Global Environmental Change xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

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

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ARTICLE INFO

Article history:
Received 10 September 2008
Received in revised form 17 April 2009
Accepted 22 April 2009

Keywords:
Maize
Africa
Genetic resources
Climate change
Adaptation
Sorghum
Millet

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.

1. 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 US$ 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 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 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 et al., 2007; Lobell 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 et al., 2007), African farmers will likely continue to adapt as the climate changes, for example by adopting new crops or varieties or by altering the timing of planting and other agronomic practices. But if future climates move as quickly outside the range of past experience as they are expected to throughout the tropics (Battisti and Naylor, 2009), farmers may be unable to adapt rapidly enough 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.

1.1. Climate adaptation and genetic resources

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

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doi:10.1016/j.gloenvcha.2009.04.003

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. While advances in biotechnology can offer alternative, more direct pathways to genetic modification of crops, traditional breeding has a long history of success in many parts of the world, 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.

Much of the diversity represented in these landraces is the direct result of centuries of farmer selection and experimentation, and this continual farmer adaptation of crops to local conditions could continue to play a direct role in adapting agriculture to a warmer world. But given the speed of climate change, the current expansion of area planted to modern varieties in Africa, and the central role that formal breeding programs and further adoption of improved varieties are expected to play in a broader development strategy on the continent (World Bank, 2008), farmer selection and local seed systems alone will likely be insufficient to adapt African agriculture to climate change. Formal breeding efforts will undoubtedly play a role, and their success will likely lean heavily on the diverse crop genetic resources that farmers have helped develop over the centuries.

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 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, potentially limiting breeding programs. For sorghum, another important African cereal crop whose center of origin is in tropical northeastern Africa, African varieties unsurprisingly represent a higher percentage of total varieties conserved internationally, but key gaps exist in both the characterization and geographical representation of existing collections (GCDT, 2007a,b). A similar situation exists for pearl millet.

Table 1
Holdings of African maize landrace accessions in four major international genebanks. Landraces are domesticated crop varieties that typically have been improved by farmer selection but not received formal attention in a breeding program. Source: (GCDT, 2007a).

Collection	Regional source of landraces	Number of landrace accessions
CIMMYT	Sub-Saharan Africa	105
	Other low/middle income	19933
	Industrialized	2623
USDA	Sub-Saharan Africa	1092
	Other low/middle income	10225
	Industrialized	3408
China	Sub-Saharan Africa	7
	Other low/middle income	13858
	Industrialized	636
IITA	Sub-Saharan Africa	610
	Sub-Saharan Africa total	1814
	World total	52497

National genebanks do conserve additional material that is not always represented in the international genebanks (Table S1), but the coverage of the diversity present in the country is usually far from complete (GCDT, 2007a,b). Furthermore, national genebanks often vary widely in their condition, and many are in need of urgent funding simply to maintain the viability of their existing collections. Finally, nations have sovereignty over the genetic resources found within their borders, and the accessibility of material in national genebanks to outside breeders can differ substantially from country to country. The long-term safety and availability of the resources on which African agricultural adaptation depends is therefore uncertain.

2. 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. Given that many investments in agricultural adaptation, such as improved crop varieties or expanded irrigation

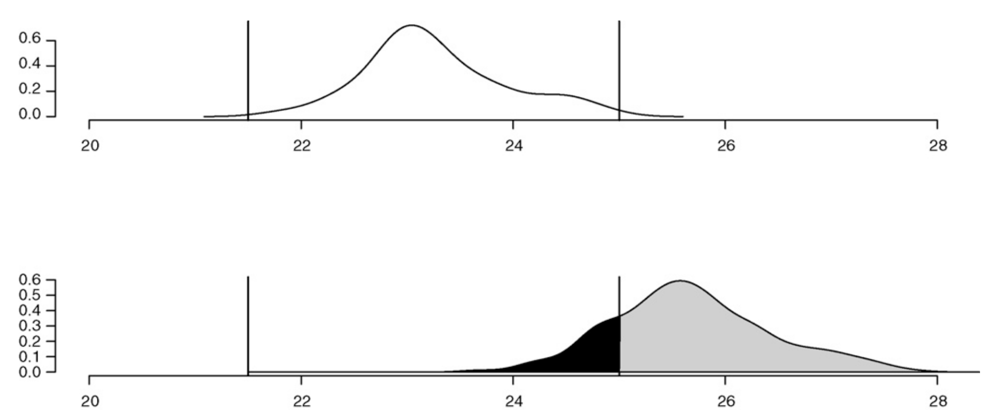

Fig. 1. Calculating overlap between historical and future (2050) growing season temperatures for a theoretical region or grid cell. Top panel: Historical (1960–2002) growing season temperatures for that grid cell in deg C, with lines indicating 5th–95th percentiles of observations. Bottom panel: Simulated growing season temperatures by 2050 at the grid cell, equivalent to historical variability plus projected change in mean temperature. Black shaded areas represent overlap between historical and future climate, grey areas non-overlap. The ratio of grey to total shaded area gives the percentage of future climate years which are outside historical experience for that region or grid cell.

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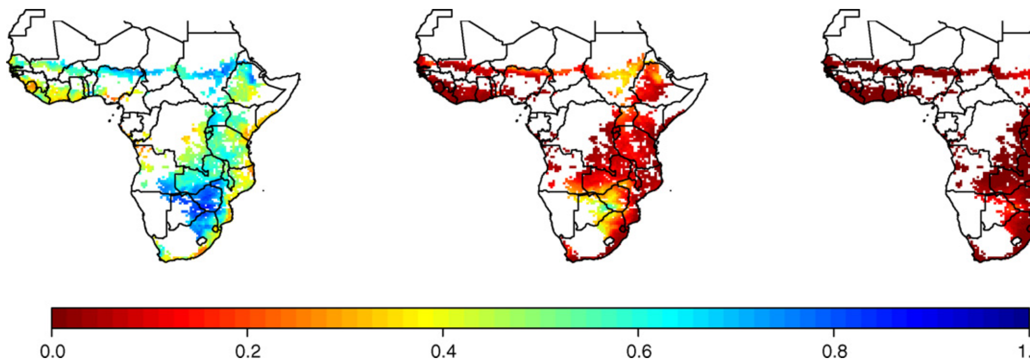

Fig. 2. Percentage overlap between historical and 2025 (left), 2050 (middle), and 2075 (right) simulated growing season average temperature at over African maize area. Dark blue colors represent 100% overlap between past and future climates, dark red colors represent 0% overlap. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

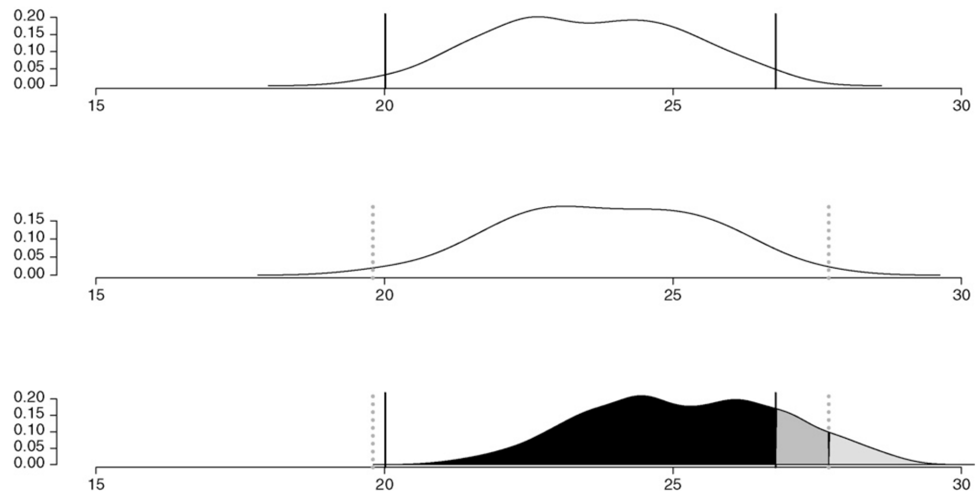

Fig. 3. Calculating overlap between crop climates in two theoretical countries, for growing season temperatures. *Top panel*: Current (1993–2002) crop growing season temperatures (°C) across Country A, with black lines indicating 5th–95th percentiles of observations. *Middle panel*: Current crop climate across Country B, with dotted lines indicating 5th–95th percentiles of observations in B. *Bottom panel*: 2050 climate in Country A. Black shaded area represents the portion of temperatures in A_{2050} represented in A_{2000} ("self overlap"). The percentage of self overlap is calculated as the ratio of the black shaded area to all shaded area for A_{2050}. The dark grey + light grey shaded areas represent the "novel" climate in A_{2050}—that which does not overlap with A_{2000}. The dark grey area is the portion of this novel climate that overlaps with the 5th–95th percentile of climate in B_{2000}. The percentage of novel climate overlap is the ratio of the dark grey area to dark + light grey area. The light grey area is the portion of novel climate with no analog in current climate in Country B.

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 explicitly 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 in coming decades, and to use this information to prioritize breeding and genetic resource conservation efforts. Nonetheless, it is important to note that warming is generally expected to cause reductions in rainfed crop yields and crop suitability in Africa (Fischer et al., 2002; Jones and Thornton, 2003; Lobell et al., 2008), so that simply shifting areas where crops are grown will be a limited adaptation strategy. Instead, adapting crops in their current locations will be critical. The specific traits to be bred for are beyond the scope of this analysis, but could include changes in maturity period, more efficient utilization of soil moisture, and expression of heat shock proteins, as discussed in several recent reviews (Araus et al., 2008; Barnabas et al., 2008).

2.1. 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 projected 2025, 2050, and 2075 values over reported crop area. We combine historical climate data (Mitchell and Jones, 2005) with maps of crop distribution (Leff et al., 2004) and estimates of the months in which crops are grown in each country (Lobell et al., 2008) to derive a 43-year time series of

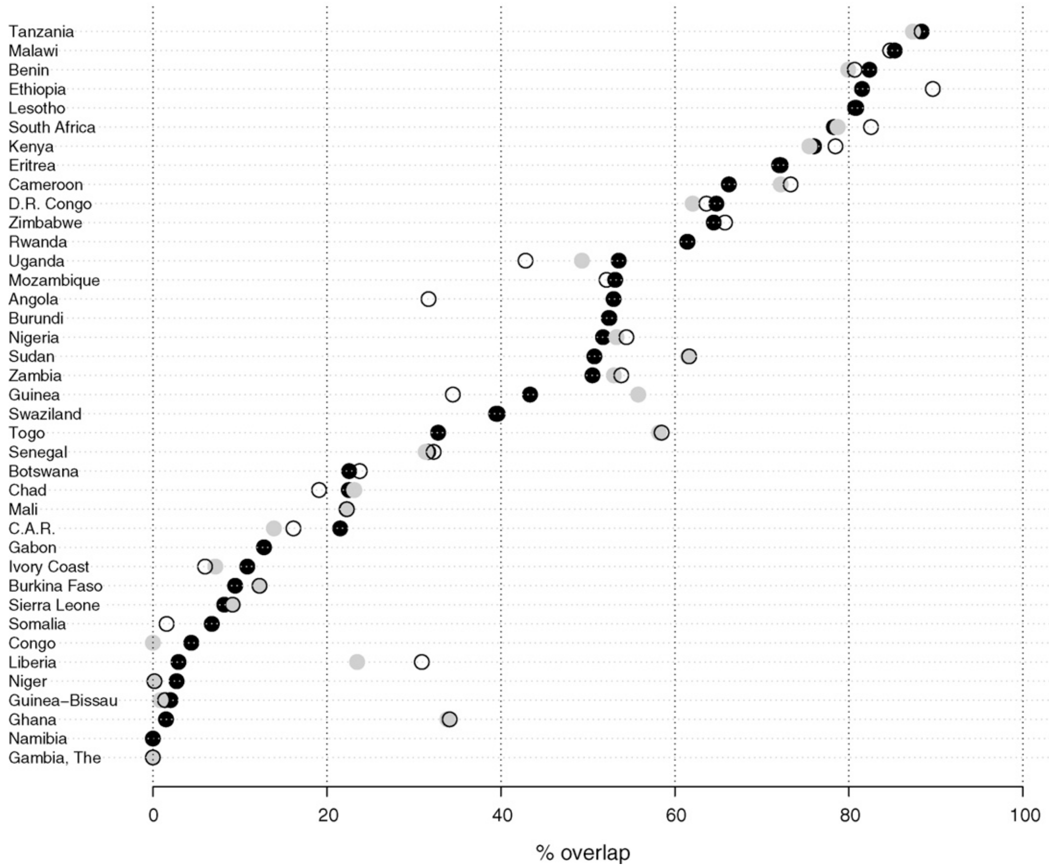

Fig. 4. Percentage overlap between the current (1993–2002 average) distribution of growing season temperatures within a country and the simulated 2050 distribution of temperatures in the same country. Black: maize; grey: millet; white: sorghum.

historical growing season climate at each 0.5° × 0.5° 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 each of the 18 climate models running the A1B emissions scenario[3]—in effect adding projected mean state changes to current observed variability at a given site. Similarly, future precipitations are computed by multiplying current values by simulated percent changes from each of the 18 climate models, which yields the range of possible future precipitation under the A1B scenario. For both temperature and precipitation, simulated changes are the difference between two 20-year averages in the model (e.g. temperature changes to 2050 are calculated as model average 2040–2060 minus model average 1990–2010 temperatures). We focus on projections under the A1B scenario, because climate for this scenario is roughly similar to other AR4 emissions scenarios through 2050, and intermediate between the A2 and B1 scenarios by 2075 (Meehl et al., 2007). All 18 models were weighted equally in the analysis, since there is no strong evidence to favor some models over others (Tebaldi and Knutti, 2007; Lobell et al., 2008).

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 et al., 2007). Smaller shifts in the length of the growing season, such as those found by Naylor et al. (2007) in Indonesian rice systems, could have important regional production effects, but would have little impact on our choice of the months in future climate when crops are grown.

2.1.1. Calculating historical overlap

To determine overlap between past and future climates, we determine the percentage of possible future climates (as calculated above) that fall within the 5th–95th percentile range of historical climate observations for a given area. An example for a hypothetical region is shown in Fig. 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. Fig. 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%)

[3] These models are: CCMA, CNRM, CSIRO, GFDL0, GFDL1, GISS.AOM, GISS.EH, GISS.ER, IAP, INMCM3, IPSL, MIROC.HIRES, MIROC.MEDRES, ECHAM, MRI, CCSM, PCM, HADCM3. See Randall et al. (2007). Climate Models and Their Evaluation. Climate Change 2007: The Physical Science Basis. S. Solomon, D. Qin, M. Manninget al. Cambridge, UK, Cambridge University Press.for a complete treatment of climate models.

overlap between historical and 2025, 2050, and 2075 growing season temperatures, respectively. For all three crops, coastal areas tend to move outside of historical experience more rapidly than inland areas, typically because interannual variation in temperature is generally higher further from the coasts.

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 (Fig. S1). 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 (Lobell and Burke, 2008). 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 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 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.

2.2. 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 (Hardon, 1996) – 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.

2.2.1. Calculating spatial overlap

To analyze crop climate analogs across space, we follow a similar procedure as above, computing the overlap between

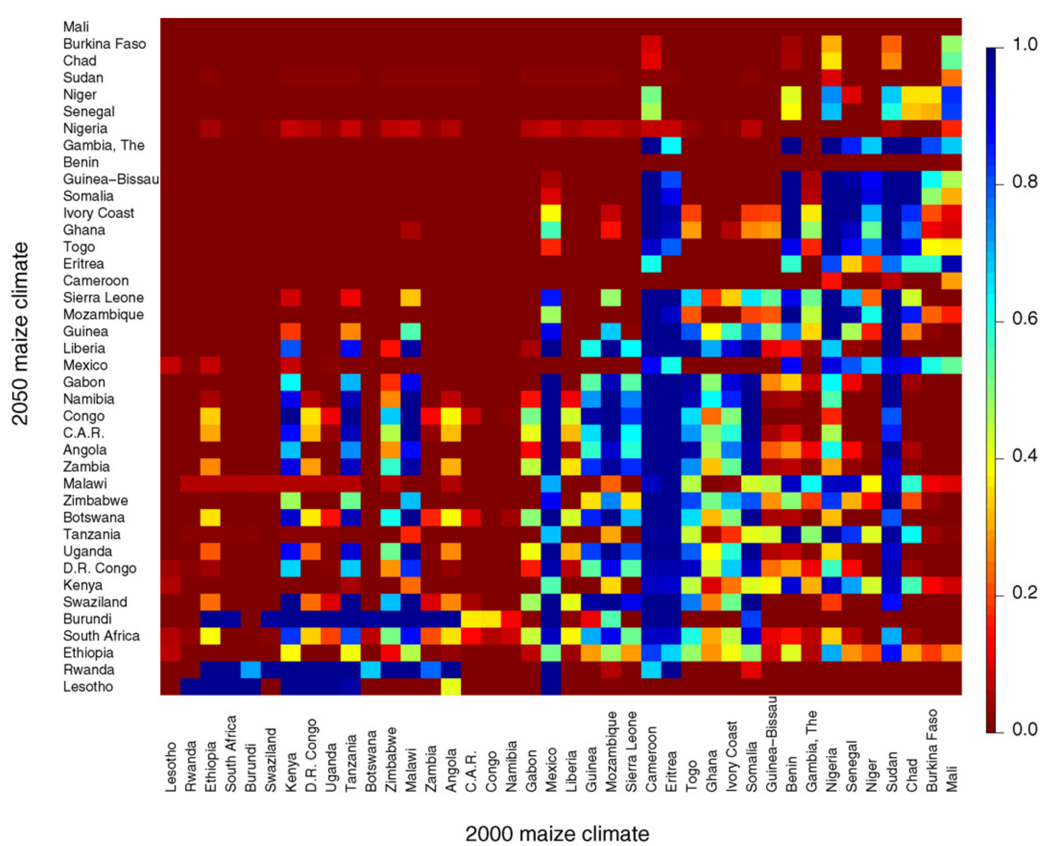

Fig. 5. Percentage overlap between 2050 novel maize climates (*y*-axis) and current (1993–2002 average) maize climates (*x*-axis) by country. Dark blue colors represent 100% overlap between past and future climates, dark red colors represent 0% overlap. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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current crop climates in a given country and future crop climates in all countries in Sub-Saharan Africa (Fig. 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. In particular, if farmers have already been selecting heat tolerant varieties as the climate has warmed over the half century, we want to best represent the climate currently selected for. 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 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") future climates in that country have analogs in current climate elsewhere on the continent (Williams 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 (Fig. 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 all other country crop climates in Africa.

3. Analogs between current and future crop climates

3.1. Self overlap

Fig. 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 This does not imply that continued breeding for moisture stress is unwarranted, since interannual rainfall variability will continue to be an important constraint on crop production, and since one of the main mechanisms of temperature-induced yield losses is via moisture stress resulting from greater evaporation rates. Rather, the result simply highlights the increasing importance of collecting, evaluating and breeding for heat tolerance, consistent with previous studies (Lobell and Burke, 2008; Battisti and Naylor, 2009).

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

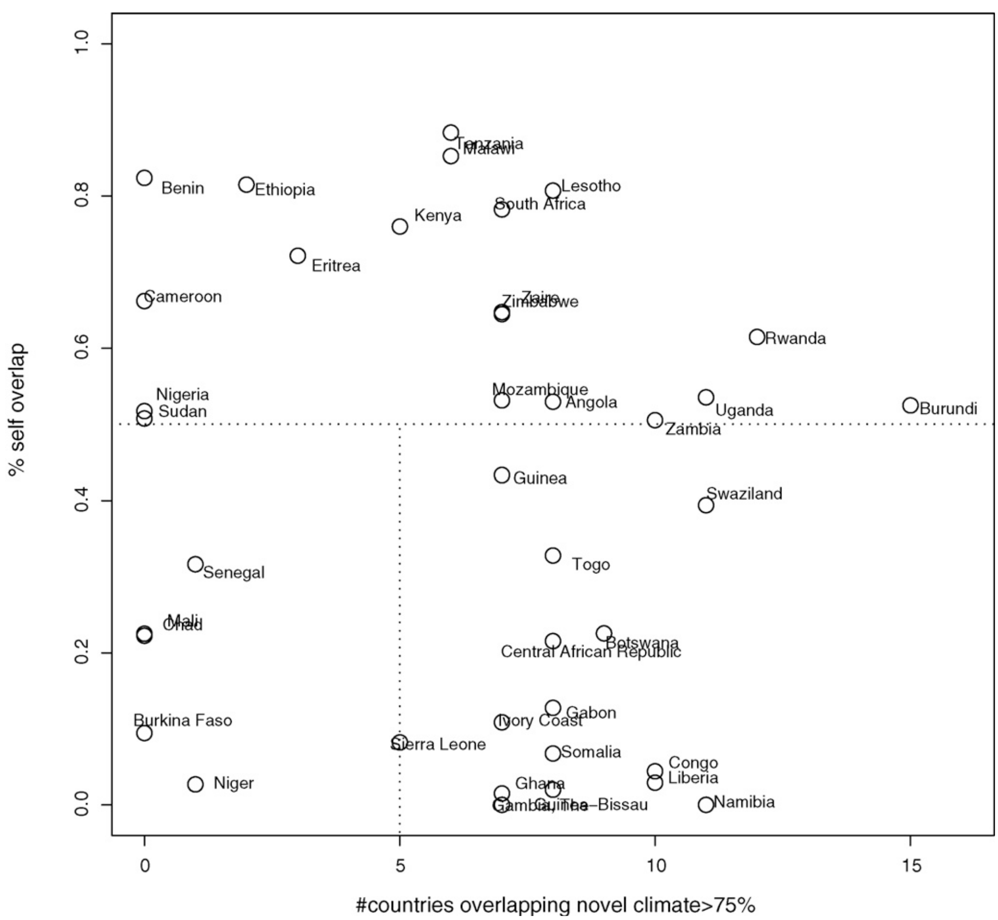

Fig. 6. Percentage of country self-overlap in current and future maize temperature (y-axis) versus the number of countries who are analogs to that country's novel climate. To count as an analog, a country must overlap a given novel climate by 75% or more. Top section: self-overlap >50%; bottom right: self overlap <50% and have >5 analogs. Bottom left: self overlap <50% and have <5 analogs.

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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 spatial 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 (e.g. Tanzania), crop areas in one region of the country could serve as analogs for crop areas in other regions of the country. Furthermore, rates of self-overlap in a few countries appear to differ substantially across cereals (maize versus millet in Ghana, e.g.), a likely result of particular cereals being farmed in different locations and thus being represented by different climate envelopes. In these cases, genetic resource strategies might differ importantly by crop.

Finally, for the majority of African countries, current growing season temperatures over maize, millet, and sorghum areas within a country will represent less than half of the range of expected 2050 growing season temperatures in the same areas. Almost uniformly, the countries with larger current climatic ranges – 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.

3.2. Identifying priorities in genetic resources conservation

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. Fig. 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. For maize, we include current and future crop climates for Mexico, a primary global center of maize genetic diversity.

First, many countries with low self-overlap have novel future climates with many analogs in present climate elsewhere. Fourteen countries (bottom right, Fig. 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 (lower left in Fig. 6), with two others only slightly above the 50% threshold. Most of these countries are clustered in the Sahel, and as shown by Fig. 5, the lack of analogs for their future climates is related to their relatively high growing season average temperatures—they are typically hottest in current climate, and thus have few analogs for their even hotter 2050 novel climates. For these countries, there is thus a much smaller potential pool of foreign genetic resources in which to seek heat tolerance, at least

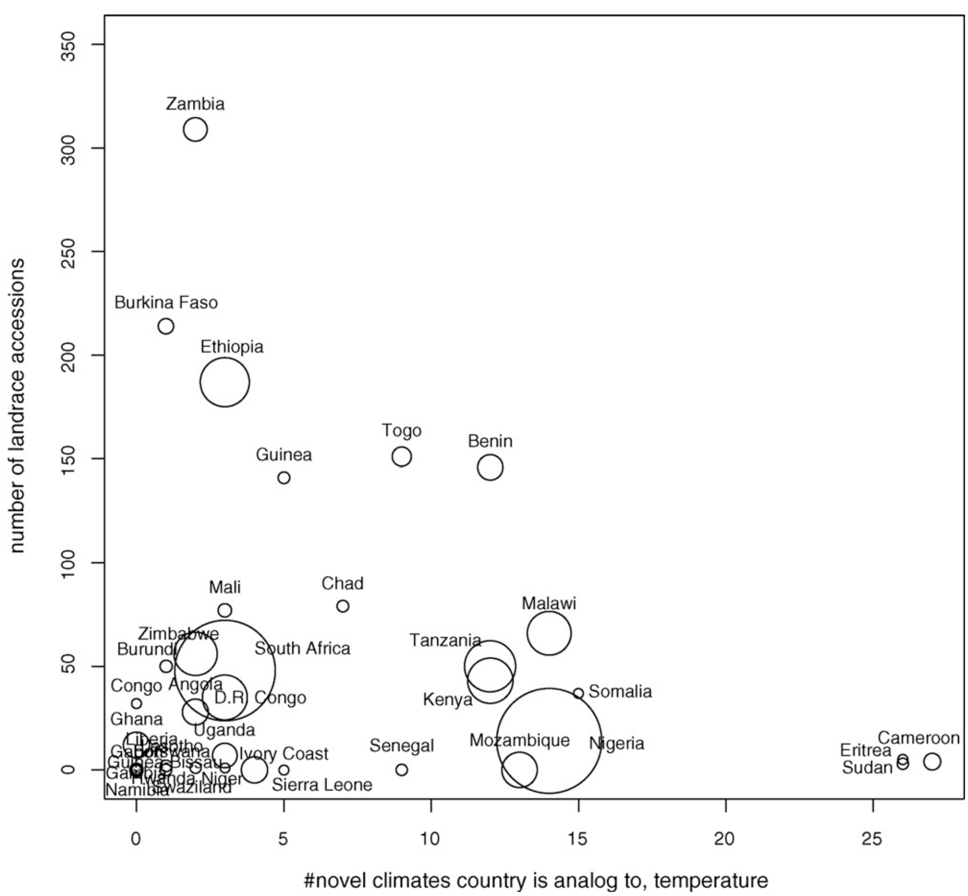

Fig. 7. Number of novel 2050 maize climates to which each country is a good temperature analog (*x*-axis), versus number of maize landrace accessions originating in that country stored in national and international genebanks from Table 1. For instance, current maize area in Mozambique is a good analog to 13 novel 2050 African climates, but has 0 reported maize accessions in major genebanks. Bubble size scales with amount of maize area in each country.

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within Africa. Unfortunately, primary centers of maize diversity outside of Africa, such as in Mexico, enjoy much cooler climates that much of Africa (Fig. 5). If breeding efforts cannot sustain yield for maize for these hottest climates in the face of warming temperatures, switches to potentially more heat-and drought-tolerant crops, such as sorghum and millet, could be necessary.

Finally, there is a set of countries whose current growing season temperatures are analogs 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 (Fig. 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 S2). These countries appear as particularly high priorities for urgent collection and conservation of maize genetic resources. Similarly, if genetic diversity is potentially greater in regions with more cropped area, 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 Fig. 7.

Because precipitation as well as temperature regimes vary across crop climates in Africa, one concern with an analysis focused solely on temperature is that countries that are good temperature analogs to many novel future climates could have precipitation regimes dissimilar from these same climates—for instance, that a currently hot and dry climate might not be a good analog for a future climate that is hot and wet. To explore this, Fig. 8 plots the strength of each country as a temperature analog to novel African climates versus their strength as both a temperature and precipitation analog. Results suggest that, with some exceptions, good temperature analogs also tend to be good precipitation analogs. Countries such as Cameroon and Nigeria currently have broad precipitation ranges as well as temperature ranges over their cereal growing areas, making them good analogs to many future precipitation and temperature regimes across the continent. Sudan and Eritrea, on the other hand, are good temperature analogs but are much drier than median African crop climates, making them perhaps less appealing analogs – and thus less important priorities for genetic resources conservation – if underlying precipitation regimes play an important role in breeding crops for hotter climates.

The results for sorghum and millet show qualitatively similar patterns as the results for maize (Figs. S2–S3 and Table S2). 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. And as with maize, primary centers of genetic diversity outside of Africa (e.g. millet in India) enjoy somewhat cooler crop climates that the hottest African countries, again reiterating both

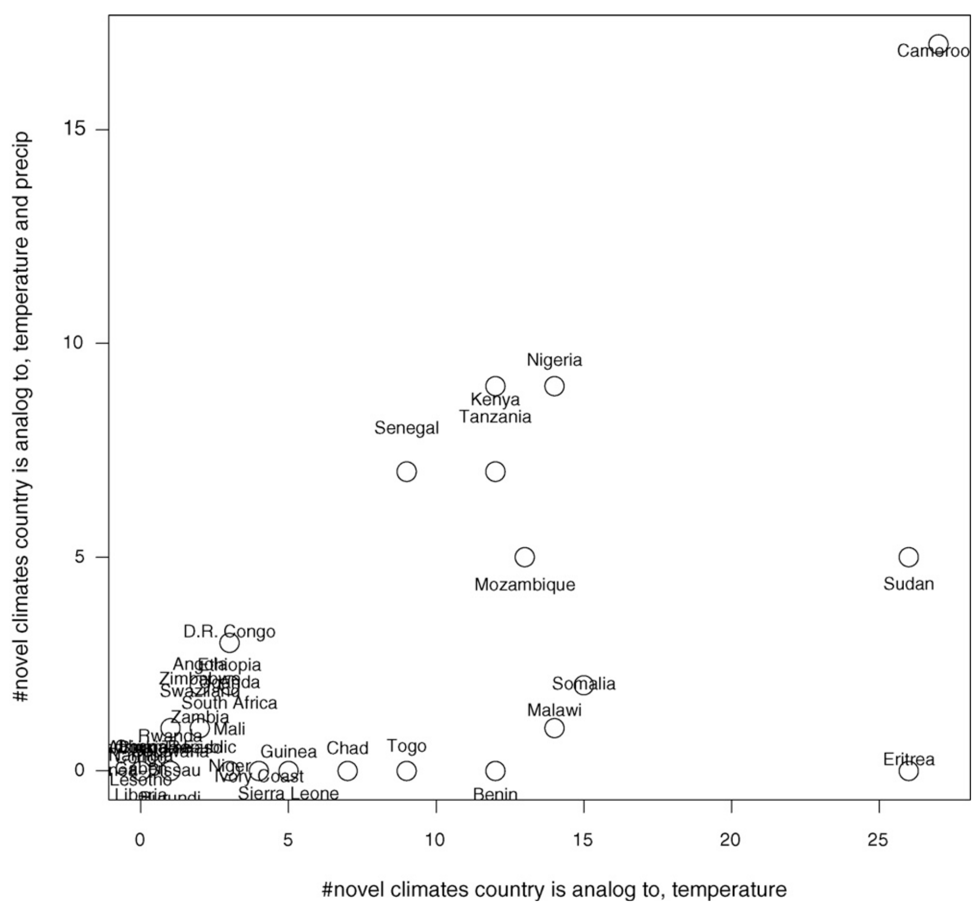

Fig. 8. Number of novel 2050 maize climates to which each country is a good temperature analog (*x*-axis), versus the number to which a given country is a good temperature analog and a good precipitation analog in current climate (*y*-axis). "Good" analogs are those that overlap a given novel climate by >75%. Total number of countries in our analysis is 39.

the importance of collecting and preserving African germplasm, and the likely importance of adaptation measures beyond cereal production if breeding for extreme heat proves difficult.

4. Conclusion

For a majority of Africa's farmers, warming will rapidly take climate not only beyond the range of their personal experience, but also 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.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2009.04.003.

References

Adger, W., Agrawala, S., et al., 2007. Assessment of adaptation practices, options, constraints, and capacity. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA.

Araus, J., Slafer, G., et al., 2008. Breeding for yield potential and stress adaptation in cereals. Critical Reviews in Plant Sciences 27 (6), 377–412.

Barnabas, B., Jager, K., et al., 2008. The effect of drought and heat stress on reproductive processes in cereals. Plant, Cell & Environment 31 (1), 11–38.

Battisti, D., Naylor, R., 2009. Historical warnings of food insecurity with unprecedented seasonal heat. Science 323 (5911), 240.

Bloom, D.E., Sachs, J.D., 1998. Geography, demography, and economic growth in Africa. Brookings Papers on Economic Activity 2, 207–273.

Chen, S., Ravallion, M., 2007. Poverty and Hunger Special Feature: Absolute poverty measures for the developing world, 1981 2004. Proceedings of the National Academy of Sciences of United States of America 104 (43), 16757.

Christensen, J. H., Hewitson, B., et al., (2007). Regional Climate Projections. Climate Change 2007: The Physical Science Basis. In: Solomon, S., Qin, D., Manning, M., et al. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Easterling, W., Aggarwal, P., et al., 2007. Food, Fibre, and Forest Products. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Evenson, R.E., Gollin, D., 2003. Assessing the impact of the green revolution, 1960 to 2000. Science 300 (5620), 758–762.

FAO, 1997. The State of the World's Plant Genetic Resources for Food and Agriculture. Rome, Food and Agriculture Organization of the United Nations: 511.

FAO, 2008. Food and Agriculture Organization of the United Nations (FAO), FAO Statistical Databases, 2008, from http://faostat.fao.org.

Fischer, G., van Velthuizen, H. T., et al., 2002. Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results, International Institute for Applied Systems Analysis.

GCDT, 2007a. Global Strategy for the Ex situ Conservation and Utilization of Maize Germplasm. Global Crop Diversity Trust, Rome, p. 60.

GCDT, 2007b. Strategy for the Global Ex Situ Conservation of Sorghum Genetic Diversity. Global Crop Diversity Trust, Rome, p. 45.

Hardon, J., 1996. National sovereignty and access to genetic resources. Biotechnology and Development Monitor 27, 24.

Jones, P., Thornton, P., 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. Global Environmental Change 13 (1), 51–59.

Leff, B., Ramankutty, N., et al., 2004. Geographic distribution of major crops across the world. Global Biogeochemical Cycles 18 (1), GB1009.

Lobell, D., Burke, M., 2008. Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. Environmental Research Letters 3 (3), 034007.

Lobell, D.B., Burke, M.B., et al., 2008. Prioritizing climate change adaptation needs for food security in 2030. Science 319 (5863), 607–610.

Meehl, G.A., Stocker, T.F., et al., 2007. Global Climate Projections. Climate Change 2007: The Physical Science Basis. In: Solomon, S., Qin, D., Manning, M., et al. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Miguel, E., Satyanath, S., et al., 2004. Economic shocks and civil conflict: an instrumental variables approach. Journal of Political Economy 112 (4), 725–753.

Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25 (6), 693–712.

Naylor, R., Battisti, D., et al., 2007. Assessing risks of climate variability and climate change for Indonesian rice agriculture. PNAS 104 (19), 7752.

Pardey, P., Beintema, N., 2001. Slow Magic: Agricultural R&D a Century After Mendel. International Food Policy Research Institute, Washington, DC, p. 30.

Randall, D., R., Wood, et al., 2007. Climate Models and Their Evaluation. In: Solomon, S., Qin, D., Manning, M. et al. (Eds.), Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, UK.

Reilly, J., Schimmelpfennig, D., 2000. Irreversibility, uncertainty, and learning: portraits of adaptation to long-term climate change. Climatic Change 45 (1), 253–278.

Tebaldi, C., Knutti, R., 2007. The use of multi-model ensemble in probabilistic climate projections. Philos. Trans. R. Soc. A 365 (1857), 2053–2075.

Williams, J.W., Jackson, S.T., et al., 2007. Projected distributions of novel and disappearing climates by 2100 AD. Proceedings of the National Academy of Sciences of United States of America 104 (14), 5738.

World Bank, 2008. World Development Report: Agriculture for Development. World Bank, Washington, DC, p. 386.