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

Crops & Climate Change: Rice

EPAR Brief No. 71

Kate Schneider, Brian Smoliak and
Professors Alison Cullen & Leigh Anderson

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

October 22, 2010

Summary

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

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

This three-pillared approach serves to identify gaps in resources dedicated to rice productivity in SSA in light of the crop's resilience to projected changes in climate and importance in the region's food security.

Overall, this analysis indicates that the importance of rice in SSA is increasing even as climate change is projected to have significant effects on the temperature in rice-growing regions. The current resources dedicated to rice research and dissemination of improved methods are insufficient to meet Africa's rice production needs, and may not reflect the importance of the crop for the region's food security under the future projected climate.

Pillar 1: The Importance of Rice in SSA

Rice is the only cereal crop that can be grown under a wide range of soil moisture regimes and in different soil conditions.[3] As such, it can play an important role in SSA's food security as the global climate changes. During the last decade, rice has become the most rapidly growing food source in SSA.[4] For example, the demand for rice in Nigeria is growing faster than for any other food staple, and across all socioeconomic groups.[5] All 49 SSA countries consume at least some rice. Forty countries also produce rice, with the highest levels of production forming a horizontal belt across the center of the continent from Western Niger to Ethiopia and dipping south into Tanzania and Malawi. Rice area harvested accounts for 9.4% of all cereal area.[6]

According to a 1999 analysis, rice accounted for 15% of total cereal consumption in SSA. Consumption far surpasses production: in 2007, 23 countries in SSA imported between 50% and 100% of their rice.[7,8] As a result, nearly 40% of rice consumed in Africa comes from the international market, making the continent particularly vulnerable to increases in global

NOTE: The findings and conclusions contained within this material are those of the authors and do not necessarily reflect positions or policies of the Bill & Melinda Gates Foundation.

rice prices.[9] Projections expect Asia to become a net rice importer by as early as 2020, increasing the urgency for additional rice production in Africa.[10]

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

Total Rice Local Supply	19,628,952 MT (15% of total cereal supply)
Total Rice Production	13,896,553 MT (13% of total cereal production)
Total Area Harvested	8,506,060 Ha (9.4% of total cereal area)
Temperature Requirements*	Temperatures above 35°C lead to spikelet sterility
Water Requirements*	Tolerates water environments ranging from dryland to wetlands
Total FTE Rice Researchers**	242.9 (7% of all SSA crop researchers)
Countries including a rice strategy in their NAPA***	Sierra Leone, Senegal, Madagascar, Guinea, The Gambia, Burundi, Togo, the Congo, Rwanda, Guinea-Bissau, Liberia

Sources: FAOSTAT, Author's Calculations, Wassman & Doberman, 2007, **ASTI (2001), ***UNFCCC NAPA database

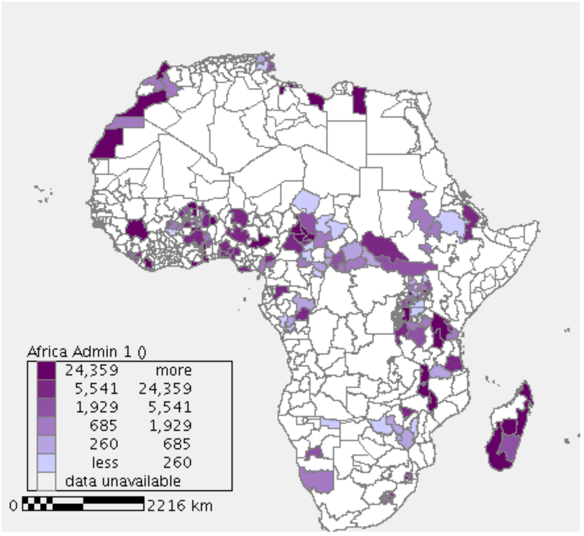
Rice Production

Rice plants are very distinct from all other food crops because of their ability to grow in a wide range of ecological conditions, including flooded environments.[11] In fact, flooded lowland rice systems are among the most sustainable and productive cropping systems in the world. Even when grown without fertilizer, lowland rice typically yields two or three times more than upland crops (such as maize and cassava) grown on the same soil.[12] In tropical climate areas with favorable temperature regimes, two or more rice crops can be grown on the same land in a year.[13]

In SSA, rice systems demonstrate low and variable yield (around only 50% of global averages).[14] Historical increases in production have occurred more as a result of expanding harvested area (often into marginal lands) than from increased productivity.[15] For example, despite 85-years of rice research in Nigeria, yields and resource-use efficiencies remain low. A recent increase in rice output resulted from policies creating incentives for farmers to grow more rice, not from improved productivity.[16]

Drought and poor rainfall in upland systems, iron toxicity in lowland areas, and salinity problems in irrigated systems together with poor soil fertility, limit rice productivity across the region.[17] Though extensive in rainfed upland ecosystems, rice is the lowest-yielding crop in that ecology and competes with several other important staple crops, including maize, sorghum, millet, cassava and yam as well as cash crops such as coffee and cocoa. As these crops become more profitable, area devoted to rice production will decrease.[18]

Figure 1: Rice Production in Africa (Metric Tonnes)



Source: FAO Agro-MAPS[19]

Rice Cultivars

Both cultivated species of rice in the world, Asian and African, grow in Africa today. Asian rice is the predominant cultivar, having widely replaced traditional African rice beginning as early as the 16th century. As a result, the African rice seed stock has largely collapsed or disappeared in much of the continent.[20] Asian rice has the advantage of being much higher yielding with a softer grain that is easier to mill. African rice has more nutritional value, wider leaves that better shade out weeds and better tolerates fluctuations in water depth, iron toxicity, low soil fertility, severe climates and human neglect.[21,22]

Recently, scientists have developed the New Rice for Africa (NERICA) by crossing Asian and traditional African rice.[23] Awarded CGIAR and World Food Prize honors, NERICA rice represents "one of the most important advances in the field of rice varietal improvement in recent decades."[24] Designed specifically for smallholder farming conditions in SSA, NERICA varietals have high yield potential and short growth cycles.[25,26,27] They can increase yield by 30% over traditional African varieties, mature 30–50 days sooner, contain nearly four times as many grains per plant and have two percent more protein.[28,29] They shade out weeds, are resistant to pests and drought, and grow well in poor soils.[30] Although its African parent is quite competitive against weeds, NERICA rice cannot thrive in an un-weeded field.[31] Like their Asian parent, there is an *indica* subspecies best adapted to wet conditions and a *japonica* subspecies more suited to drylands.[32] By 2007, NERICAs had been tested in all SSA countries and were cultivated on over 150,000 ha, with the largest areas in Guinea, Nigeria, Côte d'Ivoire and Uganda.[33]

Rice Consumption

In 2007, annual rice imports were nearly double the amount produced in the region. As a result, SSA had a trade deficit of over 5.7 million tonnes of rice.[34] Urbanization is one of the major factors causing the shift in consumer preference towards rice. Easy preparation fits better into urban lifestyles than more time consuming grains such as maize, sorghum or millet.[35]

Nutrition & Caloric Intake

Rice is an important source of carbohydrates, protein, and fat.[36] It provides more calories and protein per serving than cassava, maize, sorghum, or millet.[37] Rice is also a good source of calcium, iron, niacin, zinc, and B vitamins (thiamin, riboflavin and niacin).[38] As *Table 2* demonstrates, from 2003–2005, over 66 million people in SSA depended on rice for more than 500 kilocalories of their daily food intake.[39] The populations of Madagascar and Guinea were particularly dependent on rice for more than 800 kilocalories per person per day.[40] *Appendix 1* also demonstrates the percentage of local supply from domestic production in 2007 for each country in SSA. Only six countries produce more than 95% of rice supply (Burundi, Central African Republic, Chad, Democratic Republic of Congo, Malawi, Tanzania), while 14 countries produce less than 10% of the local supply as noted in *Table 2*.[41]

Table 2: Dependency on Rice for Caloric Intake

Level of Rice in Local Food Supply	Countries	Population
Very Highly Dependent >800 kcal/person/day	Madagascar, Guinea	28,008,000 (8% of total SSA population)
Highly Dependent 500-799 kcal/person/day	Mali, Senegal, Guinea-Bissau, Comoros, Liberia, Mauritius (produces 0%), Sierra Leone	38,206,782 (4.5%)
Moderately Dependent 300-499 kcal/person/day	Cape Verde (produces 0%), Gambia, Cote D'Ivoire, Gabon (produces 3%)	20,976,822 (2.5%)
Less Dependent <300 kcal/person/day	Remaining SSA countries	704,965,552 (85%)

Source: Adapted from Nyugen, 2005; FAOSTAT (2003–05 food supply data); FAOSTAT (2007 production data)

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

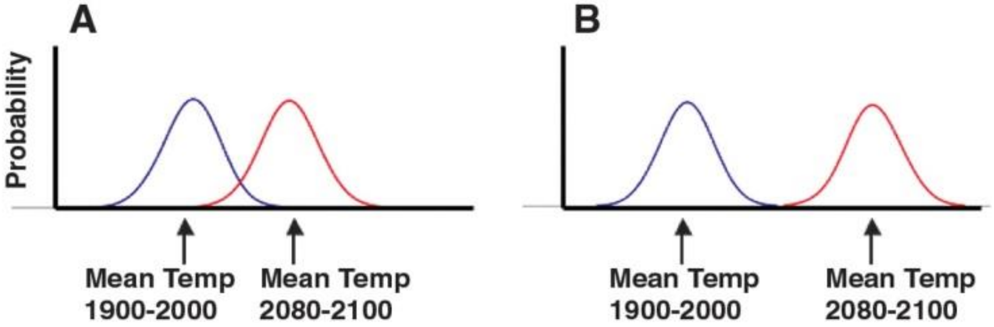
Climate change will affect agriculture by altering yields and changing the area where crops can grow.[42] The combination of climate factors and plant physiological responses will affect rice cultivation in complex ways, both positive and negative.[43] The first portion of this analysis will use historical data and climate model projections to provide novel regional estimates of climate conditions, variability, and projected climate change in SSA.[1] The second portion of the analysis will review the literature to provide an overview of rice's agronomic and physiological vulnerability to climate change.

Climate Analysis: Background

Under an emissions scenario consistent with current development trends, 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 3–4°C by 2100. Elevated areas in southern Africa may see increases of up to 7°C by 2100.[44,45,46]

In 11 SSA countries, the coincidence between current growing season temperature and projected future conditions (overlap) is projected to be less than 20% by 2050. In other words, by 2050 four out of five years will have an average growing season temperature above the warmest observed during the twentieth century. Projections vary for the rest of SSA, with only Tanzania, Malawi, Benin, Ethiopia, and Lesotho projected to experience temperature overlap of 80%.[47] *Figure 5* 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. Some countries will likely approach climate conditions that are novel at the continent level, especially those in the hotter Sahelian region. Senegal, Mali, Chad, Niger, and Burkina Faso are projected to achieve climate conditions with little to no current representation in the world.[48]

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



Source: Battisti & Nayor, 2009

Projected changes in precipitation are generally less robust than their temperature counterparts.[49] 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.

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

Despite pronounced uncertainty in some regions, IPCC has characterized several robust changes related to precipitation.[50] The IPCC considers several specific changes in rainfall patters to be likely. Firstly, mean annual rainfall will increase in tropical and eastern Africa. Secondly, winter rainfall will decrease in southern Africa. Thirdly, summer rainfall will increase in equatorial regions (north of 10ºS and east of 20ºE). And finally, summer rainfall will decrease in regions south of 10ºS. The onset and length of the rainy season are not projected to change in response to anthropogenic global warming.[51]

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.[52] Average overlap between distributions of historical and future precipitation is projected to fall to 86% by 2025, 84% by 2050, and 82% by 2075. These changes are for the entire western Sahel, not specific to rice-growing portions of that region, which is presented more specifically in the following section. Across Africa changes in precipitation will occur in both directions; some areas will become wetter and some will become drier. These projections are consistent with previous, independent assessments of African climate change and the robust changes in precipitation projected by IPCC.[53] 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 Intertropical Convergence Zone, a region of persistent intense thunderstorm activity.

The most sophisticated global climate models can produce robust projections with a resolution of 250 by 250 kilometers.[54,55] 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.[56,57,58]

For this analysis, global crop distribution data and twentieth century climate data were used to define four representative categories of growing season climates in SSA: Sahel, Coastal West Africa, Southern Africa, and Madagascar.[59,60] *Figure 2* 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 prolonged climate change over the twentieth century apart from year-to-year variability. Considering future change in the context of this historical variability may yield a comprehensive interpretation of climate change.

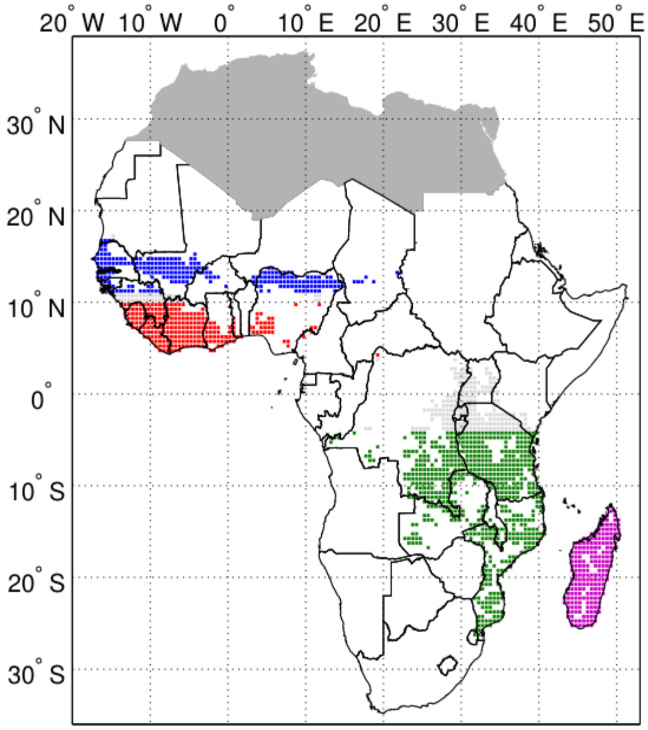


Figure 2: Rice growing regions in SSA, including: Sahel (blue), Coastal West Africa (red), Southern Africa (green), Madagascar (purple), and regions not included in the regional analysis (grey)

Source: Crop distribution data from Leff et al., 2004

Data

The historical temperature and precipitation data for this analysis come 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, grids them 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. It incorporates monthly-mean observations of six climate variables including temperature and precipitation for stations around the world. The observations are quality controlled using a state-of-the-art methodology and output to a regular 0.5 degree latitude by 0.5 degree longitude grid. Only observations for sub-Saharan Africa are used for this analysis.Although there is a paucity of data over SSA compared to developed countries, nearly complete spatial coverage is available.[61] Furthermore, strong statistics may be obtained for the complete twentieth century and the most recent two or three decades.

Methods

The future projections are based on model output from 23 models used for the IPCC AR4. These models originate from independent modeling centers around the world. Each is a unique representation of Earth's climate system, including the land surface, the atmosphere, the ocean, and the cryosphere, Earth's frozen water. While all of the models share the same governing equations, they differ in their treatment of phenomena that cannot be fully resolved (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 consensus between the various models.

The four rice-growing regions were defined based on an objective assessment of SSA areas where rice is grown and a subjective grouping of grid cells into four macro-regions with similar growing season climates. Growing season is defined for each region based on digitization and geo-referencing of observed crop planting and harvesting dates.[62] Historical distributions are defined by an area-average of grid points within rice-growing regions with a 1976–2006 mean and variability based on the entire twentieth century record (see *Table 3*). Mean and standard deviation are calculated only for growing season months and only for those grid cells in which rice is grown. To provide relevance for current agronomic conditions, this analysis considers average conditions over the last 30 years, but variability over the entire twentieth century.

The analysis of projected climate change uses a methodology similar to previous studies,[63] quantifying the percentage of overlap between various projected climate variable distributions and historical observations. Our analysis is performed for growing season average temperature and extended to growing season total precipitation. Projected future distributions of temperature and precipitation are presented at three years: 2020, 2050, and 2090, corresponding to near, intermediate, and long time horizons. The distributions are defined by two averages: the same area-average as in the historical distribution and an ensemble average of output from 23 climate models included in the IPCC AR4, each having one or more simulations totaling over 50 realizations of future climate.

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

Results

Current and Historical Climate Conditions of Rice Growing Regions

Table 3 presents area-averaged mean and standard deviation for growing season average temperature and growing season total precipitation over the four SSA sub-regions (shown in *Figure 2*). Temperature and precipitation differ markedly between the four regions. The Sahel is characterized by a comparatively hot and dry growing season, unsurprising given its proximity to the Sahara desert. Coastal West Africa's mean climate is strongly influenced by the North Atlantic Ocean and the steady march of seasonal wind patterns that bring moist maritime air ashore. Of the four regions, Coastal West Africa is the wettest in recent history. Southern Africa and Madagascar are both cooler and wetter than the Sahel. While both of the former have approximately the same growing season mean temperature, Madagascar is much wetter, due largely to its mountainous terrain and close proximity to the warm waters of the Indian Ocean.

Table 3: Mean (μ; ºC, cm) and standard deviation (σ; ºC, cm) for growing season average temperature and growing season total precipitation over four rice growing regions in SSA. 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; standard deviation based on entire period of record, 1901-2006).

Region	Growing season	μ(T)	σ(T)	μ(P)	σ(P)
Sahel	May - October	28.7	0.39	70.2	1.62
Coastal West Africa	May - November	25.6	0.28	139.0	0.87
Southern Africa	November - May	23.9	0.29	97.7	0.83
Madagascar	November - May	24.0	0.31	126.3	1.02

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

While mean temperature gives a static 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. For temperature, the Sahel stands out above the other regions with nearly 0.4ºC deviation from the mean on average. For precipitation, the Sahel is similarly far above the other regions, with a 1.62 centimeter deviation from the mean on average. This is significant because of its magnitude and because the Sahel already experiences lower mean growing season precipitation than all other regions.

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

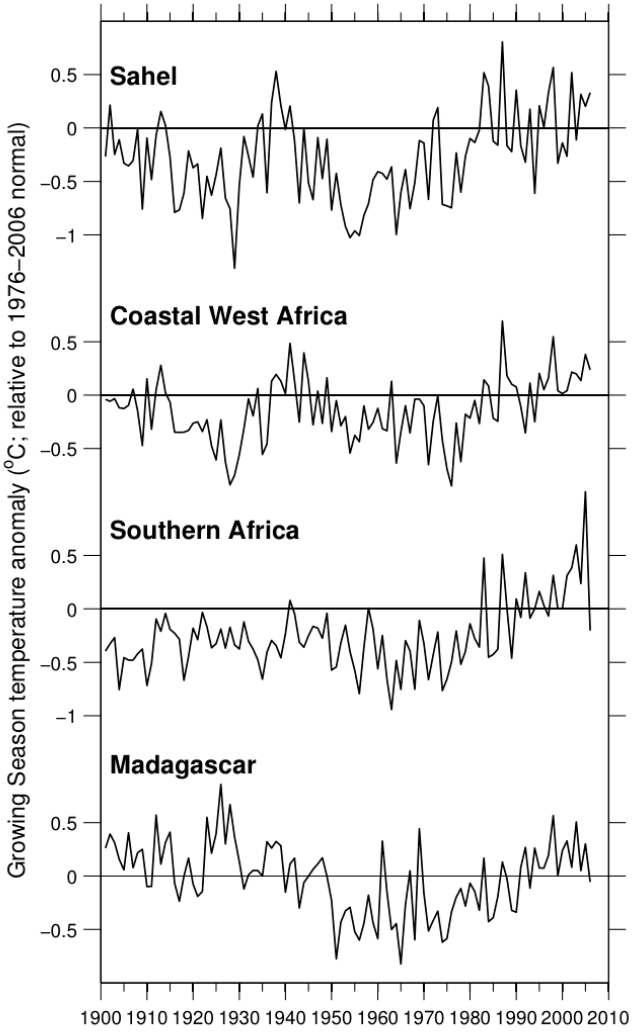
Temperature

Consistent with the larger climate system, Africa's average growing season temperature is warmer today than it was 100 years ago. While farmers on the ground must cope with the reality of a warmer climate, agronomists 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. Coastal West Africa also exhibits some multi-decadal variability in temperature, but less so than the Sahel. The warming over Coastal West Africa is approximately half of what was observed in the Sahel, which is to be expected given their different land surface types and proximities to the moderating influence of the North Atlantic Ocean. Growing season average temperature over Southern Africa was constant in the first half of the twentieth century; in contrast, there is a pronounced positive trend characterizing the second half of the twentieth century. Madagascar is the only region where little to no century long warming trend has been observed. However, as in the other three regions, a warming trend has been recorded over the past thirty years, beginning in the 1970s.

Precipitation

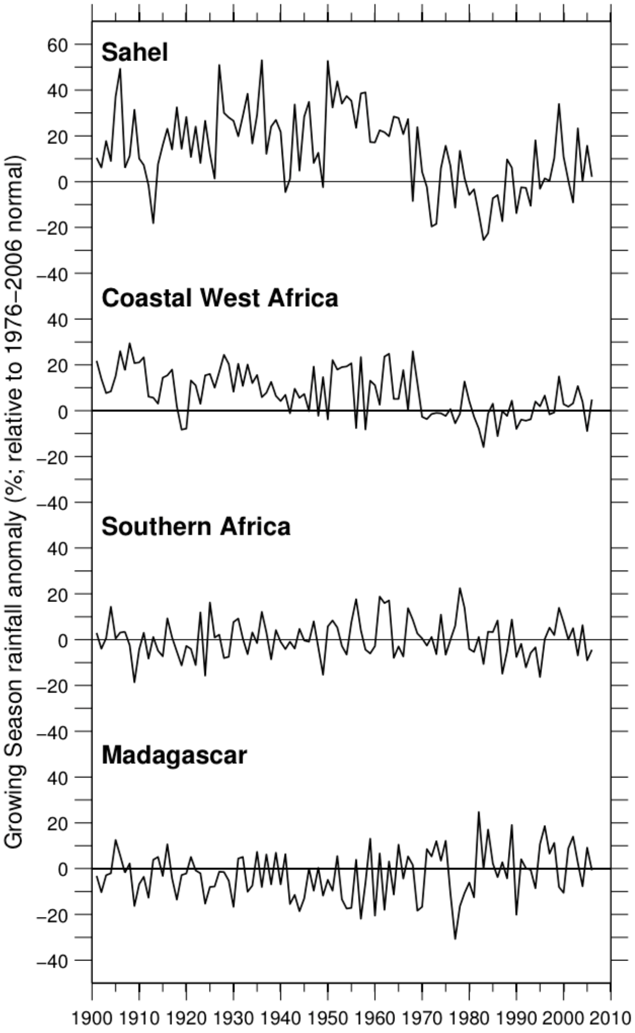
With the exception of the Sahel, precipitation variations over the twentieth century are far less dramatic over Africa than elsewhere around the globe. Coastal West Africa has seen a small, but not statistically significant, trend over the century. Southern Africa and Madagascar have seen virtually no trend detectable outside of year-to-year variability. On the other hand, 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 contributing to some improvement, however growing season total precipitation remains below the long-term Sahelian average.

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



Source: UEA CRU TS 3.0

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

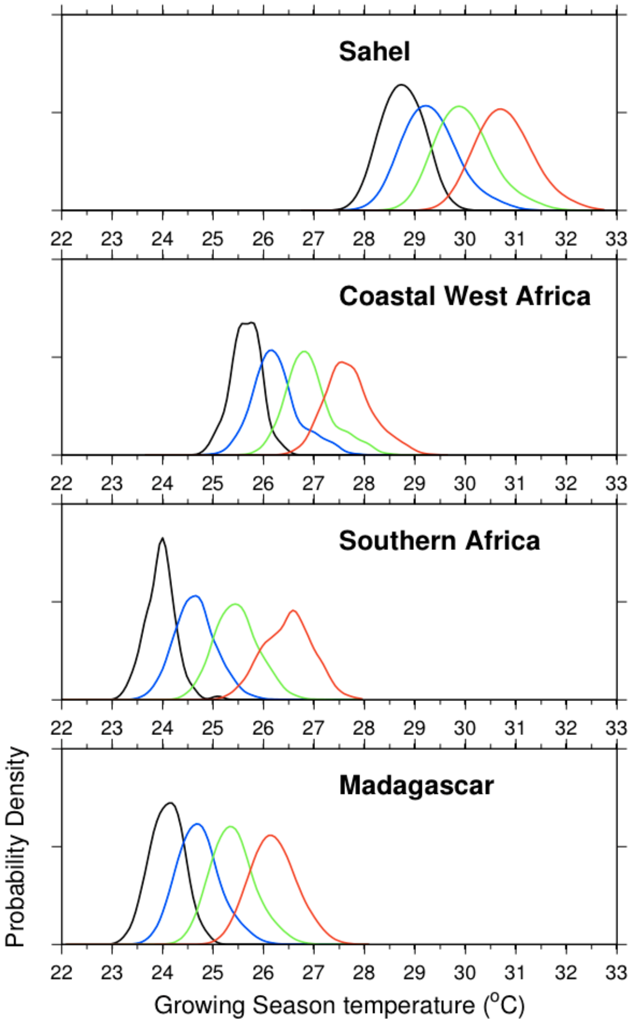


Source: UEA CRU TS 3.0

Projected 21st Century Climate Change in Rice Growing Regions

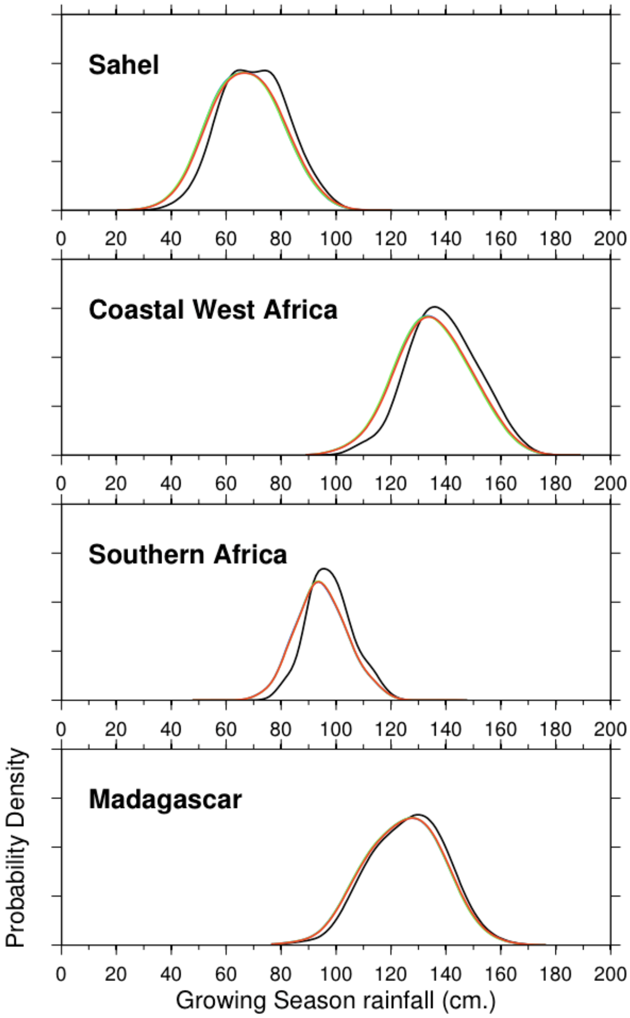
Temperature shift predictions are robust among the 23 models included in our analysis. *Figure 6* shows historical distributions of growing season average temperature for the four regions and three future distributions corresponding to climate at 2020, 2050, and 2090. The magnitude of the shifts themselves is similar, but the percentage of overlap varies spatially according to the degree of natural variability observed across each area. For example, over the Sahel where large temperature variability is observed, the percentage of overlap is larger than the others at 2020 and 2050. In other words, an equivalent shift in the mean climate at a location with low variability (e.g., Southern Africa) will mean less overlap than for one with high variability (e.g., the Sahel). Notwithstanding this nuance, by 2090, each of the four regions is projected to move into a completely novel warmed climate, distinct from the observed 20th century climate there. *Table 4* illustrates this numerically, depicting the percentage of overlap between the historical and projected future distributions by 2020, 2050, and 2090.

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



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

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



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

The shifts are less pronounced for precipitation than for temperature, reflecting a larger degree of agreement in the size of the shift amongst the models in time and space (*Figure 7*). In other words, the models disagree over how large and of what sign precipitation changes will be across Africa.[64,65] Thus, 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 changes and allow a better characterization of shifts over these representative regions. Another way to increase confidence in precipitation projections would be to weight the results according to how well the model reproduces current and historical climate variability. Thus, models performing poorly would essentially be thrown out in favor of higher performers. Nonetheless, such an endeavor is beyond the scope of this analysis and also leads to additional assumptions regarding proper metrics, which themselves must be justified.

Table 4: 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	64%	20%	0%
	P	90%	90%	91%
Coastal West Africa	T	44%	4%	0%
	P	90%	90%	90%
Southern Africa	T	38%	1%	0%
	P	88%	88%	88%
Madagascar	T	50%	5%	0%
	P	93%	93%	93%

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

Discussion

The results presented are consistent with previous studies, which find significant shifts in temperature and uncertain changes in precipitation.[66] Temperature shifts are a well-understood response to rising greenhouse gas concentrations and associated radiation and circulation changes. As noted earlier, precipitation trends were small over the twentieth century and set amongst large year-to-year variability. Thus, despite pronounced uncertainty in the direction of precipitation changes, year-to-year changes will almost certainly overwhelm trends that do occur. Farmers in SSA 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 or flood). On the other hand, persistent temperature increases constantly change the baseline from which rice farmers in SSA have to judge the present conditions.

Agronomic and Physiological Vulnerability

Rice Temperature Requirements

The ideal thermal climate for Asian rice is between 25ºC and 30ºC.[67] For the grain-fill stages, the optimal temperature is slightly lower, between 20ºC and 25ºC.[68] African rice does well at temperatures between 30ºC and 35ºC.[69] For both species, exposure to extreme maximum temperature is most hazardous during the flowering stage; even a few hours of high temperatures during this stage can greatly reduce pollen viability and result in yield loss.[70] Specifically, the upper temperature threshold during flowering is 35ºC; spikelet sterility occurs after only one hour of exposure to temperatures above this threshold.[71,72] Susceptibility to temperature-induced sterility also increases with elevated CO_2 levels.[73] Regarding minimum temperature tolerance, a study of irrigated rice in the Sahel showed that an air temperature drop from 18ºC to 16ºC increased spikelet sterility from zero percent to 100%.[74] Male plants are less sensitive to high temperatures during their reproductive phase, and are instead more sensitive to cool temperatures.[75]

Rice Water Requirements

The rice plant is best adapted to swampy conditions and is sensitive to water stress, making wetlands the most suited areas.[76] Nevertheless, rice grows in a variety of ecosystems in SSA: 33% on rainfed lowlands (wetlands), 20% on irrigated wetlands, 38% on drylands (upland) and nine percent in swamps.[77,78,79] Rainfed rice thrives in areas with annual rainfall ranging from 0.5 to more than 1.5 meters and flourishes in locations where the growing season is 90 days or longer.[80] Areas with annual rainfall between 0.5 and 1 meter generally have only one growing season and sustain a single rice harvest. Two rice harvests are possible where rainfall peaks twice annually.[81]

Changes in Plant Physiology under Climate Change

Photosynthesis & Biomass Production

In general, increased temperatures accelerate plant development, however, they may decrease yield as a consequence of more rapid growth.[82] 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.[83,84] Elevated CO_2 suppresses photorespiration and increases the ideal temperature for photosynthesis.[85] Studies on the effect of higher temperatures alone present contradictory findings; some researchers found higher temperatures to increase photosynthesis in rice, others found rice canopy photosynthesis relatively unchanged under a variety of air temperatures.[86] Therefore, the net effect of increased CO_2 and temperatures on rice photosynthesis depends upon the relative magnitude of the changes and the interplay of combined physiological responses.[87]

Evapotranspiration

While climate change predicts an overall increase in precipitation, higher temperatures will also increase evapotranspiration (the evaporation of plant transpiration into the atmosphere)–most drastically in areas where the temperature is already high, such as SSA.[88] Evapotranspiration also increases with lower precipitation, thus subjecting plants to a greater demand for water when there is less supply. The relative increase in the probability of low yield is, therefore, greater than the relative decrease in precipitation.[89]

Water Use Efficiency

Elevated CO_2 causes plant stomata to narrow, decreasing water loss and thereby improving water use efficiency (WUE).[90,91] Conversely, increases in temperature decrease WUE by increasing evaporation.[92] In conjunction, doubling CO_2 has been shown to increase WUE by 50% but that increase declines sharply above optimum temperatures.[93]

Changes in Agricultural Conditions under Climate Change

Temperature

Changes in temperatures will change the areas where rice can grow. For example, an average temperature increase of 2.5°C is projected to decrease Guinea's suitable rice growing land 17% by 2050 and 37% by 2100. A temperature rise of 4.5°C would nearly double this loss.[94] Evidence from the International Rice Research Institute (IRRI) demonstrates that rice yields may decrease as a result of the higher night temperatures as well.[95] On the other hand, increased temperatures may allow crops to grow at higher altitudes.[96] The length of the growing season in mid-higher latitudes will also increase, which may permit earlier planting and multiple cropping.[97]

Water Availability

In general, rainfed crops are likely to be worse hit by climate change because of the limited mechanisms for coping with precipitation variability.[98] Declining rainfall reduces the soil's capacity to retain moisture.[99] Rice root systems penetrate about 20 centimeters into the soil; water stress thus ensues when the moisture content of topsoil layers is depleted.[100]

Weeds & Pests

Weed competition presents a significant constraint particularly for upland rice, which lacks standing water to combat weed growth. Weeds are generally more competitive than rice in this ecosystem therefore extensive weeding is required to achieve a decent yield.[101] With lower water requirements, C4 weeds are better able to tolerate drought stress and are thus more competitive than rice in upland ecosystems.[102] While elevated CO_2 levels increase biomass production in C3 weeds, this is not true for C4 weeds, which will likely become less aggressive, especially in fields of C3 crops such as rice.[103]

Increased climate extremes may also promote plant disease and pest outbreaks and affect crop-pest relationships.[104,105] Pest and disease concerns for rice plants include rice yellow mottle virus, rice blast, and African Rice Midge.[106] Plant tissue quality degrades in high-CO_2 environments, which increases feeding damage by pest species.[107] A meta-study of research in Asia demonstrated that higher temperatures inhibited rice blast development, in general. Rainfall variation, on the other hand, was not shown to have a significant effect.[108]

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.[109] 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.[110]

Overall Impact of Climate Change on Rice Yields

The overall impact of climate change on rice yields depends on the complex interplay of changes in plant physiology and agricultural conditions. To the extent that these combined effects have been studied, models typically look at average changes and exclude the effects of extreme events, variability, and agricultural pests, all of which are likely to increase.[111] In addition research investigating the combined impacts of climate changes on weeds, pests and plant diseases is still insufficient.[112,113] The majority of scientific studies on rice vulnerability to climate use Asian rice.

Existing studies have shown that yields increase with increasing CO_2 and decrease with increasing temperature.[114] Yield losses are primarily caused by high-temperature-induced spikelet sterility, however there is a lack of more detailed studies addressing the interaction of CO_2 and temperature.[115] Furthermore, these studies often hold precipitation constant, even though seasonal water availability also affects rice yields.[116] Matthews et al (1997) found that an increase in temperature at all CO_2 levels would cause a decline in rice yields and an increase in CO_2 would increase yields at all temperature levels.[117] The study used this data along with climate models to project the overall impact on rice yields for several rice-producing countries in Asia. Such research has not been replicated for SSA, unfortunately.

The customized novel climate analysis presented earlier offers some clues regarding the vulnerability of the rice growing regions it focused on. For example, the growing season climate of the Sahel is expected to increase to above 30ºC by 2090, well above the ideal thermal climate for Asian rice but still within the tolerances for African rice. This suggests that by the end of the century, some species may become highly vulnerable in the Sahel, particularly in the grain-fill stages, where the optimal temperature range is lower.

On the other hand, the novel climate analysis also suggests that rice agriculture may become more ideal in regions further to the South (e.g., Madagascar, Coast West Africa, Southern Africa), where warming could bring the growing season average temperature more into the middle of the optimal thermal zone for Asian rice.

Caution is warranted, however, because the foregoing analysis is based on growing season average temperature, not on the month-to-month or day-to-day changes (i.e., weather) that drive plant growth on a scale relevant to farmers on the ground. At present, such an analysis is not possible given the coarse time resolution of climate projections. Even if high temporal resolution were available, the projections might not offer any practical results because of the inherent limits of weather prediction and 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.

Pillar 3: Current Resources Dedicated to Rice in SSA

Resilience to the risks associated with climate variability and extreme events depends on adaptation and mitigation strategies at the international level all the way down to the farm-level.[118] The constraints to rice production in SSA include climate-related factors as well as a lack of inputs, lack of infrastructure, high post-production losses and poor market access. There are some inexpensive adaptation strategies to cope with climate change, such as shifting planting dates or switching to another existing crop variety. The largest benefits, however, will likely come from more costly adaptation measures that address additional constraints, including the development of new crop varieties and expanding irrigation.[119]

Research & Development

Increased attention to rice by the New Partnership for Africa's Development (NEPAD) and its Comprehensive Africa Agriculture Development Programme (CAADP), the African Rice Center (WARDA), and the Africa Rice Initiative has strengthened the institutional environment for African rice development in recent years.[120] However, the ratio of researchers to extension workers remains much lower in SSA than Asia. This suggests that the lack of profitable technology, not the lack of extension, most constrains improving rice productivity.[121]

Full time equivalent researchers (FTE) serve as a proxy for the magnitude of institutional resources devoted to rice 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 crops researchers, of which 242.9 (7%) were focused on rice.[122] Among resources dedicated to cereals, FTE rice researchers comprise 26% of all cereal researchers.[123] The top five rice-producing countries (Nigeria, Madagascar, Guinea, Tanzania and Mali) account for 65.3% of these resources.[124]

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 BMGF) the International Rice Research Institute (IRRI), the Africa Rice Center (WARDA) and the Centro Internacional de Agricultura Tropical (CIAT) are the main agencies focused on rice research. Other CGIAR centers conducting rice research include Bioversity and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). Additionally, IRRI established the Rice and Climate Change Consortium in 2007 to assess the consequences of climate change for rice production and develop adaptation strategies.[125] Published research from the Consortium to date concentrates on irrigated rice systems, Asian rice systems and rice's contribution to climate change.

Improved Varieties

In 2002, the governments in sub-Saharan Africa–with the initial support of the United Nations Development Programme (UNDP), WARDA and the FAO–established the Africa Rice Initiative (ARI) to promote the dissemination of NERICA rice.[126,127] While demand for NERICAs is very high, seed availability presents a key constraint.[128] The seed system has collapsed in most SSA countries; the private sector is reluctant to invest in rice seed, thus ARI produces both foundation and breeder seed.[129] Therefore, strengthening the formal and informal seed systems is an important adaptive strategy.[130]

Irrigation

Irrigated rice in Africa can be just as productive as anywhere else in the world, however, irrigation covers only 14% of the cultivated rice area and is concentrated in only a few countries.[131,132] Irrigation covers 80% of rice in Cameroon and nearly 100% in Mauritania. The yield potential of irrigated rice increases with high solar radiation and low disease stress in drier zones such as Niger (55% irrigated), Mali (30%) and Burkina Faso (20%).[133] When irrigation is not possible, rice varieties and production technologies developed for the irrigated ecology can be easily adapted for cultivation in rainfed wetlands with favorable conditions.[134]

Improved Crop Management Strategies

In 2000, the Expert Consultation on Yield Gap and Productivity Decline in Rice Production identified improved crop management and technology transfer as the principal mechanisms for enhancing rice yield.[135] The FAO and member countries have conducted pilot tests.[136] In 2002, the International Rice Commission recommended that funding donors, FAO, partner institutions and all stakeholders should increase funding support for such activities aimed at the sustainable increase in rice production to reduce hunger and poverty.[137]

National Adaptation Programmes of Action

The current capacity of human systems in Africa to adapt to climate change is very low due to lack of economic and technological resources.[138] As part of the Least Developed Countries (LDC) Work Programme, 27 SSA countries have submitted 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.[139]

Increasing and adapting rice cultivation figures prominently into the NAPAs of 11 countries. Common foci across many countries include increasing irrigation, dissemination of improved varieties, and increasing lowland rice cultivation. Several countries also have unique strategies tailored to their specific circumstances. Liberia includes plans to promote integrated cropping and livestock systems–such as lowland rice and small ruminant rearing–to encourage crop diversification and improve food security.[140] Guinea-Bissau plans to rehabilitate marginal mangrove forests for rice cultivation.[141] The Gambia plans to invest in waterway infrastructure such as causeways and dams to protect lowland rice fields from flooding and also develop tidal irrigated land for rice cultivation.[142] NAPAs are only proposed plans, however, and are not accompanied by any committed funding. Unfortunately, funding for implementation has been very limited to date, despite the fact that submitted NAPAs are ready for the implementation phase.[143]

Table 5: NAPA Strategies for Rice Production

Adaptation Strategy	**Countries**
Increase irrigation for rice cultivation	Sierra Leone, Senegal, Madagascar, Guinea, The Gambia, Burundi
Increase dissemination of improved varieties	Togo, Senegal, Guinea, The Gambia, Congo
Increase cultivation in lowlands, marshes, swamps, and mangrove forests	Sierra Leone, Rwanda, Guinea, Guinea-Bissau, Burundi
Promote integrated cropping and livestock systems	Liberia
Rehabilitate mangrove forests	Guinea-Bissau
Waterway infrastructure	The Gambia

Source: National Adaptation Programmes of Action[144]

Conclusion

Rice represents 15% of total cereal consumption, 13% of production and receives 25% of all FTE cereal researchers in SSA, though only seven percent of total crop researchers in the region. Given that rice plants can grow under a variety of conditions, it can play an important role as the climate in SSA changes and becomes less favorable for agriculture. Limited and low-resolution climate data and prediction capabilities for Africa, however, present a critical constraint to planning and implementing adaptation mechanisms. 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.[145] Several SSA countries include adaptation strategies to improve or increase rice cultivation in their National Adaptation Programme of Action (NAPA). Some international research and development in recent years has focused on rice cultivation in Africa, however, efforts to date have not been sufficient to decrease the continent's negative net rice trade.

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

Appendix 1. Rice Production & Trade Compared to All Cereal Production

	Rice Production*	Net Trade** (Exports – Imports)	Rice Production as % of Total Cereal Production
Angola	4635	-166100	0.66%
Benin	72960	0	6.30%
Botswana		470	0.00%
Burkina Faso	68916	-14988	2.22%
Burundi	70911	-10971	24.33%
Cameroon	65000	-203168	3.38%
Cape Verde		0	0.00%
Central African Republic	37595	-6	15.89%
Chad	106379	-1530	5.39%
Comoros	20000	-35354	83.33%
Congo	1300	-55662	6.50%
Côte d'Ivoire	606310	0	48.75%
Democratic Republic of the Congo	316180	-7201	20.74%
Djibouti		-49182	0.00%
Equatorial Guinea		-5264	0.00%
Eritrea		-122	0.00%
Ethiopia	11244	-34516	0.09%
Gabon	1100	-32230	3.23%
Gambia	11395	0	7.57%
Ghana	185340	0	11.08%
Guinea	1401592	0	53.88%
Guinea-Bissau	127250	0	69.21%
Kenya	47256	-132045	1.31%
Lesotho		-4550	0.00%
Liberia	231800	0	100.00%
Madagascar	3000000	-183944	88.70%
Malawi	113166	923	3.29%
Mali	1082384	0	27.86%
Mauritania	82165	0	44.78%
Mauritius	0	-59254	0.00%
Mozambique	104655	-425299	7.20%
Namibia		-571	0.00%
Niger	70000	0	1.81%
Nigeria	3186000	0	11.73%
Rwanda	62000	-18556	17.61%
Sao Tome and Principe		-2283	0.00%
Senegal	193379	0	25.04%
Seychelles		-4480	0.00%
Sierra Leone	1000000	0	90.95%
Somalia	16000	0	8.16%
South Africa	3300	-115453	0.03%

Sudan	23000	-948901	0.34%
Swaziland	170	-52523	0.62%
Togo	74843	-20615	8.53%
Uganda	162000	-22477	6.16%
United Republic of Tanzania	1341846	11547	21.56%
Zambia	18317	-5398	1.19%
Zimbabwe	600	-2356	0.05%

Source: FAOSTAT (2007 data); *Production of rice paddy; **Net Trade includes trade of rice paddy and milled rice

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