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

Climate Change and Crops: Executive Summary

EPAR Brief No. 118

Stephen Po-Chedley, Brian Smoliak, Cecily Stokes-Prindle,
Kate Schneider, Justin Paulsen, Jacob Lipson, and
Professors Alison Cullen and Leigh Anderson

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Introduction

This report combines analyses from four previous EPAR briefs[1] on the effects of climate change on maize, rice, wheat, sorghum, and millet production in Sub-Saharan Africa (SSA). In addition, this brief presents new analysis of the projected impact of climate changes in SSA. Like the original EPAR briefs, the summary is presented in three parts:

- Pillar 1: A comparison of the importance of the five evaluated cereal crops within SSA as indicated by production, net imports, caloric need, and nutritional profile
- Pillar 2: Crop-specific analyses of historical and projected climate conditions in crop-growing regions, accompanied by a comparison of the agronomic and physiological requirements of each crop
- Pillar 3: A summary of research and policy resources dedicated to each crop as indicated by full-time researchers, and crop-specific initiatives in National Adaptation Programmes of Action

This three-part structure is intended to illustrate any imbalances between the relative importance of the crops, their predicted vulnerability to climate change, and the current research and policy resources devoted to crop production and adaptation. Especially with respect to climatic susceptibility, these rankings provide a comparative summary based upon the analysis conducted in the four previous EPAR briefs, statistical analyses of historical yield and climate data, and future climate model predictions. The end goal is to estimate current susceptibility to anticipated regional climate change, with the understanding that the models do not address scenarios in which income, farmer behavior, or other factors change.

According to the indicators analyzed, our research suggests that **maize** leads the cereal crops in terms of importance within SSA and in terms of research and policy attention. Our analysis of climate conditions and the crop's physical requirements suggests that many maize-growing areas are likely to move outside the range of ideal temperature and precipitation conditions for maize production. **Rice** is the third most important crop in terms of consumption dependency, fourth in terms of production, but second only to maize in terms of research funding and FTEs. **Sorghum and millet** rank second and third in production importance and second and fifth in consumption importance, but rank below maize and rice in terms of FTE researchers. Their role is complicated by the fact that they are often considered inferior goods; SSA consumers often substitute away from sorghum and millet consumption if they are able to do so. **Wheat** is the least-produced crop of the five, and the second to last in terms of consumption importance. However, it still ranks above millet in terms of FTE researchers.

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[1] EPAR Briefs 62, 71, 114 and 115

Table 1. Comparison of cereal crops across selected indicators.

	Maize	***Rice***	***Sorghum***	***Millet***	***Wheat***
Production (Million Tonnes, 2007)	41.3	13.9	24.3	17.2	5.7
Net Imports (Million Tonnes, 2007)	1.6	2.6	0.5	0.05	22
Portion of SSA Population Dependent for >300 kcal/day	46%	15%	30%	7.5%	13%
FTE Researchers (% of Total SSA FTEs)	300 (8%)	242.9 (7%)	188.9 (5%)	100.1 (3%)	161 (5%)
NAPAs	9	11	10		0
CGIAR Centers	IRRI, WARDA, CIAT	CIMMYT, IITA	ICRISAT	ICRISAT	CIMMYT

Source: FAOSTAT, Authors' calculations, EPAR Briefs 62, 71, 114 and 115

Pillar 1: The Importance of Maize, Rice, Wheat, Sorghum and Millet in SSA

Importance in this section is discussed according to four indicators: production, net imports, caloric dependency, and nutritional value. All production, import, and caloric dependency data in the following section are retrieved from FAOSTAT, the statistical database of the Food and Agriculture Organization (FAO). Nutritional values are reported from FAO's Food and Nutrition series (1995).

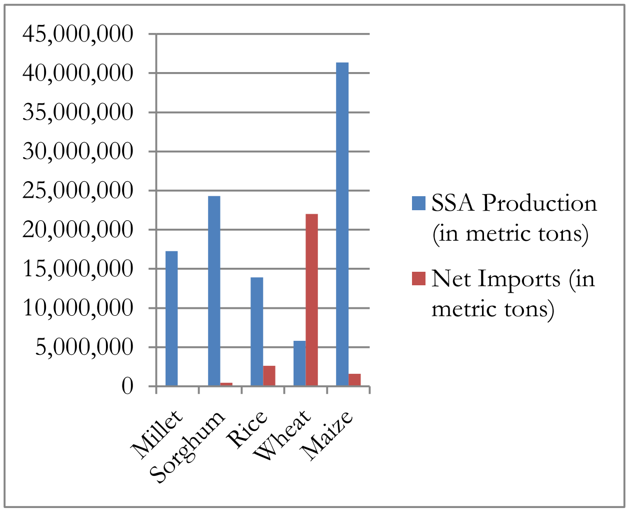
Of the five crops studied, maize has the highest production and largest caloric dependency. Wheat imports, at 22 million tonnes per year, exceed other grain imports by a factor of ten. The nutritional profiles of all five grains are distinct; the most nutritionally valuable grain for a given population or sub-population will therefore vary according to circumstance and availability of other goods. It is also important to note that the nutritional profiles do not address issues of bioavailability, which may be of particular concern for micronutrients such as iron.

Maize

Maize is grown throughout SSA, most intensively in Southern Africa and in a band from Somalia to Mali and Mauritania. South Africa, Nigeria, Tanzania, Ethiopia and Malawi are the five SSA countries that produce the most maize. Overall, maize is the most-produced cereal in SSA: total maize production in SSA in 2007 was 41.3 million tons. However, maize yield levels in SSA are significantly lower than yield levels worldwide.[1]

Maize is one of the most important food crops in SSA, providing a higher proportion of calories in the SSA diet than any other crop. Over 1.6 million tons of maize were imported into SSA in 2007. Eighteen countries, comprising 46% of SSA's total population, are dependent on maize for more than 300 daily kilocalories per-capita. The average per-capita protein consumption from maize in SSA is 8 grams per day. However, where maize is the main source of calories, maize provides about half the 46-56 grams of protein recommended per day. Maize is also an important source of fat and carbohydrates.

Figure 1: Cereal Production in Sub Saharan Africa (Metric Tonnes)



Source: FAOSTAT (2007 data)

Rice

Rice production in SSA is concentrated in a band across the center of the continent, from West Niger to Ethiopia. SSA rice systems produce low yields relative to other rice-growing regions; historical increases are a result of expanding harvesting area. Total rice production in SSA in 2007 was 13.9 million metric tons. Nigeria, Madagascar, Guinea, Tanzania and Sierra Leone are the five SSA countries that produce the most rice.

Rapid urbanization has shifted consumer preferences towards rice. SSA rice production has not increased at the same pace as this rising demand, and net imports of rice in 2007 were 2.6 million metric tons. 13 countries, comprising 15% of the total SSA population, are dependent on rice for more than 300 daily kilocalories per-capita. Rice provides more calories and protein per serving than maize, sorghum or millet. Rice is also an important source of carbohydrates and fat.

Sorghum & Millet

Sorghum and millet are often grown in areas where other grains do not grow as well. Sorghum is typically grown in regions where it is too hot, too dry, or the growing season is too short to grow maize. Millet tends to be grown where it is too hot, too dry, too sandy of soil, or too short a season to grow sorghum. The highest production of both cereals occurs in a belt across the Sahel from Burkina Faso to Ethiopia. Production of these cereals is currently limited by farmer and consumer preferences for other cereal crops. 24.3 million tons of sorghum and 17.2 million tons of millet were grown in SSA in 2007. Nigeria, Sudan, Ethiopia, Burkina Faso and Niger are the five SSA countries that produce the most sorghum. Nigeria, Niger, Mali, Burkina Faso and Sudan are the five SSA countries that produce the most millet.

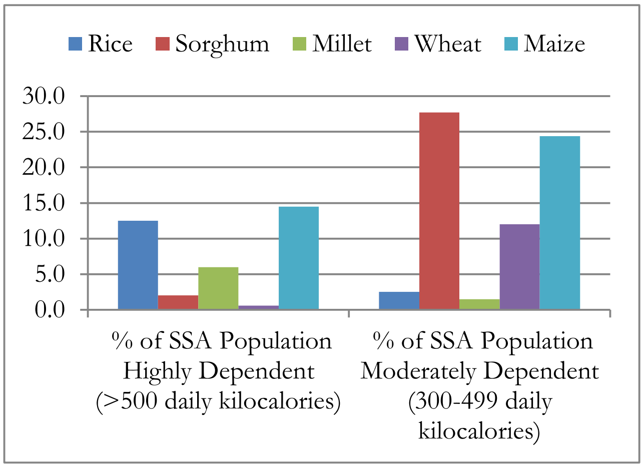
Sorghum and millet are primarily consumed by poor and marginalized populations and are generally considered less-desirable cereal crops. Because of high levels of subsistence consumption, international trade levels for sorghum and millet are relatively low: in 2007, a little over 500,000 metric tons of sorghum, and 50,000 metric tons of millet were imported into SSA. Four countries, comprising 30% of SSA's total population, are dependent on sorghum for at least 300 daily kilocalories per-capita; five countries, comprising 7.5% of SSA's total population, are dependent on millet for at least 300 daily kilocalories per-capita. Like other cereals, both sorghum and millet are primarily starchy in content. Sorghum and pearl millet also contain protein levels comparable to other cereals, though pearl millet also has a more beneficially complex amino acid profile than does sorghum.

Wheat

Wheat is predominantly grown in the temperate highlands of Eastern SSA. South Africa alone accounts for over 15% of total SSA wheat production. Wheat yields in SSA are much lower than worldwide yields, but experts suggest wheat production is at its efficiency frontier in SSA given temperature, precipitation and soil conditions. 5.7 million metric tons of wheat were produced in SSA in 2007. South Africa, Kenya, Ethiopia, Zimbabwe and Sudan are the five SSA countries that produce the most wheat.

Wheat is the most-imported cereal in SSA, with over 22 million tons imported in 2007. 12 countries, comprising 13% of SSA's total population, are dependent on wheat for over 300 daily kilocalories per-capita. The average per-capita protein consumption from wheat in SSA is 6.7 grams per day, but in the small portion of SSA that is highly dependent on wheat for caloric needs, it provides approximately half the 46-56 grams of protein recommended per day. Wheat has a high protein content (comparable to pearl millet) and more iron than rice or maize.

Figure 2: Population Dependency on Cereals for Caloric Intake



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

Table 2: Average Nutritional Composition of Common Cereals (per100 g edible portion; 12 percent moisture)

Food	Protein[a] (g)	Fat (g)	Carbohydrate (g)	Energy (kcal)	Ca (mg)	Fe (mg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)
Rice (brown)	7.9	2.7	76	362	33	1.8	0.41	0.04	4.3
Wheat	11.6	2	71	348	30	3.5	0.41	0.1	5.1
Maize	9.2	4.6	73	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	363	42	11	0.38	0.21	2.8
Finger millet	7.7	1.5	72.6	336	350	3.9	0.42	0.19	1.1

Source: Adapted from FAO 1995

Pillar 2: Projected Effects of Climate Change Within Cereal Regions in SSA

Please refer to EPAR briefs 62, 71, 114 and 115 and Appendices I and II for a detailed description of the data and methodology used in the novel analysis of the effects of climate change on cereal production in SSA[2].

Climate change models provided by the Intergovernmental Panel on Climate Change (IPCC) project that annual mean surface temperature will increase approximately 0.5–1.0°C by 2029 and 3–4°C by 2100. Elevated areas in southern Africa may see increases of up to 7°C by 2100. [2,3,4] The coincidence between current growing season temperature and projected future conditions (overlap) is projected to be less than 20% by 2050. [5] 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. The ensemble average of 23 models used in the IPCC AR4 do not show robust changes in precipitation; the model mean change for precipitation in SSA as a whole is near zero.

This section is presented in two parts: first, an overview of climate requirements and responses to climate stress for the five studied cereal crops; and second, a model of future climate-yield interactions within the cereal-growing regions in SSA. Taken together, the two parts provide an overview of likely plant-level responses to future changes in temperature or precipitation.

Cereal Climate Requirements

Maize

Maize is grown throughout SSA, predominantly in the subtropics and tropical lowlands.[6] Most SSA maize is rainfed.[7] Maize grows best in areas with at least 500mm annual rainfall and in temperatures ranging from 20ºC to 35ºC.[8] There are multiple improved and landrace varieties planted throughout SSA, with varying optimal temperature ranges and levels of tolerance to climate-related stressors.[9,10,11]

Rice

Rice is most suitable for production in rainfed or irrigated wet lowland and swamp conditions, although dry upland areas are also currently cultivated in SSA.[12,13,14] Rainfed rice thrives in regions with between 500mm and 1500mm of rain, and is sensitive to water stress.[15] The ideal thermal climate for Asian rice growth is between 25°C and 30°C, although optimal temperature is slightly lower, at 20ºC and 25ºC, during the grain-fill stages.[16,17]African rice does well at higher temperatures,

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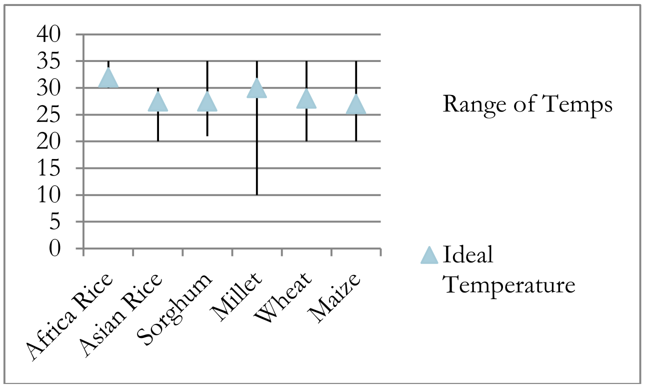
[2] The novel analysis extension represents the Capstone Project of Stephen Po-Chedley, graduate student in the Program on Climate Change at the University of Washington.

between 30ºC and 35ºC.[18] For both rice species, exposure to extreme maximum temperatures is most hazardous during the flowering stage; even a few hours at high temperatures can result in yield loss. [19]

Sorghum & Millet

The ideal growth climate for pearl millet (the predominant millet variety) is around 30ºC, while Sorghum's optimum growth temperature is about 27.5ºC.[20,21] These optimum temperatures vary according to stage of plants' life cycle. For example, sorghum germinates well in a temperature range of 21-35ºC, maximizes growth in a temperature range of 26-34ºC, and maximizes reproductive growth from 25-28ºC.[22] Both sorghum and millet are relatively drought-tolerant in comparison to other cereals. Sorghum can tolerate as little as 400mm, and pearl millet can tolerate as little as 125mm.[23] Both cereals have high water use efficiency.[24]

Figure 3: Cereal Temperature Ranges and Ideal Temperatures



Source: Porter and Gawith, 1999; FAO 2010; National Research Council, 1995; Brink and Belay, 2006

Wheat

Wheat is grown predominantly in temperate highland areas along the Eastern Coast of SSA, with some additional production along the Gulf of Guinea. Wheat's optimum temperature range is generally between 20-30ºC, but temperatures up to 35ºC may be tolerable. Photosynthesis levels increase with rising temperatures up to 25ºC, before slowing and finally ceasing entirely at about 40ºC. The optimum annual precipitation range for wheat is 450 to 650mm, but much of the current wheat-growing area in SSA is already below this threshold.

General Changes in Plant Physiology under Water and Temperature Stress

Changes in temperature and precipitation can have a variety of effects on agricultural crops. The majority of crop water loss is caused by evaporation, particularly in winter-rainfall regions. High temperatures—such as those projected throughout SSA—increase evaporation rates, reducing soil moisture levels and increasing crop water stress.[25,26] Seedlings under drought and temperature stress are likely to have a longer lag time to leaf growth, increasing the period of vulnerability to high rates of evaporation in the absence of a developed leaf canopy. Crop varieties with rapidly-developing large leaf areas are less vulnerable to evaporation, but increased leaf production can reduce harvest index and overall yield.[27]

Water deficits during floral development can reduce floral fertility and prematurely abort grain filling, leading to severe—sometimes complete—loss of yield in maize and other crops. Water stresses during grain filling can result in increased vegetative growth but reduced grain biomass and lowered harvest index. Yield losses can occur by these pathways even in the presence of adequate rainfall throughout the rest of the season.[28]

Transpiration efficiency (TE) is the ratio of water assimilated to water transpired (lost from foliage). Higher TE translates to increased water use efficiency (WUE). TE decreases in drier air, and decreases in precipitation may therefore reduce crop WUE.[29]

Damage from insect pests may increase as well, both pre- and post-harvest. Higher temperatures may expand the range of several pests. They also increase the insect population by shortening the time span between insect generations and reducing the number of insects killed during the colder season.[30,31]

Increased CO_2 concentrations may stimulate photosynthesis and promote plant growth through increased water use efficiency. Rice and wheat, as C_3 plants, would benefit relatively more from elevated CO_2 levels. However, for millet, sorghum, and maize, which utilize C_4 photosynthetic pathways, the growth benefits of elevated CO_2 levels are muted because of their relative photosynthetic efficiency. These plants may also face more intense competition from C_3 plant pests, such as witchweed (striga). C3 plants such as striga outperform C4 plants at higher temperatures, and their TE becomes more efficient in the presence of elevated CO_2. Rising CO_2 levels also reduce the advantage of C4 plants in nitrogen-poor soil.[32]

In general, rainfed crops are likely to be more vulnerable to climate change than are irrigated crops because of limited mechanisms for coping with water scarcity.[33] In the case of reductions in rainfall, the effect would be exacerbated in a warmer future climate where higher evaporation rates are more likely.[34]

Overall Impact of Climate Change on Cereal Yields

Plant-level productivity impacts are not only the result of single climate factors, but also of the interactions between those factors. Temperature, precipitation, CO2 levels, radiation, changes in weed or pest populations, and changes in farming behavior can all work singly or in tandem to affect the environment and physiological state of a cereal crop. Depending on the relative weighting of these factors, analyses of climate change's effects on crop production may feature widely divergent predictions that fundamentally disagree as to whether crop yields will decrease or increase.

Despite the complicated nature of the crop and climate relationship, we have attempted to characterize historical yield-climate relationships for the crops and regions studied in this paper series. This analysis, based on historical climate and crop data, has a large degree of uncertainty and should not be taken as an absolute prediction for future yields. Instead this work should be viewed as an assessment of current crop vulnerabilities to climate change alone.

Historical Climate Yield Relationships and Current Vulnerability to Climate Change

In order to assess the relationship between climate change and crop yields, an analysis similar that of Lobell and Field (2007)[35] was carried out for the entire African continent. In this analysis FAO yield data for the five major regions of Africa was spatially averaged for each year since 1961, with regions weighted according to harvesting area. Similarly, spatially averaged seasonal climate time series for precipitation and temperature were created for the 1961-2006 time period with greater weight placed on larger harvesting areas. Non-climatic influences (i.e. spurious trends) were removed from the yield datasets using a first difference technique (more information about the removal of non-climatic influences is in Appendix III).

Once the yield and climate data were de-trended, the time series data within Africa for each crop (yield anomaly, temperature anomaly, and precipitation anomaly) were combined in a linear regression model to determine the extent that climate influences yields. In the ideal case, using both precipitation and temperature, between 18 and 62% of the yield variance was explained. The wheat and rice models were not significant at $p<0.05$. This indicates that climatic variability is currently not the most important factor determining yields; this may be due to farming practices (i.e. irrigation) or the fact that these crops are currently grown in a climatic range that is ideal, so inter-annual variability does not have a large effect on production.

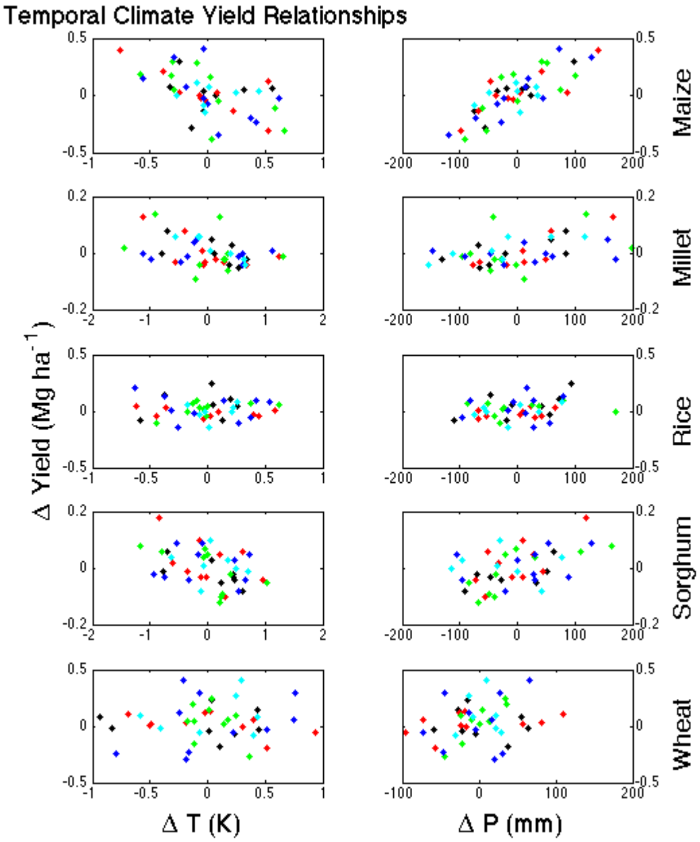


Figure 4. Year-to-year anomaly relationships between seasonal temperature and yield (left) and seasonal precipitation and yield (right) for 1962-1969 (black), 1970-1979 (red), 1980-1989 (green), 1990-1999 (blue), 2000-2006 (cyan). All relationships are significant to $p<0.01$, except for rice and wheat (not significant to $p<0.05$).

This does not mean that these crops are not subject to climatic effects in the future.

While there is a wide range of projections for climate impacts on agriculture, most of the regression models in this analysis showed negative or near-zero yield trends for the 21st century (Appendix I).

One important consideration in this analysis is that precipitation and temperature are inversely correlated. In general, increasing precipitation leads to greater yields and increasing temperature leads to lower yields; *a priori* it is impossible to choose just one of these variables to predict yields even though higher temperatures are often associated with decreased rainfall. Using both historic temperature and precipitation records as predictors leads to higher yield trends, compared to using the historic temperature record as a predictor alone. Even though it would be convenient to express yield changes in terms of temperature alone (since the climate signal due to temperature has widespread model consensus and the changes in temperature are expected to be large) we will refrain from overemphasizing temperature given that precipitation is important in controlling yields in today's climate. With this in mind, it should be noted that future seasonal temperatures are expected to be outside the range of present day variability and these relationships between temperature, precipitation, and yield are not expected to hold into the future as temperature change outpaces precipitation change. For this reason, the yield projections presented in Figures 5 and 6 and Appendix I should be interpreted as near-term responses to the expected rate of regional climate trends; these yield changes are not long-term projections.

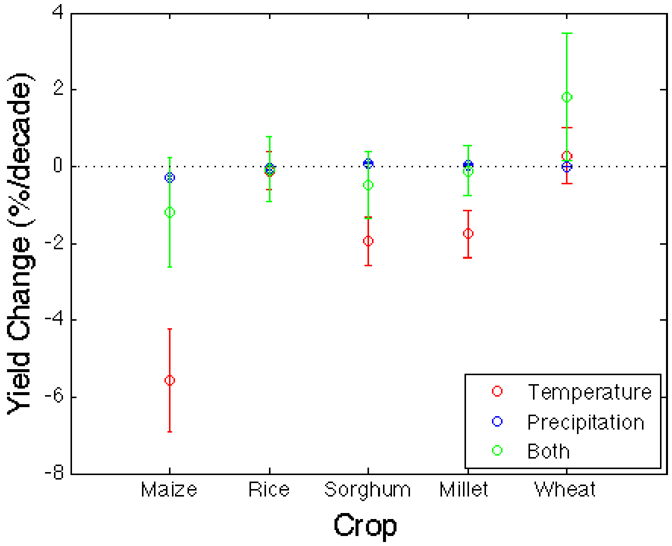


Figure 5. *Expected yield changes for crops studied in EPAR's Crops and Climate Series. Red indicates projections using models that used only temperature as a predictor, blue indicates models where precipitation was used as a predictor, and green represents models that used both temperature and precipitation as a predictor. Note that the regression models for wheat do not have significant predictive power and for rice are only significant when precipitation alone is a predictor .*

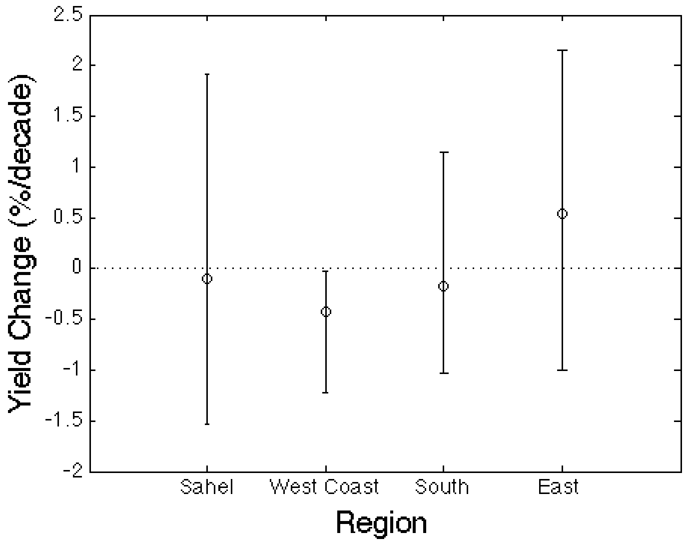


Figure 6. *This graph represents the mean of the yield trends for all the crops in a given region using regression models that include both precipitation and temperature. Note that the error bars represent the spread of the models for different crops. The upper bound for each region is wheat in every case and the lower bound is maize in every case. Although the wheat model was not significant at $p<0.05$, the data was included in the plot, because the influence of climate on wheat yields is not implausible.*

In interpreting yield changes, it is most convenient to understand the climate trajectory, or, in other words, the changes of temperature and precipitation as a function of time. Appendix II demonstrates the regional changes in temperature and precipitation over the next century relative to idealized estimates for optimal climatic ranges for individual crops. In general, the overall predictive trends in climate change impact analyses for production of each cereal crop are summarized below:

<u>Maize</u>

Climate change projections predict maize production losses across the majority of current SSA maize-agriculture environments. Variability in maize varietal susceptibility to temperature and water stresses renders the extent of the maize production losses uncertain. The recent adoptive spread of improved yield maize varieties that are not drought or heat tolerant could exacerbate the susceptibility of maize to climate change.

<u>Rice</u>

Popular and high-yield Asian rice varietals may no longer be viable in the Sahel because of increases in growing season temperatures to above 30ºC. At the same time, rice agriculture in Southern Africa, Madagascar and Coastal West Africa may benefit from an increased growing season temperature that is closer to the optimal thermal conditions for Asian Rice production.

<u>Sorghum & Millet</u>

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. On the other hand, warming in the Sahel, where the majority of sorghum and millet in SSA is currently grown, could decrease crop yields and suitable planting areas as temperatures begin to exceed optimum temperature ranges. As a result, some analyses have predicted local or overall SSA sorghum and millet production yield increases as a result of climate change, while other analyses have predicted yield decreases.

Wheat

The impact of climate change on wheat yield is uncertain, with predicted overall decreases in most areas, but with predicted increases in certain temperate regions of SSA. Many wheat-growing regions in SSA are already near the limit of their maximum temperature tolerance, and predicted climate change scenarios could render these areas unsuitable for future wheat production.

Pillar 3: Current Resources Dedicated to Cereals in SSA

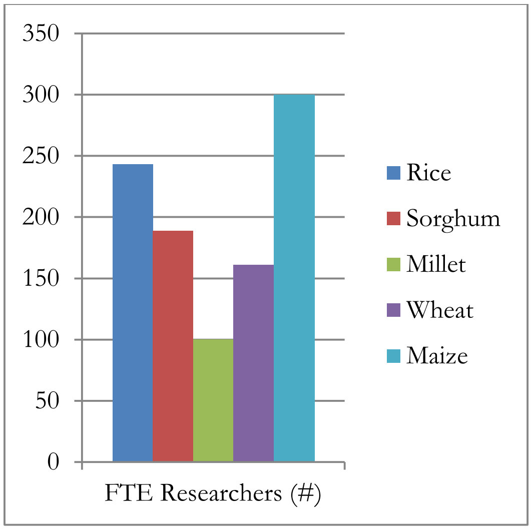
The resources devoted to each crop are assessed according to three parameters: (1) the number of full time researchers (FTEs) dedicated to the crop; (2) the number of CGIAR centers including each crop in their research agendas; and (3) the number of National Adaptation Programmes of Action (NAPAs)[3] containing crop-specific initiatives. FTEs and NAPA initiatives are in a sense proxy indicators and may not give a complete picture of the research and policy resources dedicated to each crop—for instance, not every country is required to submit a NAPA, and there may therefore be relevant policies or initiatives not captured in this analysis. However, these indicators in combination can provide a broad sense of relative priorities within the agricultural research community.

The data for full time researchers are obtained from the Agricultural Science and Technology Indicators survey of agricultural research in the developing world.[36] The CGIAR centers were assessed according to their mission statements and publications.[37] The NAPAs were obtained from the UNDP website, and each country's NAPA was analyzed for crop-specific initiatives.[38]

Maize

Most tropical maize is grown for subsistence and provides little incentive for private sector R&D; the majority of private sector research focuses on the temperate varieties more common outside of SSA.[39] Maize funding in SSA is nonetheless significant. Three hundred FTE researchers (8%) and two CGIAR centers focus on maize research (CIMMYT and IITA).

Nine NAPAs propose activities specifically in the context of maize production. An additional six countries mention maize specifically throughout the NAPA, but do not explicitly target maize in their proposed activities. The most common adaptations involving maize feature the promotion of small-scale irrigation, development and dissemination of improved varietals, and crop diversification.



Source: ASTI, 2001; author's calculations
Figure 7: FTE Researchers by Crop

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[3] As part of the Least Developed Countries Work Programme, 31 countries in SSA have submitted National Adaptation Plans of Action (NAPAs) proposing climate change adaptation projects to address urgent national needs.[3] Proposed project types common to multiple cereal crops include (1) promoting small-scale irrigation; (2) breeding and disseminating improved or local varieties, particularly short-cycle or drought-tolerant varieties of staple crops; (3) improving crop management and (4) crop diversification.

Rice

The recent focus on rice from NEPAD, WARDA, and CAADP has strengthened the institutional environment around rice research. Of 3570 FTE crop researchers, 242.9 (7%) focused on rice. Of 15 CGIAR research centers, 3 are focused on rice research (IRRI, WARDA, CIAT).

Increasing and adapting rice cultivation figures in 11 NAPAs. The most common proposed adaptations involving rice are increased irrigation, dissemination of improved varieties, and increased cultivation in lowlands and wetlands.

Sorghum & Millet

Sorghum and millet are generally less funded for research. 188.9 (5.2%) FTE researchers focused on sorghum and 100.1 (2.8%) focused on millet. ICRISAT is the only CGIAR research center primarily focused on sorghum and millet.

Ten countries' adaptation strategies explicitly include sorghum and millet in proposed projects. Notably, three of the countries (Burundi, Guinea and Malawi) that include sorghum or millet in their proposed NAPA projects have current per-capita daily consumption levels of both cereals below 20 kilocalories. The most common adaptation strategies involving sorghum and millet are increasing irrigation, development and dissemination of improved sorghum and millet varieties, diversification of grains consumed, and a switch from other cereal crops to sorghum and millets because of sorghum and millets' drought-resistant properties and short growing seasons.

Wheat

One hundred and sixty-one (5%) FTE researchers focus on wheat, with CIMMYT as the CGIAR center primarily responsible for wheat research.

Conclusion

Our analysis suggests that there is no single method or metric to best determine whether or not cereal crops are receiving resources in amounts corresponding to their importance and potential vulnerability. In part, the difficulty arises from the definition of vulnerability. A crop such as rice may be physiologically vulnerable but grown mainly in irrigated areas, reducing its vulnerability, while a crop such as sorghum could be well adapted to changes in temperature but predominantly grown by subsistence farmers with little access to improved technologies. There is also difficulty in determining the importance of a crop, now and in the future. Maize leads the way in production and consumption under current conditions, but sustained increases in temperature could result in significant changes. In sum, context may be the overall arbiter of the perceived vulnerability to climate change. The picture will vary according to whether the unit of analysis is an individual country, a large-scale region, or the collective area of SSA; it will also vary across time scales and across crops.

Despite these uncertainties, it is possible to draw some broad conclusions about the future of crops and climate change in SSA. Suitable production areas for maize are likely to decrease, while wheat and rice will likely see increases in some regions and decreases in others, for an uncertain net effect. Sorghum and millet may see increased production due to new cultivation in land formerly used for higher-value crops, but some current production regions may warm past the margin of viability for sorghum and millet cultivation.

In the models presented here, temperature and precipitation fluctuations were significant predictors of historic yields for sorghum, millet and maize, explaining between 18 and 62% of the yield variance, but were not significant predictors of historic yields for wheat and rice. The models suggest that climatic variability is not usually the most important factor in determining yields, though the effect varies by crop.

This climate analysis is indicative of current crop susceptibility to the mean rate of climate change as projected by a suite of general circulation climate models. Because of the large changes expected in temperature over the next century, climate may soon become a more important factor in determining yields, likely altering these linear predictions for yield changes. An important consideration in this report is that precipitation and temperature are inversely correlated with one another. In general, increasing precipitation leads to greater yields and increasing temperature leads to lower yields; thus, a priori it is impossible to choose just one of these variables to predict yields even though higher temperatures are often associated with decreased rainfall. While it would be useful to determine the effects of temperature alone, given that there is consensus around increasing temperatures, precipitation is important in controlling yields in today's climate. However, future seasonal temperatures are expected to be outside the range of present day variability and these relationships between temperature, precipitation, and yield will likely not hold into the future as temperature change outpaces precipitation change.

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

Appendix I: De-trending and Regression Model Characteristics

Positive trends exist in yield datasets since 1961 as a result of multiple factors including non-climatic influences such as irrigation and fertilizer and pesticide usage. In order to isolate the effect of climate on yield, these trends were removed from the yield, temperature, and precipitation datasets, a procedure known as detrending. In order to de-trend the time series, a first-difference technique was used. This method acts as a high-pass filter, emphasizing the year-to-year variability. Linear regression models were then created for individual crops in order to understand the relationship between climatic anomalies relative to mean values and yield. Other methods for isolating the effect of climate were also explored, such as taking out a least-square linear fit trend, ignoring trends in the datasets, and utilizing ensemble empirical mode decomposition to remove the monotonic (but non-linear) mode in the datasets. First-difference was selected from among these approaches for presentation in this brief because, as a whole, it was significant in most cases and because it explained more variance than the other methods explored.

*Table 3. Table with three regression models based on the first difference time series of mean seasonal temperature, mean seasonal accumulated precipitation, and yield. For the yield-temperature model and the yield-precipitation model, significance of $p<0.01$ is denoted with **. Other models were not significant to 95% confidence. The right hand side of the table includes both precipitation and temperature as yield predictors in the linear regression model.*

Model	Yield-Temperature		Yield-Precipitation		Yield-Temperature,Precipitation			
Parameter	Beta (Mg/ha)/K	Adj. R^2	Beta (Mg/ha)/mm	Adj. R^2	Beta (Mg/ha)/K	Beta (Mg/ha)/mm	Adj. R^2	Model p-value
Maize	-0.307	0.27**	0.00253	0.62**	-0.05100	0.00236	0.61930	0.000
Millet	-0.033	0.14**	0.00028	0.20**	-0.00300	0.00026	0.17906	0.006
Rice	-0.009	-0.02	0.00038	0.05	-0.00200	0.00038	0.02930	0.202
Sorghum	-0.051	0.16**	0.00046	0.21**	-0.01400	0.00037	0.19330	0.004
Wheat	0.022	-0.02	0.00086	0.03	0.14900	0.00187	0.08806	0.054

With each linear-regression model, we calculated a rate of yield change per decade for each crop and region using:

$$
\left\{
\begin{aligned}
\%Yield/decade &= \frac{\Delta T}{decade} \, x \, \frac{\Delta Yield}{\Delta T} \, x \, \frac{100}{\overline{Yield}} \\
\%Yield/decade &= \frac{\Delta P}{decade} \, x \, \frac{\Delta Yield}{\Delta P} \, x \, \frac{100}{\overline{Yield}} \\
\%Yield/decade &= \left(\frac{\Delta T}{decade} \, x \, \frac{\Delta Yield}{\Delta T} + \frac{\Delta T}{decade} \, x \, \frac{\Delta Yield}{\Delta P} \right) \frac{100}{\overline{Yield}}
\end{aligned}
\right.
$$

where $\frac{\Delta T}{decade}$ is the least square linear trend for temperature in the 21st century, $\frac{\Delta P}{decade}$ is the trend for precipitation, $\overline{Yield}$ is the year 2000 mean yield, and $\frac{\Delta Yield}{\Delta T}$ and $\frac{\Delta Yield}{\Delta P}$ are the terms from our linear regression models. Figures 4 and 5 express these projections for different regions and crops.

***Appendix II**: Yield changes in percent per decade by crop and region analyzed in this series. Green represents linear regression models significant to $p<0.01$, blue represents models significant to $p<0.05$, and red represents models with $p>0.05$.*

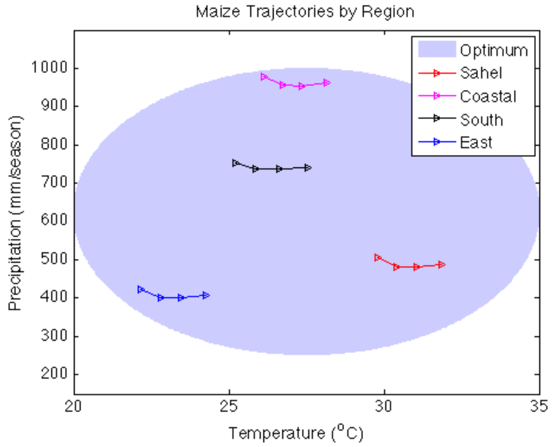
Crop (Region)	Predictors (Percent per Decade)					
	T-Projection	Error	P-Projection	Error	T,P-Projection	Error
Maize (Sahel)	-6.89908	1.66614	-0.41954	0.04886	-1.53519	1.38269
Maize (Coast)	-5.51701	1.33237	-0.32290	0.03761	-1.21590	1.37525
Maize (South)	-5.18095	1.25121	-0.19012	0.02214	-1.03629	1.55320
Maize (East)	-4.65018	1.12302	-0.24140	0.02812	-0.99615	1.40981
Rice (Sahel)	-0.10269	0.44421	-0.04855	0.02631	-0.07192	0.78824
Rice (Coast)	-0.10621	0.45940	-0.06032	0.03269	-0.08446	0.79237
Rice (South)	-0.12595	0.54478	-0.03342	0.01812	-0.06216	0.81531
Rice (Madagascar)	-0.12016	0.51977	-0.04951	0.02683	-0.07688	0.98196
Soghum (Sahel)	-2.35395	0.76616	0.03688	0.01044	-0.63557	0.90652
Sorghum (Coast)	-1.73036	0.56320	0.13893	0.03933	-0.37816	0.80526
Sorghum (East)	-1.65223	0.53777	0.08524	0.02413	-0.39884	0.85970
Sorghum (South Central)	-2.15962	0.70291	0.25685	0.07271	-0.40552	0.83747
Sorghum (South)	-1.78069	0.57958	-0.07783	0.02203	-0.56498	0.90877
Millet (Sahel)	-1.85193	0.64297	0.02696	0.00783	-0.14292	0.68821
Millet (Coast)	-1.24828	0.43339	0.09313	0.02706	-0.02633	0.61104
Millet (East)	-1.28587	0.44644	0.06165	0.01791	-0.05915	0.65254
Millet (South Central)	-1.66858	0.57932	0.18441	0.05358	0.02075	0.63511
Millet (South)	-2.69689	0.93634	-0.10953	0.03182	-0.34708	0.68983
Wheat (Sahel)	0.28744	0.77491	-0.01438	0.00956	1.91724	1.60300
Wheat (Southern East Africa)	0.31268	0.84297	0.01339	0.00890	2.14826	1.59918
Wheat (South)	0.17958	0.48414	-0.03506	0.02331	1.14155	1.90013
Wheat (Northern East Africa)	0.30351	0.81824	-0.01651	0.01097	2.02156	1.60378

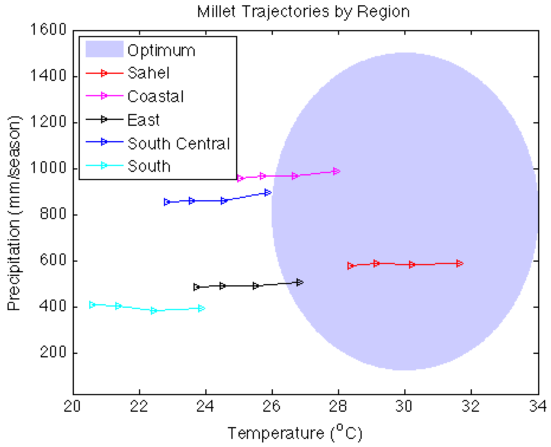
This table describes the projected regional yield changes given the African mean historical relationship between yield, precipitation, and temperature and projected climate change in the A1B climate scenario. Models with low R^2 values (Table 3) signify that the climate explains little of the year to year seasonal variability (i.e. millet). Similarly, models that are statistically insignificant with $p>0.05$ (i.e. rice) are models in which there is not a strong relationship between precipitation, temperature, and yield over the 1961-2006 time period. In some cases, notably in the case of wheat in the Sahel, projections are likely not accurate because the regression model is based on continental responses to temperature assuming that the relationship is similar across the continent, but given the use of different crop varieties with distinct growing seasons, this first order approximation should be interpreted cautiously.

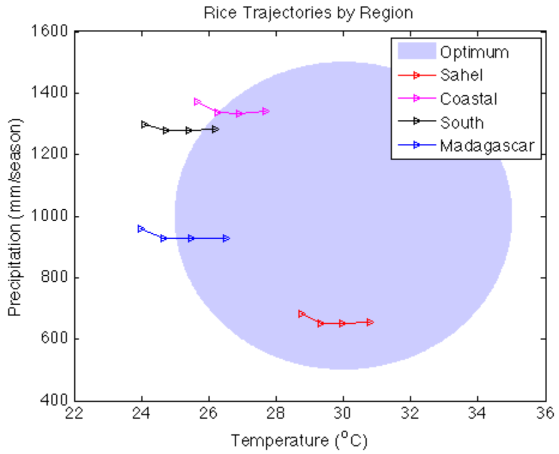
Appendix III: 21st Century Precipitation and Temperature Projections for different crops and regions.

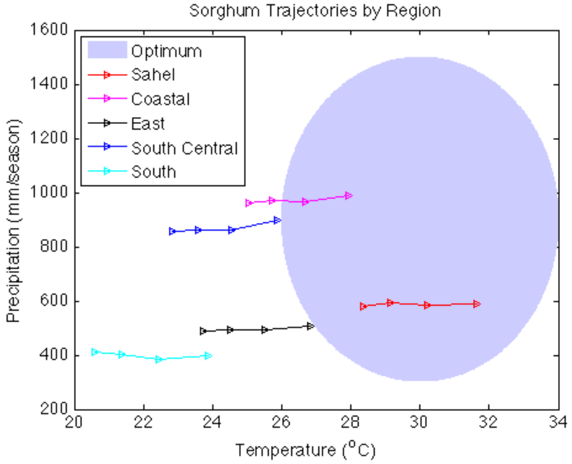
In each figure below the climate trajectory represents the path that the regional climate is expected to take (from left to right going forward in time) with dots indicating the mean climate in 1990, 2020, 2050, and 2090. The blue shading is idealized, average crop growing conditions. Note that local practices such as irrigation can compensate for water deficiencies.

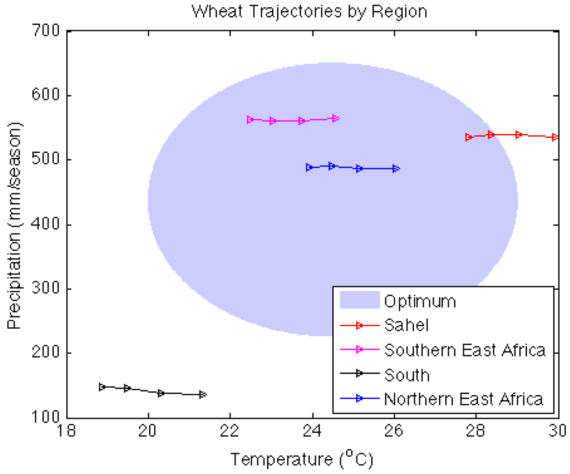
These figures are meant to illustrate the climate changes that are expected to take place over the next century in relation to crop growing areas. These growing regions (in precipitation and temperature space) are highly idealized because ideal growing conditions are studied in terms of the stage of the plant's life, but EPAR analysis has focused on seasonal averages, which is a multi-month average. Because some areas have large tolerances for growing conditions, it is difficult to determine the "ideal" seasonal temperature and precipitation range. In the cases in which regions are within the optimal temperature range or approaching the optimal temperature range, yield changes due to precipitation and temperature changes may be small now, but if the upper boundary of the ideal range is exceeded it is likely that yields will decrease in ways that the EPAR linear regression model is not designed to predict.











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Note: This brief is a summary of four previous briefs (EPAR Briefs 62, 71, 114 and 115) each of which contained a comprehensive literature review. For the list of works cited in each individual brief, please refer to the original documents.

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