# Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation

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## Abstract

Increased understanding of the substantial threat climate change poses to agriculture has not been met with a similarly improved understanding of how best to respond. Here we examine likely shifts in crop climates in Sub-Saharan Africa under climate change to 2050, and explore the implications for agricultural adaptation, with particular focus on identifying priorities in crop breeding and the conservation of crop genetic resources. We find that for three of Africa's primary cereal crops – maize, millet, and sorghum – expected changes in growing season temperature are considerable and dwarf changes projected for precipitation, with the warmest recent temperatures on average cooler than almost 9 out of 10 expected observations by 2050. For the "novel" crop climates currently unrepresented in each country but likely extant there in 2050, we identify current analogs across the continent. The majority of African countries will have novel climates over at least half of their current crop area by 2050. Of these countries, 75% will have novel climates with analogs in the current climate of at least five other countries, suggesting that international movement of germplasm will be necessary for adaptation. A more troubling set of countries – largely the hotter Sahelian countries – will have climates with few analogs for any crop. Finally, we identify countries, such as Sudan, Cameroon, and Nigeria, whose current crop areas are analogs to many future climates but that are poorly represented in major genebanks – promising locations in which to focus future genetic resource conservation efforts.

## Introduction

Climate is a significant constraint on agriculture throughout much of Sub-Saharan Africa (hereafter "Africa"). With over 40% of the continent's population living on less than $1/day, and 70% of these poor located in rural areas and largely dependent on agriculture for their livelihoods (Chen and Ravallion 2007), adverse shifts in climate can cause

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devastating declines in human welfare.  Such shifts have been implicated in everything from famine to slow economic growth to heightened risk of civil conflict (Bloom and Sachs 1998; Miguel, Satyanath et al. 2004).  As a result, increased attention is being paid to assessing risks to African agriculture under climate change, with some studies finding moderate to severe adverse effects on agricultural productivity occurring in as early as two decades (Easterling, Aggarwal et al. 2007; Lobell, Burke et al. 2008).

Increased understanding of climate threats to agriculture in Africa, however, has not been met with a similarly improved understanding of how best to respond.  Given the adaptability displayed by farmers in the face of past climate variability (Adger, Agrawala et al. 2007), there appears to be some scope for African farmers to adapt on their own to climate change, for example by switching crops or varieties or by altering the timing of planting.  But if future change is exceedingly rapid, or if it dwarfs the magnitude of past variability, farmers may be unable to adapt without some help.  As a result, there exists a widely acknowledged need for significant investment in agricultural adaptation, but there has been little systematic assessment of how to prioritize these so-called “planned” adaptations – what form they should take, and on what crops and locations they should focus.

Here we analyze data on shifting climates to help inform priorities for one major adaptation strategy:  breeding crop varieties to tolerate future climates.  Past crop varietal improvement through breeding has contributed to unprecedented gains in human well-being throughout much of Asia and Latin America (Evenson and Gollin 2003).

Unfortunately, to date this “green revolution” has largely bypassed the African continent, an absence implicated in Africa’s decades-long track record of poor agricultural development and economic performance (World Bank 2008). As a result, the development of improved crop varieties suited to Africa’s diverse agroecologies is seen as a central priority by the international development community.

Numerous strategies exist for such crop improvement, and while advances in biotechnology can offer alternative, more direct pathways to genetic modification of crops, traditional breeding has a long history of success, is typical for most African breeding programs, and thus likely will continue to be a critical strategy for crop improvement. Central to past successes with traditional breeding has been the availability and use of diverse crop genetic resources that contain the traits being bred for – for instance, landraces or crop wild relatives with resistance to drought, heat, or a particular pest or disease.

Unfortunately, African crop genetic resources conservation is generally poorly supported at a national level, and material from the region is not fully represented in the major international genebanks that provide the foundation for sustained public breeding efforts. Table 1 shows representation of African maize landraces in selected major genebanks, with African varieties making up roughly 5% of the total holdings. Although the center of origin of maize is Mesoamerica, maize has been grown in Africa for hundreds of years, during which farmer selection has produced varieties adapted to the diverse and often harsh growing conditions on the continent. And while the number of accessions in hand is often an imperfect estimate of diversity conserved, African maize varieties are clearly under-represented in major genebanks, constraining breeding programs. For sorghum, another important African cereal crop whose center of origin is in the Sahel, African varieties represent a higher percentage of total varieties conserved internationally, but key gaps exist in both the characterization and geographical representation of existing collections (GCDT 2007).

National genebanks do conserve additional material that is not always represented in the international genebanks (Table A1), but the coverage of the diversity present in the country is usually far from complete (GCDT 2007). Furthermore, national genebanks often vary widely in their condition, and many are in need of immediate funding simply to maintain the viability of their existing collections. Finally, countries have sovereignty over genetic resources, and the accessibility of material in national genebanks to outside breeders can differ substantially from country to country. As a result, identifying where to focus efforts to collect and conserve African landraces is seen as a major priority in the crop genetic resources community.

## Approach and methods

Using historical climate data, maps of crop area, and climate model ensembles drawn from the recent Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4), we take two approaches to investigating how crop climates will change across the continent. The first compares historical climate at a given location to the projected future climate at that location, asking how quickly climate change will push local crop climates beyond recent experience[3]. Given that many investments in agricultural adaptation, such as improved crop varieties or expanded irrigation infrastructure, can take decades to realize returns (Reilly and Schimmelpfennig 2000), understanding the rate and magnitude of climate change can inform the magnitude and timeliness of needed adaptation investments.

Because climates often vary as much across space in a country as they do over time, our second approach compares present and future crop climates within and across countries, determining to what extent the spatial range of future climate in a country is represented in that country today, and whether any un-represented portion has analogs elsewhere on the continent presently. We use this approach to identify both future problem regions with no analogs on the continent in today's climate, and countries whose current crop areas appear likely analogs to many future climates, with the latter case representing promising areas for genetic resource collection and preservation. For both approaches, we focus on crop climates for Africa's three primary rainfed cereals – maize, sorghum, and pearl millet – which together provide on average roughly 30% of calories consumed in Africa, rising to over 65% in some countries (FAO 2008). Our overall approach is not intended to map changes in crop suitability under climate change, nor to determine the effect of climate change on crop yields – both very important topics in their own right – but rather to characterize the climates under which Africa's cereals will need to be grown

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[3] We thank D. Battisti for this suggestion.

in coming decades, and to use this information to prioritize breeding and genetic resource conservation efforts.

## How fast are crop climates changing?

To explore the magnitude and speed of climate change over major crop areas in Africa, we calculate the percentage overlap between historical (1960-2002) growing season temperature and precipitation and their potential 2025, 2050, and 2075 values over reported crop area.  We combine historical climate data (Mitchell and Jones 2005) with maps of crop distribution (Leff, Ramankutty et al. 2004) and estimates of the months in which crops are grown in each country (Lobell, Burke et al. 2008) to derive a 43-year time series of historical growing season climate at each 0.5 x 0.5 degree grid cell – the scale at which our historical climate data and crop maps are available.  Future temperatures are determined by adding to historical time series data the simulated changes in average temperature for the 18 climate models running the A1B emissions scenario. Similarly, future precipitations are computed by multiplying current values by simulated percent changes from the range of climate models, which yields the range of possible future precipitation under the A1B scenario.  Climate for the A1B scenario is roughly similar to other AR4 emissions scenarios through 2050, and intermediate between the A2 and B1 scenarios by 2075 (Meehl, Stocker et al. 2007).

Perhaps importantly, our analysis assumes no shifts in the main growing season months for African cereals.  While this might be an unreasonable assumption for irrigated areas where a shift in planting dates could optimize changing growing-season temperatures, it is a more likely scenario for the vast majority of African cereal area where production is rainfed and where planting is constrained by the onset of the rainy season – the latter which is unlikely to shift substantially under future climate (Christensen, Hewitson et al. 2007).

To determine overlap between past and future climates, we determine the percentage of possible future climates (as calculated above) that fall within the 5th to 95th percentile range of historical climate observations for a given area. An example for a hypothetical region is shown in Figure 1. We repeat this procedure for every grid cell in the primary African cereal areas, and for the future climate years of 2025, 2050, and 2075.

Results show that for temperature, nearly all crop regions move rapidly outside of historical experience. Figure 2 maps the overlap between historical and projected future growing season temperatures for maize in Africa. Results indicate that growing season temperature at any given maize growing region in Africa will overlap on average 58% with its historical observations by 2025, 14% by 2050, and 3% by 2075. This suggests that within two decades, growing season average temperature will be hotter than any year in historical experience for 4 years out of 10 for the majority of African maize area, growing to nearly 9 out of 10 by 2050 and nearly 10 out of 10 in 2075. Similar results were obtained for millet (sorghum), with 54% (57%), 12% (15%), and 2% (3%) overlap between historical and 2025, 2050, and 2075 growing season temperatures, respectively.

Projections of precipitation change over African crop areas represent considerably smaller departures from historical experience. For maize, average overlaps between historical and future growing season precipitation across Africa are 86%, 84%, and 82% for 2025, 2050, and 2075, respectively, with quantitatively similar results for millet and sorghum. Larger overlaps of past and future precipitation relative to temperature are a reflection of high year-to-year variability in historical rainfall relative to projected trends. The non-overlapping part of the potential rainfall distribution includes both wetter and drier growing seasons, reflecting the substantial climate model disagreement over the direction of precipitation change across most of Africa (Christensen, Hewitson et al. 2007).

Given that growing season average temperatures will quickly and increasingly exceed the range of historical experience at a given location, and that yields can be quite sensitive to these temperature shifts (Lobell, Burke et al. 2008), adaptations will undoubtedly be needed to moderate the impacts of warming. Importantly, one primary adaptation option for agriculture – the development of crops suited to changed climates – can involve large time lags, with more than a decade often required to develop and screen new crop varieties and get them in the hands of farmers. Given this lag, and with a 40% chance by 2025 that growing season climate will be hotter than anything in recent historical experience, our results suggest a pressing need to develop breeding programs that anticipate these rapidly warming growing environments.

## Spatial analogs in crop climates

While the importance of both private-sector crop breeding and the use of advanced genetic techniques has grown rapidly in importance throughout the developed and developing world, crop improvement in Africa remains a primarily public-sector endeavor, usually with strong reliance on classical breeding techniques (Pardey and Beintema 2001). Such techniques rely on *ex-situ* collections of crop genetic diversity – i.e. genebanks – and thus breeding for a warmer world requires that the necessary crop diversity be conserved and available within the relevant genebanks. As noted above, African cereals are often poorly represented in international genebanks, and national genebanks on the continent are frequently resource-constrained and not always representative of the crop genetic diversity in the country.

To help identify priorities with respect to collection and conservation of these genetic resources, we evaluate the extent and location of places whose current climate serves as an analog for the future climate in the location of interest. Such climate analogs represent regions of crop genetic diversity highly relevant to future growing conditions on the continent, and thus a promising source for germplasm on which needed breeding efforts could be based. Given the important role that political boundaries play in shaping agricultural development – i.e, the continued importance of national breeding programs and the political constraints to cross-border movement of genetic resources – we focus our analysis on the country level.

To analyze crop climate analogs across space, we follow a similar procedure as above, computing the overlap between current crop climates in a given country and future crop climates in all countries in Sub-Saharan Africa (Figure 3). Current crop climate for a given country is defined by the area-weighted distribution of growing season average temperature and precipitation across all grid cells reporting area for a given crop within that country, averaged over the last decade for which data are available (1993-2002). We use the last decade of climate data instead of the full 40-year time series to define current climate because it is long enough to mask high year-to-year climate variability, but short enough to realistically capture current growing conditions in the context of a rapidly-warming continent. Future crop climates are again defined by adding (multiplying) projected changes by 2050 for each climate model running the A1B scenario to the current range of growing-season temperatures (precipitation) within the country. Consistent with other assessments (Fischer, van Velthuizen et al. 2002), we assume no major changes in crop suitability across the continent by mid-century, and thus no large expansion of crop area.

To understand how well a country's current range of growing season climate represents its likely future range, and if and where any un-represented (or "novel") climates in that country have analogs in current climate elsewhere on the continent (Williams, Jackson et al. 2007), we estimate two types of overlap between present and future crop climates. The first calculates the amount of overlap a country's present range of climate will have with its future range (or "self-overlap"). Self-overlap is defined as the percentage of 5th-95th percentile present climate observations that fall within the range of possible future climates projected for a given country (Figure 3). For any novel future climate un-represented by that country's present climate, we calculate the percentage of that novel climate falling within the present 5th-95th percentile of each of all other country crop climates in Africa.

Figure 4 shows percentages of self-overlap between a country's current and 2050 growing season temperatures for maize, millet, and sorghum, with countries sorted by percent overlap of maize temperature. Results provide three insights. First, they confirm the importance of model-predicted temperature shifts relative to precipitation shifts (not shown). For 85% of countries, simulated future precipitation regimes overlap with current climate better than do future temperature regimes – again reiterating the importance of collecting, evaluating and breeding for heat tolerance.

Second, results suggest that climate is typically more variable across space than across time – that is, the range of growing-season climates within a country in a given year is larger than the range of historical growing season climates at any given point in that country. Looking across African countries, the average overlap between a country's current range of maize growing season temperatures and its 2050 range is 40%; the average overlap is only 10% when comparing historical and likely future temperatures at any single maize-growing point on the continent. This suggests that even within countries, substantial variation in the range of growing season climate could indicate exploitable genetic variation in the suitability of crops to different climates. For a country with large overlap between current and future climate, crop areas in one region of the country could serve as analogs for crop areas in other regions of the country.

Finally, for the majority of African countries, current growing season temperatures within a country will represent less than half of the range of expected 2050 growing season temperatures over maize, millet, and sorghum areas in that country. Almost uniformly, the countries with larger climatic ranges currently – such as the topographically diverse countries of East Africa – overlap better with their future climate. For the 51% of countries where more than half of maize area in 2050 will experience temperatures currently unrepresented in present climate, it is likely that they will have to look outside their borders to find varieties suitable to their new climates.

To match the need for outside genetic resources with promising locations in which to find them, we compare novel 2050 climates from each country with current climates in all African countries. Figure 5 plots the overlap of these novel 2050 climates (y-axis) with current climates for maize, with countries sorted vertically by average temperature (Mali hottest, Lesotho coolest), and warmer colors indicating higher overlap. Again, three stories emerge from the data.

First, many countries with low self-overlap have novel future climates with many analogs in present climate elsewhere. Fourteen countries (orange countries, Figure 6) overlap less than 50% with their future maize area, but have five or more countries that overlap at least 75% with their novel climates. For these countries, breeding efforts to cope with warming could greatly benefit from accessing genetic resources beyond their own borders.

Second, there is a more worrying set of countries with little self-overlap *and* few current analogs for their novel climates. For maize, there are five countries with <50% overlap and fewer than five country analogs (red countries in Fig 6), with two others only slightly above the 50% threshold. These countries are clustered in the Sahel and tend to have warmer than average current growing season climates. For these countries, there is thus a much smaller potential pool of foreign genetic resources in which to seek heat tolerance, at least within Africa. If breeding efforts cannot sustain yield for maize in these countries in the face of warming temperatures, switches to more heat- and drought-tolerant crops, such as sorghum and millet, could be necessary.

Finally, there is a set of countries whose current climate is an analog to many future novel climates, suggesting promising potential sources of germplasm for future breeding efforts in anticipation of climate change. Importantly, landraces from many of these countries – for example Sudan, Nigeria, Cameroon, and Mozambique – are particularly poorly represented in national and international genebanks (Figure 7). The top ten analog countries for maize – those which overlap most with anticipated novel climates on the continent – each have fewer than 150 landrace accessions in major genebanks (see Table A2). These countries appear as particularly high priorities for urgent collection and conservation of maize genetic resources. An additional criterion for prioritization could also be the total area sown to maize in each country, which varies by a factor of over 100 between Eritrea and Nigeria and is also shown in Figure 7.

The results for sorghum and millet show qualitatively similar patterns (Figure A3-4 and Table A2). Roughly 9 out of 10 years by 2050 are warmer at a typical location than any historical year experienced at that point; the area with climate analogs within the same country varies from above 80% for a handful of countries to below 50% for a majority of countries; and analysis of cross-country analogs reveals several countries with numerous foreign analogs, several countries without analogs, and a handful of countries that serve as near-universal analogs. Furthermore, many of these near-universal analogs – Tanzania, Kenya, Cameroon, Nigeria, Sudan – are consistent across the three cereals.

## Conclusion

For a majority of Africa's farmers, warming will rapidly take climate not only beyond the range of their personal experience, but beyond the experience of other farmers within their own country. Knowledge about the speed and magnitude of these shifts in crop climates could be useful in at least two ways. First, our results provide specific information to donor and research institutions that can be used to prioritize where to focus collecting, evaluation and conservation of genetic resources. While great strides have been made in the *ex situ* conservation of plant genetic resources over the last half-century, collections in key areas of likely African diversity are either non-existent, incomplete, in need of investment to maintain current collections, and/or poorly integrated with larger public breeding efforts (FAO 1997). Importantly, our results suggest that the diversity currently conserved might not represent that which will be most useful in adapting crops to climate change in Africa. Investments in the collection and conservation of crop diversity in key analog countries such as Tanzania, Cameroon, Nigeria, and Sudan appear to be promising initial priorities.

Perhaps more importantly, the results demonstrate how international cooperation on genetic resources conservation and use will be crucial in adapting to the imminent threats of climate change. With maize, for example, 28% of the population of Africa lives in countries where less than half of the area will have an analog in the current climate of locations in their own country. Many of these countries stand to benefit from the genetic resources of other nations within Africa, if these resources can be effectively managed and shared. This is further evidence of the interdependence among countries for plant genetic resources that has led to the development of such collaborative mechanisms as the Multilateral System for access and benefit sharing of the International Treaty on Plant Genetic Resources for Food and Agriculture (http://www.planttreaty.org/). It is clear that such interdependence is set to increase under climate change, and with it the necessity of international collaboration in the conservation and use of crop genetic diversity.

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