

In sum, complicated interactions between temperatures, precipitation, pests, crop growing locations, crop growing seasons and adaptive farming practices underlie divergent predictions of the effects on climate change on sorghum and millet crop yields. One the one hand, the drought and heat tolerant physiological attributes of sorghum and millet mean that these crops could be expected to experience more favorable growing conditions, and could even become the only viable grain-production option in certain portions of SSA. On the other hand, the variation in reported results across studies indicates uncertainty as to whether the beneficial effects of climate change on sorghum and millet yields will be outweighed by accompanying negative effects. It is clear, however, that context may be the overall arbiter of the perceived vulnerability to climate change. In other words, a varying picture of climate impact may be obtained whether the unit of analysis is an individual country, a large-scale region, or the collective area of SSA. While the SSA-wide impact of warming on sorghum and millet appears to be negative in terms of yields, we have suggested that warming could be beneficial in some locations (e.g. highland regions) and detrimental in others (e.g. semi-arid locations); case studies appear to confirm this on a country-by-country and SSA-wide basis.

Pillar 3: Current Resources Dedicated to Sorghum and Millet in SSA

A crop or crop system's resilience to the risks associated with climate change depends on adaptation and mitigation strategies from the international level all the way down to the farm-level.[144] The constraints to sorghum and millet production in SSA include climate-related factors as well as limited farmer inputs, lack of infrastructure, lack of seed production, and consumer preferences for other grains. Some existing inexpensive adaptation strategies, such as shifting planting dates or switching to existing and locally available crop varieties, have the potential to help populations cope with climate change. [145] The largest benefits, however, will likely come from more costly adaptation measures that address additional constraints, including the development of new crop varieties.[146]

Research & Development

Full time equivalent researchers (FTE) serve as a proxy measure for the institutional resources devoted to sorghum and millet research and development. The Agricultural Science and Technology Indicators (ASTI) initiative surveyed government agencies, NGOs, and private sector researchers in 26 countries in SSA. They identified nearly 3600 full-time equivalent crop researchers, of which 188.9 (5.2%) were focused on sorghum and 100.1 (2.8%) were focused on millet.[147] Among resources dedicated to cereals, FTE sorghum researchers comprise 17.9% and millet researchers 9.5% of all cereal researchers.[148] Additional information is available in EPAR brief 54. The top five sorghum producing countries (Nigeria, Sudan, Ethiopia, Burkina Faso and Niger) and the top 5 millet producing countries (Nigeria, Niger, Mali, Burkina Faso and Sudan) account for 49.1% and 49.6% of these resources, respectively.[149]

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 BMGF), the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is the primary agency focused on sorghum and millet research.[150] The CGIAR also funds some sorghum and millet research through the Generation Challenge Programme, a multi-crop and multi-center plant breeding and improvement effort. Other research organizations which have contributed to sorghum and millet research are the International Millet and Sorghum Collaborative Research Support Program (INTSORMIL) based out of the University of Nebraska, and the West and Central Africa Millet Research Network (ROCAFREMI).[151]

National Adaptation Programmes of Action

The current capacity of human systems in Africa to adapt to climate change is very low due to limited economic and technological resources.[152] When feasible, farmers may switch varieties, cropping patterns, or begin irrigating their land in response to climate change.[153] Some adaptations to changing climate are already underway; for example, a majority of farmers in drought-prone regions of Chad and Cameroon have begun utilizing varieties of sorghum with shorter growing seasons.[154] Studies which examine the effects of climate change on crop yields without examining small-scale adaptation responses by farmers might overestimate negative impacts on yields.[155] However, the large-scale climate change adaptation projects underway have been mainly donor-driven; many developing countries may perceive more urgent investment priorities than adaptations to mitigate the impacts of future climate change.[156]

As part of the Least Developed Countries (LDC) Work Programme, 31 SSA countries have submitted National Adaptation Programmes of Action (NAPAs) to the United Nations Framework Convention on Climate Change (UNFCCC) delineating their strategies to adapt to climate change. NAPAs make use of existing information and focus on the urgent and immediate needs that, if left unaddressed, could increase vulnerability or costs at a later stage.[157]

Common foci across the NAPAs of many SSA countries include increasing irrigation, developing and disseminating improved varieties, including increasing production of drought-tolerant crops with short growing cycles, and diversifying overall cereal consumption. In the NAPAs of many countries, these strategies are not linked to specific crops, but for the 10 countries listed in Table 6, the above adaptation strategies explicitly include sorghum and millet in proposed projects. Notably, three of the countries (Burundi, Guinea & Malawi) that include sorghum or millet in their proposed NAPA projects have current per-capita daily consumption levels of both sorghum and millet below 20 kilocalories.[158] NAPAs are only proposed plans, however, and are not accompanied by any committed funding. Funding for implementation has been very limited to date, despite submitted NAPAs being ready for the implementation phase.[159]

Table 6: NAPA Strategies for Sorghum and Millet Production

Adaptation Strategy	**Countries**
Increase irrigation for sorghum and millet cultivation	Eritria, Burkina Faso (millet only)
Increase development and dissemination of improved varieties	Burkina Faso, Mali, Burundi (sorghum only), Lesotho (sorghum only), Guinea (millet only)
Switch to drought-tolerant crops with short growing seasons	Tanzania, Mozambique (millet only), Burundi (sorghum only)
Diversification of grains consumed	Malawi, Guinea-Bissau (sorghum only)

Source: National Adaptation Programmes of Action[160]

Conclusion

In SSA, sorghum accounts for 15.7% of total cereal production, provides at least 300 daily per-capita kilocalories for 236 million people and receives 17.9% of all FTE cereal researchers. Millet accounts for 10.8% of total cereal production, provides at least 300 daily per-capita kilocalories for 58 million people, and receives 9.5% of all FTE cereal researchers. Because sorghum and millet are more suitable than other cereals for drought-prone and high-temperature environments, they could play an increasingly important role in SSA agriculture, even as the growing conditions in current sorghum and millet producing countries are expected to change in potentially unfavorable ways. However, the predicted outcomes differ across models of climatic effects on sorghum and millet production, and it remains unclear whether the net impact of climate change will be positive or negative in terms of SSA's sorghum and millet production. [161,162,163,164]

Farming and food systems in SSA have proven highly adaptable in the past, suggesting the capacity to further adjust in the face of climate change.[165] Several SSA countries include adaptation strategies to improve or increase sorghum and millet cultivation in their National Adaptation Programme of Action (NAPA). The tolerance of sorghum and millet to hot and dry conditions could render these crops the most viable future cereal production option in some areas where other cereals are currently grown. Current development resources devoted to sorghum and millet may understate the potential of these crops to become increasingly important in SSA.

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

	Millet Production	Millet Production as % of Total Cereal Production	Sorghum Production	Sorghum Production as % of Total Cereal Production
Angola	79345	11.26%	0	0.00%
Benin	35303	3.05%	117322	10.13%
Botswana	125	0.31%	25290	63.52%
Burkina Faso	966016	31.07%	1507162	48.48%
Burundi	11500	3.95%	85565	29.36%
Cameroon	60000	3.12%	600000	31.16%
Cape Verde	0	0.00%	0	0.00%
Central African Republic	10000	4.23%	49199	20.80%
Chad	495486	25.13%	576571	29.24%
Comoros	0	0.00%	0	0.00%
Congo	8500	42.50%	0	0.00%
Côte d'Ivoire	57000	4.58%	34379	2.76%
Democratic Republic of the Congo	37530	2.46%	6230	0.41%
Djibouti	0	0.00%	0	0.00%
Equatorial Guinea	0	0.00%	0	0.00%
Eritrea	63254	13.69%	302515	65.48%
Ethiopia	397002	3.35%	2173599	18.35%
Gabon	0	0.00%	0	0.00%
Gambia	89186	59.24%	17951	11.92%
Ghana	113040	6.76%	154830	9.26%
Guinea	323000	12.42%	37800	1.45%
Guinea-Bissau	26169	14.23%	14633	7.96%
Kenya	119599	3.31%	147365	4.08%
Lesotho	0	0.00%	7837	10.78%
Liberia	0	0.00%	0	0.00%
Madagascar	0	0.00%	1200	0.04%
Malawi	32251	0.94%	63698	1.85%
Mali	1175107	30.24%	900791	23.18%
Mauritania	1601	0.87%	79674	43.42%
Mauritius	0	0.00%	0	0.00%
Mozambique	25213	1.73%	169543	11.66%
Namibia	60000	41.96%	10000	6.99%
Niger	2781928	72.09%	975223	25.27%
Nigeria	8090000	29.77%	9058000	33.34%
Rwanda	4000	1.14%	164000	46.59%
Sao Tome and Principe	0	0.00%	0	0.00%
Senegal	318822	41.29%	100704	13.04%
Seychelles	0	0.00%	0	0.00%
Sierra Leone	25000	2.27%	23000	2.09%
Somalia	0	0.00%	80000	40.82%
South Africa	12000	0.13%	176000	1.85%
Sudan	796000	11.90%	4999000	74.71%

Swaziland	0	0.00%	600	2.20%
Togo	45456	5.18%	210298	23.96%
Uganda	732000	27.82%	456000	17.33%
United Republic of Tanzania	219000	3.52%	900000	14.46%
Zambia	21707	1.41%	12800	0.83%
Zimbabwe	43800	3.44%	76200	5.98%

Source: FAOSTAT (2007 data);

Appendix 2. Comparison of Production to Net International Trade of Sorghum and Millet (metric tonnes)

	Millet Production	Millet Net Trade	Sorghum Production	Sorghum Net Trade
Angola	79345	203	0	-200
Benin	35303	-67	117322	1235
Botswana	125	-17	25290	-21959
Burkina Faso	966016	-583	1507162	5994
Burundi	11500	*	85565	*
Cameroon	60000	0	600000	*
Cape Verde	0	*	0	*
Central African Republic	10000	*	49199	*
Chad	495486	-3970	576571	-38174
Comoros	0	*	0	*
Congo	8500	*	0	*
Côte d'Ivoire	57000	60	34379	591
Democratic Republic of the Congo	37530	*	6230	-159
Djibouti	0	*	0	*
Equatorial Guinea	0	*	0	-35715
Eritrea	63254	310	302515	*
Ethiopia	397002	92	2173599	-14066
Gabon	0	*	0	*
Gambia	89186	0	17951	*
Ghana	113040	-41	154830	-3690
Guinea	323000	*	37800	*
Guinea-Bissau	26169	*	14633	*
Kenya	119599	-38446	147365	314
Lesotho	0	*	7837	-3000
Liberia	0	*	0	*
Madagascar	0	*	1200	-4980
Malawi	32251	0	63698	-2
Mali	1175107	868	900791	106
Mauritania	1601	*	79674	*
Mauritius	0	-144	0	*
Mozambique	25213	-1526	169543	-310
Namibia	60000	-6000	10000	-45
Niger	2781928	-1188	975223	-34107

Nigeria	8090000	529	9058000	378
Rwanda	4000	*	164000	-1647
Sao Tome and Principe	0	*	0	*
Senegal	318822	8	100704	-20
Seychelles	0	*	0	*
Sierra Leone	25000	*	23000	*
Somalia	0	*	80000	-85314
South Africa	12000	-8544	176000	-23565
Sudan	796000	5581	4999000	-85818
Swaziland	0	-10	600	-2945
Togo	45456	0	210298	-1
Uganda	732000	1028	456000	-77449
United Republic of Tanzania	219000	999	900000	37
Zambia	21707	29	12800	-6156
Zimbabwe	43800	-231	76200	-26202

Source: FAOSTAT (2007 data); *Indicates lack of import or export data in FAOSTAT.

Appendix 3. Climatological analysis: Data and methodology

As indicated in Pillar 2, historical temperature and precipitation data for the climatological analyses originate from the University of East Anglia (UEA) 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 previously available 5º latitude by 5º longitude datasets. CRU TS 3.0 incorporates monthly-mean observations of six climate variables including temperature and precipitation for stations around the world. Only observations for sub-Saharan Africa were used for the analyses in Pillar 2. Although there is a paucity of data over SSA compared to developed countries, nearly complete spatial coverage is available.[166] Furthermore, strong statistics may be obtained for the complete 20th century and the most recent two or three decades.

Future projections utilized in Pillar 2 are based on model output from 23 global climate models used for the most recent IPCC assessment report, the fourth such publication. These numerical 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 (i.e., operate on spatial scales smaller than the models grid spacing), such as 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.

The most sophisticated global climate models can produce robust projections with a resolution of 250 by 250 kilometers.[167,168] At this level of detail, only about 500 grid cells, each approximately the size of Sierra Leone, represent all of SSA. While this scale is sufficient to describe continental and regional changes, it is difficult to describe changes at the country level or below. Novel statistical techniques, broadly referred to as downscaling, can produce higher resolution climate projections.[169,170,171]

The five sorghum and millet-growing regions were defined based on an objective assessment of SSA areas where sorghum and millet are grown and a subjective grouping of grid cells into five 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.[172] Historical distributions are defined by an area-average of the grid points that make up each representative growing region. To provide relevance for current agronomic conditions, the mean of the distribution is calculated from the most recent thirty years in the record, 1976–2006. In order to give a complete depiction of historical variability, the shape of these historical distributions is based on variability over the entire 20^{th} century record (see *Table 4*). Mean and standard deviation are calculated only for growing season months and only for those grid cells in which sorghum or millet is grown.

The analysis of projected climate change uses a methodology similar to previous studies,[173] quantifying the percentage of overlap between projected distributions of a particular climatological variable and a distribution of its historical observations. Our analysis is performed for growing-season average temperature and extended to growing-season accumulated precipitation.

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, the first with means centered at either 2020, 2050, or 2090 in simulations driven by emissions consistent with current development trends (SRES A1B) and the second with a mean centered at 1990 in each model's Climate of the 20^{th} century simulation (20C3M). Calculating a future shift relative to each model's 20^{th} century simulation lessens the chance that model biases will influence the results. Most known model biases do not change with increasing time. For example, due to the fact that temperature decreases with height in the atmosphere, failure of a model to resolve high (low) topography can cause a warm (cold) bias relative to observations. Model topography does not change with time, thus this bias should not either.

The historical distribution of variance constrains the corresponding variance of future distributions, based on the assumption that variability has not changed significantly over the 20^{th} century and the fact 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. A simple assessment of changes in variability between the first and second halves of the 20^{th} century indicates the validity of the constant variability assumption for strongly temperature and modestly for precipitation. The analysis is based on growing seasons as defined in *Table 4*, and assumes no shift in growing-season dates or changes in farming strategies (such as double cropping or altering spatial distributions of crop planting).

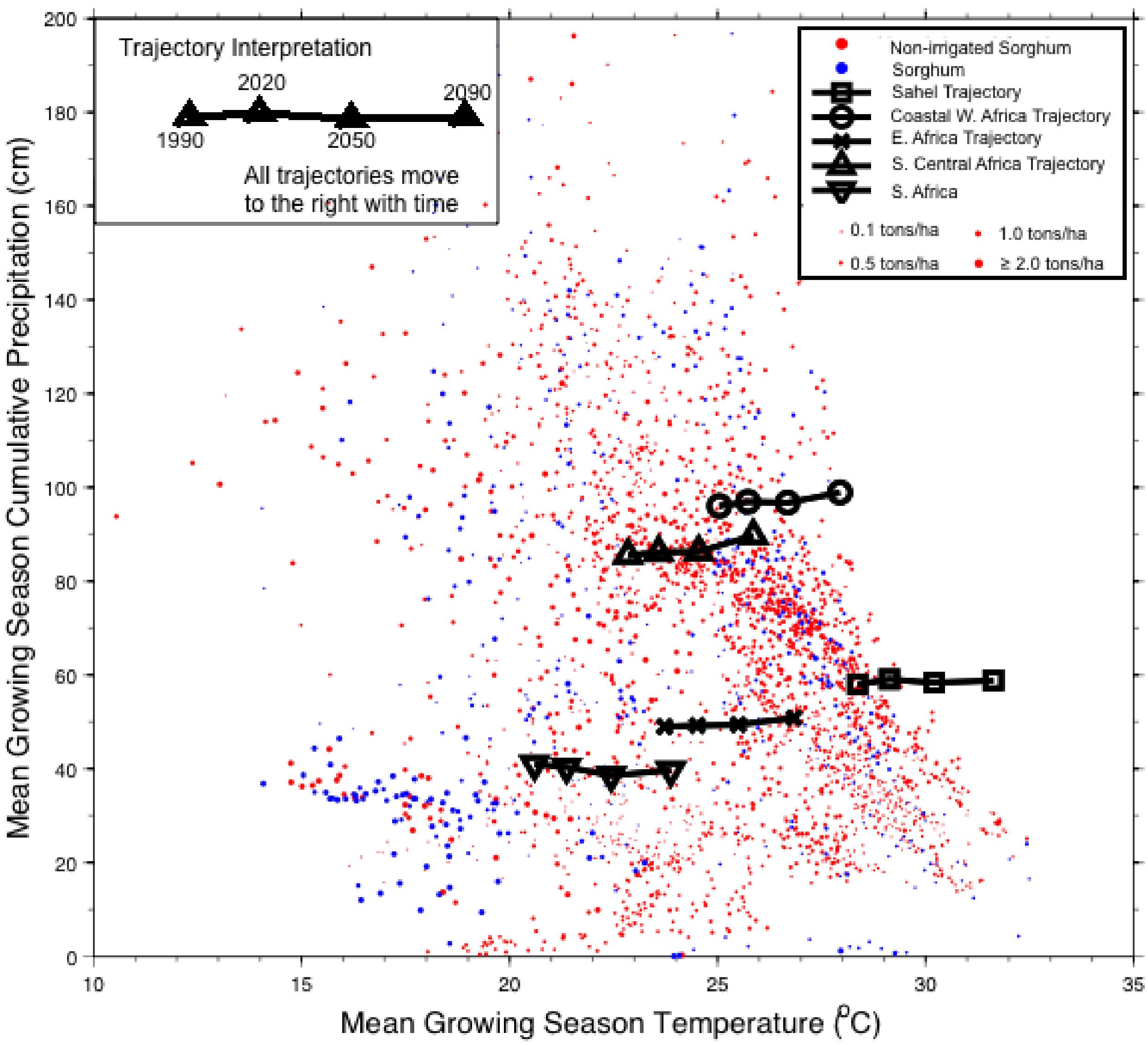
Appendix 4. Climatological analysis: Background and historical context

At the start of the 21^{st} century, agriculture across SSA covers a diverse set of climates in terms of growing season average temperature and accumulated precipitation. Figure A1 shows the range of climates wherein sorghum is grown. A similar figure for millet is shown in the main text, Figure 7. The symbols indicating the trajectory of change in each of the five representative growing regions all move to the right, emphasizing warming over the 20^{th} century. As was discussed in the main text, this future change can be better understood in the context of historical variability.

<u>Temperature</u>

Consistent with the larger climate system, Africa's average growing season temperature is warmer today than it was 100 years ago (Figure A2). While farmers on the ground must cope with the reality of a warmer climate, agronomists may benefit from analyzing the unique trajectories of temperature and precipitation. For example, growing season average temperature in the Sahel has warmed slightly more than 0.5ºC 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 1920s and 1950s. Southern Africa also exhibits some multi-decadal variability in temperature, but less so than the Sahel. Growing-season average temperature anomalies over South Central Africa and East Africa were fairly flat throughout the first half of the 20^{th} century; in contrast, both exhibit a pronounced positive trend in the second half of the 20^{th} century. In fact, a warming trend is evident in all five time series in the period since the mid-1960s.

Figure A1. Observed climate range for sorghum growing regions in SSA. Each point represents the mean (1976-2006) growing season temperature and accumulated rainfall at a $0.5^o \times 0.5^o$ grid cell where any sorghum 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. Similar results were obtained for millet, which are shown in the main text, Figure 7.*



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).

Precipitation

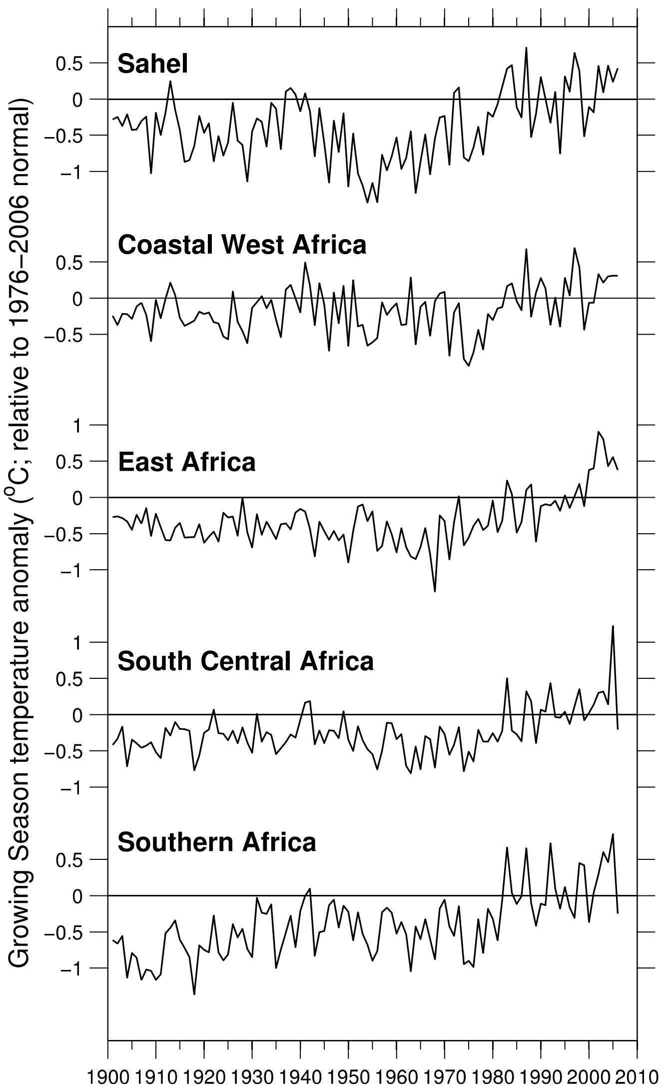
Of the five regions examined, only the Sahel has a time series that exhibits a statistically significant precipitation trends over the 20th century. In addition to depicting variations in area-averaged precipitation in the five SSA regions, Figure A3 shows that the Sahel is 25–30% drier during the growing season today than it was 75 to 100 years ago. Combined with increased temperature, drought conditions have persisted since the late 1970s. Precipitation has increased slowly since about 1979, contributing to some improvement, however growing season total precipitation remains below the long term Sahelian average. With the exception of the Sahel and Southern Africa, precipitation variations over the 20th century are far less dramatic over Africa than elsewhere around the globe. The timescale of variability is noticeably short in all but one of the time series. Whereas variability in Southern

Africa shows dramatic year-to-year and decade-to-decade variability in growing season accumulated precipitation, slower one-to-two decade variations are evident in the the Sahel time-series.

Looking forward, the IPCC Fourth assessment report has characterized several robust changes related to precipitation.[174] The IPCC considers several specific changes in rainfall patters to be likely: increased mean annual rainfall in tropical and eastern Africa, increased summer rainfall in equatorial regions (north of 10ºS and east of 20ºE), decreased winter rainfall in southern Africa and decreased summer rainfall in regions south of 10ºS. The onset and length of the rainy season are not projected to change in response to anthropogenic global warming.[175]

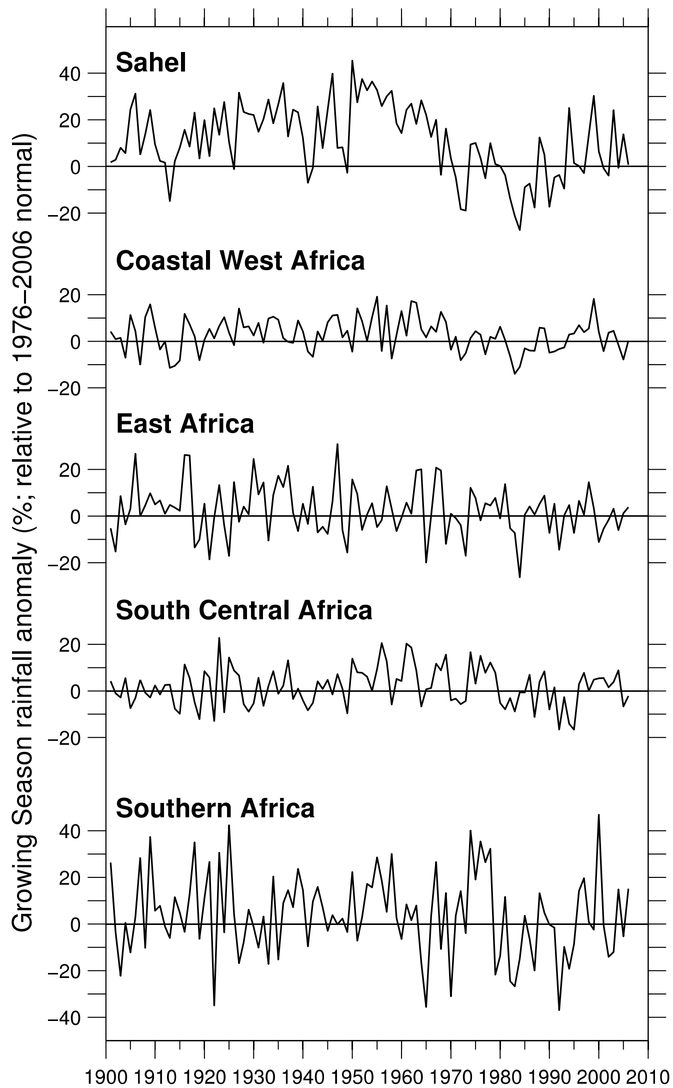
Notwithstanding agreement on the direction of precipitation changes for the aforementioned regions and seasons, some models project a drying of the western Sahel, while others project increased precipitation more consistent with the strong multi-decadal variability historically observed in that region.[176] This notion is consistent with our characterization of precipitation changes as small and relatively uncertain when compared to temperature changes.

Figure A2: Growing season average temperature anomalies relative to recently (1976-2006) observed temperatures. Five sorghum and millet growing regions shown, corresponding to Figure 3 and Table 4.



Source: UEA CRU TS 3.0

Figure A3: Growing season total rainfall anomalies expressed as a percentage relative to recently (1976-2006) observed growing-season accumulated precipitation. Five sorghum and millet growing regions shown, as in Figure 4.



Source: UEA CRU TS 3.0

References

Adejuwon, J. (2006). Food Crop Production in Nigeria II: Potential Effects of Climate Change. *Climate Research*, *32*(4), 229-245. doi: 10.3354/cr0322229

Adejuwon, J. (2005). Food Crop Production in Nigeria I: Present Effects of Climate Variability. *Climate Research*, *30*, 53-60. doi: 10.3354/cr030053.

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

Akintayo, I. and Sedgo, J. (ed) (2001) Towards Sustainable Sorghum Production, Utilization, and Commercialization in West and Central Africa: Proceedings of a Tehcnical Workshop of the West and Central Africa Sorghum Research Network, 19-22 April 1999, Lome, Togo. Retrieved from test1.icrisat.org/uploads/presentations/07032003212942CPE131_p1.pdf

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

Bidinger, F.R., Yadav, O.P. & Weltzien Rattunde, E. (2008). Genetic Improvement of Pearl Millet for the Arid Zone of Northwestern India: Lessons from Two Decades of Collaborative ICRISAT-ICAR Research. *Experimental Agriculture*, *45*(01),107. doi: 10.1017/S00144790800807059

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.

Butt, T, McCarl, B. Angerer, J., Dyke, P., & Stuth, J. (2005). The Economic and Food Security Implications of Climate Change in Mali. *Climactic Change, 68*(3), 355-378. Doi:10.1007/s10584-00506014-0.

Camara, Y Bantilan, M. & Ndjeunga, J. (2006). Impacts of Sorghum and Millet Research in West and Central Africa (WCA): A Synthesis and Lessons Learnt. *ICRISAT Open Access Journal, 2*(1).

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.

Chinpashi, A., Chanda, R., & Totolo, O. (2003). Vulnerability Assessment of the Maize and Sorghum Crops to Climate Change in Botswana. *Climactic Change, 61*(3), 339-360 doi: 10.1023/B:CLIM.000004551.55872.eb.

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.

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 (2010a). *ECOCROP Database*. Retrieved from http://ecocrop.fao.org/ecocrop/srv/en/home

FAO. (2010b). *Grassland Species Profiles*. Retrieved from http://www.fao.org/ag/agp/agpc/doc/gbase/Default.htm

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

FAO. (1995). *Sorghum and Millets in Human Nutrition.* Retrieved from http://www.fao.org/docrep/T0818E/T0818E00.htm#Contents

FAO & ICRISAT (1996). *The World Sorghum and Millet Economies: Facts, Trends and Outlook*. Retrieved from http://www.fao.org/docrep/w1808e/w1808e00.htm#Contents

Gregory, P.J., Johnson, S., Newton, A., & Ingraham, J. (2009) Integrating Pests and Pathogens Into the Climate Change/Food Security Debate. *Journal of Experimental Botany, 60*(10), 2827-38. Doi: 10.1093/jxb/erp080.

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.

Horie, T., Baker, J. T., Nakagawa, H., Matsui, T. & Kim, H. Y. (2000). *Crop ecosystem responses to climatic change: Sorghum and millet.* In Climate Change and Global Crop Productivity, Reddy, K. R. & Hodges, H. F. (Eds). Wallingford, U.K.: CAB International, 81-106.

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.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) (2010). *ICRISAT Mandate Crops.* Retrieved from http://www.icrisat.org/Icrisat-crops.htm

Kurukulasuriya, P., & Rosenthal, S. (2003). Climate Change and Agriculture: A Review of Impacts and Adaptations. *World Bank Climate Change Series, 91*. Retrieved from www.c-ciarn.uoguelph.ca/updates_archived/World_Bank_Paper.pdf

Larsson, H. (1996). Relationships Between Rainfall and Sorghum, Millet and Sesame in the Kassala Province, Eastern Sudan. *Journal of Arid Environments 32*, 211-223. Doi: 10.1006/jare.1996.0018

Liu, J., Fritz, S., Vanwesenbeeck, C., Fuchs, M., You, L., Obersteiner,M., et al. (2008). A Spatially Explicit Assessment of Current and Future Hotspots of Hunger in Sub-Saharan Africa in the Context of Global Change. *Global and Planetary Change, 64*(3-4), 222-235. Doi: 10.1016/j.gloplacha.2008.09.007

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.

Lobell, D.B. and C. B. Field. (2007) Global scale climate–crop yield relationships and the impacts of recent warming. *Environ. Res. Lett. 2* 014002 .7 doi:10.1088/1748-9326/2/1/014002.

Mertz, O., Halsnaes, K., Olesen, J., & Rasmussen, K. (2009) Adaptation to Climate Change in Developing Countries. *Environmental Management, 43*(5), 743-52. Doi:10.1007/s00267-008-9259-3

Mertz, O., Mbow, C., Reenberg, A. & Diouf, A. (2009) Farmers' Perceptions of Climate Change and Agricultural Adaptation Strategies in Rural Sahel. *Environmental Management, 43*(5), 804-16. Doi:10.1007/s00267-008-9197-0.

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.

Mohamed, A.B., Van Diuvenbooden, N. & Abdoussallam, S., (2002). Impact of Climate Change on Agricultural Production in the Sahel- Part 1. Methodological Approach and Case Study for Millet in Niger. *Climactic Change, 54* 327-348

Muchow, R. (1989). Comparative Productivity of Maize, Sorghum and Pearl Millet in a Semi-Arid Tropical Environment II: Effect of Water Deficits. *Field Crops Research, 20.* 207-219

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

Parry, M., Rosenzweig, C., & Livermore, M. (2005). Climate Change, Global Food Supply and Risk of Hunger. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 360* (1463), 2125-38. Doi:10.1098/rstb.2005.1751.

Passioura, J. & Angus, J. (2010) Improving Productivity of Crops in Water-Limited Environments. *Advances in Agronomy, 106* DOI: 10.1016/S0065-2113(10)06002-5

Prasad, V., Boote, K., & Allen Jr. L.H. (2006). Adverse High Temperature Effects on Pollen Viability, Seed-Set, Seed Yield and Harvest Index of Grain-Sorghum [Sorghum bicolor(L.) Moench] are More Severe at Elevated Carbon Dioxide Due to Higher Tissue Temperatures. *Agricultural & Forest Meteorology 139(*3-4) 237-251. Doi: 10.1016/j.agrformet.2006.07.003.

Rai, K., Murty, D., Andrews, D., Bramel-Cox, P (1999). Genetic Enhancement of Pearl Millet and Sorghum for the Semi-Arid Tropics of Asia and Africa. *Genome, 42* (4). 617-628. Doi: 10.1139/gen-42-4-617.

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.

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.*

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

Schlenker, W., & Lobell, D.B. (2010). Robust Negative Impacts of Climate Change on African Agriculture. *Environmental Research Letters, 5*(1) 014010. Doi: 10.1088/1748-9326/5/1/014010

Seo, N, Mendelsohn, P., Kurukulasuriya, P., Dinar, A. & Hassan, R. (2008) Differential Adaptation Strategies to Climate Change in African Cropland by Agro-Ecological Zones. *World Bank Policy Research Working Paper 4600*. Retrieved from:

http://www-wds.worldbank.org/servlet/WDSContentServer/WDSP/IB/2008/04/17/000158349_20080417104850/Rendered/PDF/WPS4600.pdf

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

St. Clair, S., & Lynch, Jonathan. (2010) The Opening of Pandora's Box: Climate Change Impacts on Soil Fertility and Crop Nutrition in Developing Countries. *Plant Soil, 335* (1-2) 101-115. Doi: 10.1007/s11104-010-0328-z.

Stige, L., Stave, J., Chan, K., Ciannelli, L., Pettorelli, N., Glantz., M., Herren, H & Stenseth, N. (2006). The Effect of Climate Variation on Agro-Pastoral Production in Africa. *Proceedings of the National Academy of Sciences of the United States of America,103*(9), 2049-53. Doi: 10.1073/pnas.06000057103.

Tingem, M, Rivington, M, & Bellocchi, G. (2009). Adaptation Assessments for Crop Production in Response to Climate Change in Cameroon. Agronomy for Sustainable Development, 29, 247-256. Doi:10.1051/agro.

Wassmann, R., & Dobermann, A. (2007). Climate Change Adaptation through Sorghum and millet Production in Regions with High Poverty Levels. *SAT eJournal, ICRISAT*, *4*(1), 1-24. Retrieved from http://dx.doi.org/10.3914/ICRISAT.0095

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.

Yadav, O. (2010). Drought Response of Pearl Millet Landrace-Based Populations and their Crosses with Elite Composites. *Field Crops Research, 118* (1). 51-56. Doi: 10.1016/j.fcr.2010.04.005

Zaongo, C., Wendt, C., Lascano, R. & Juo, A. (1997). Interactions of Water, Mulch and Nitrogen on Sorghum in Niger. *Plant and Soil, 197*. 119-126.

Endnotes

[1] World Bank, 2009b, p. 146

[2] St. Clair & Lynch, 2010, p. 103

[3] Schmidhuber & Tubiello, 2007, p. 19705

[4] FAO, 2010a

[5] FAO, 1995

[6] Yadav, 2010, p. 51

[7] Burke et al., 2009, p. 324

[8] FAOSTAT

[9] ICRISAT, 2010

[10] FAO, 1995
[11] FAOSTAT, author's calculations
[12] FAO, 1995
[13] FAO, 1995
[14] FAO, 1995
[15] FAO & ICRISAT, 1996
[16] Mohamed et al.,2002, p. 329
[17] Muchow, 1989, p. 208
[18] FAO & ICRISAT, 1996
[19] Chinpashi et al., 2003, p.341
[20] Zaongo et al.,1999, p. 119
[21] FAOSTAT, Author's calculations
[22] FAOSTAT, author's calculations
[23] FAOSTAT, author's calculations
[24] FAOSTAT, 2001 data
[25] FAO, 1995
[26] FAO& ICRISAT, 1996
[27] FAOSTAT, Author's calculations
[28] FAOSTAT, Author's calculations
[29] FAO & ICRISAT, 1996
[30] FAO & ICRISAT, 1996
[31] FAO, 1995
[32] FAO & ICRISAT, 1996
[33] FAOSTAT, Author's calculations
[34] FAOSTAT, 2007, author's calculations
[35] FAOSTAT, Author's calculations
[36] FAOSTAT, Author's calculations
[37] FAOSTAT, Author's calculations
[38] FAO, 1995.
[39] FAO & ICRISAT, 1996
[40] Rai et al., 1999, p. 617
[41] FAO, 1995.
[42] FAO, 1995.
[43] FAO & ICRISAT, 1996
[44] FAO & ICRISAT, 1996
[45] ICRISAT, 2010
[46] FAO, 2010a
[47] Bidinger et al., 2008, p. 110
[48] Yadav et al., 2010, p. 51
[49] Mertz et al., 2009b, p. 806
[50] FAO & ICRISAT, 1996
[51] Bidinger et al., 2008, p. 109
[52] Rai et al., 1999, p. 625

[53] Yadav et al., 2010, p. 51

[54] Camara et al., 2006, p. 11

[55] FAO & ICRISAT, 1996

[56] Bidinger et al., 2008, p. 113

[57] ICRISAT, 2001, p. 44

[58] World Bank, 2009a, p. 9

[59] FAO, 2003, p. 78

[60] Christensen, 2007

[61] Ruosteenoja, 2003

[62] Randall et al., 2007, p.611

[63] Burke et al., 2009

[64] Solomon et al., 2008

[65] Burke et al. 2009

[66] Leff et al., 2004

[67] Mitchell & Jones, 2005

[68] Burke et al., 2009

[69] IPCC AR4, Figure SPM.7

[70] Christensen et al., 2007

[71] FAO, 2010b

[72] FAO, 2010b

[73] Liu et al., 2008, p. 228

[74] Liu et al., 2008, p. 228

[75] Prasad et al., 2006, p. 238

[76] Prasad et al., 2006, p. 238

[77] Prasad et al., 2006, p. 247

[78] Prasad et al, 2006, p. 248

[79] FAO, 2010b

[80] Passioura & Angus, 2010, p. 55

[81] Challinor et al., 2006, p. 382

[82] Adejuwon, 2005, p. 59

[83] Larsson, 1996, p. 213

[84] Monfreda et al., 2008

[85] Siebert et al., 2007

[86] Rosenzweig & Hillel, 1998, p. 89

[87] G & Dobermann, 2007, p. 2

[88] FAO, 2003, p. 78

[89] Horie et al., 2000, p. 87

[90] Adejuwon, 2006, p. 243

[91] Adejuwon, 2006, p. 243

[92] Prasad et al., 2006, p. 238

[93] Chinpashi et al., 2003, p. 354

[94] Schlenker & Lobell, 2010, p. 6

[95] Rosenzweig & Hillel, 1998, p. 96

[96] FAO, 2003, p. 79

[97] Horie et al., 2000, p. 90

[98] Horie et al., 2000, p. 90
[99] Conley et al., 2001, p. 411
[100] St. Clair & Lynch, 2010, p.105
[101] St. Clair & Lynch, 2010, p.107
[102] St. Clair & Lynch, 2010, p.108
[103] Parry et al., 2005, p. 2125
[104] Rosenzweig & Hillel, 1998, p. 89
[105] Burke et al., 2009, p. 320
[106] Liu et al., 2008, p. 228
[107] Liu et al., 2008, p. 228
[108] Lobell & Field, 2007
[109] Wassmann & Dobermann, 2007, p. 2
[110] Hope, 2009, p. 457
[111] Larsson, 1996, p. 221
[112] FAO, 2010b
[113] Larsson, 1996, p. 214
[114] Tingem et al., 2009
[115] Adejuwon, 2005, p. 56-57
[116] Rai et al., 1999, p. 620
[117] Adejuwon, 2005, p. 56-57
[118] Sivakumar (1992) cited in Kurakulasuriya et al., 2003, p. 13
[119] Adejuwon, 2005, p. 59
[120] Kurakulasuriya et al., 2003, p. 22
[121] World Bank, 2009a, p. 14
[122] Rosenzweig & Hillel, 1998, p. 99
[123] Adejuwon, 2006, p. 243
[124] Akintayo & Sedgo, 2001, p. 101
[125] Akintayo & Sedgo, 2001, p. 42
[126] Gregory et al., 2009, p. 2830
[127] Charaborty et al., 1999, p. 320
[128] Lobell & Burke, 2008
[129] World Bank, 2009b, p. 146
[130] Easterling et al., 2007, p. 283
[131] Challinor et al., 2007, p. 383
[132] Liu et al., 2008, p. 224
[133] Liu et al., 2008, p. 228
[134] Liu et al., 2008, p. 228
[135] Schlenker & Lobell, 2010, p. 2
[136] Schlenker & Lobell, 2010, p. 6
[137] Schlenker & Lobell, 2010, p. 5
[138] Adejuwon 2006, p. 229
[139] Adejuwon 2006, p. 239
[140] Adejuwon 2006, p. 240

[141] Adejuwon 2006, p. 244
[142] Butt et al, 2005, p. 359
[143] Butt et al, 2005, p. 363
[144] Challinor et al., 2007, p. 389
[145] Tingem et al., 2009, p. 248
[146] Lobell et al., 2008, p. 607
[147] ASTI, 2001; Authors' calculations
[148] ASTI, 2001; Authors calculations
[149] ASTI, 2001; Authors calculations
[150] Camara et al., 2006, p. 6
[151] Camara et al., 2006, p. 6
[152] Osman-Elasha, 2008, slide 3
[153] Seo et al., 2008, p.10
[154] Camara et al., 2006, p. 12
[155] Kurukalasuriya et al., 2007, p.2
[156] Mertz et al., 2009a, p. 744
[157] Africa Partnership Forum, 2009, p. 3
[158] FAOSTAT, Author's calculations
[159] Africa Partnership Forum, 2009, p. 3
[160] National Adaptation Programmes of Action (NAPAs) available from the UNFCCC Web site: http://unfccc.int/national_reports/napa/items/2719.php
[161] Liu et al., 2008, p. 228
[162] Schlenker & Lobell, 2010, p. 5
[163] Adejuwon 2006, p. 239
[164] Butt et al, 2005, p. 363
[165] Challinor et al., 2007, p. 389
[166] Mitchell & Jones, 2005, p.706
[167] Solomon et al., 2008
[168] IPCC
[169] Wilby & Wigley, 1997
[170] Hewitson & Crane, 2006
[171] Challinor et al., 2009
[172] Sacks et al., 2010
[173] Burke et al., 2009
[174] Solomon et al., 2008
[175] Christensen et al., 2007
[176] Hulme et al. 2001