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Agriculture and food systems in sub-Saharan Africa in a 4°C+ world

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Agricultural development in sub-Saharan Africa faces daunting challenges, which climate change and increasing climate variability will compound in vulnerable areas. The impacts of a changing climate on agricultural production in a world that warms by 4°C or more are likely to be severe in places. The livelihoods of many croppers and livestock keepers in Africa are associated with diversity of options. The changes in crop and livestock production that are likely to result in a 4°C+ world will diminish the options available to most smallholders. In such a world, current crop and livestock varieties and agricultural practices will often be inadequate, and food security will be more difficult to achieve because of commodity price increases and local production shortfalls. While adaptation strategies exist, considerable institutional and policy support will be needed to implement them successfully on the scale required. Even in the 2°C+ world that appears inevitable, planning for and implementing successful adaptation strategies are critical if agricultural growth in the region is to occur, food security be achieved and household livelihoods be enhanced. As part of this effort, better understanding of the critical thresholds in global and African food systems requires urgent research.

Keywords: food security; adaptation; climate change; livelihoods

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1. Introduction

Agricultural and food systems globally face considerable challenges in the coming decades. The demand for food continues to increase rapidly, as a result of various drivers. Current estimates of human population in 2050 range from 7.96 billion to 10.46 billion; the medium variant estimate is 9.19 billion [1]. Continued population growth could be a significant impediment to achieving improvements in food security in some countries, even as world population stabilizes sometime during the present century. Food demand is also strongly affected by urbanization. More people now live in urban settings than in rural areas. The next few decades will see unprecedented urban growth particularly in Africa and Asia. Urbanization has considerable impact on patterns of food consumption [2], but it is not necessarily associated with a reduction in food insecurity. Recent data from southern Africa indicate both chronic poverty and food insecurity in a survey of 11 cities [3]. A third key driver affecting food demand is income growth. Between 1950 and 2000, world *per capita* income grew at an annual rate of 2.1 per cent [4]. As income grows, patterns of food expenditure change, often to more meats, fats and sugar [5]. Projections of future economic growth vary considerably, but it is expected to continue. Fourth, the agricultural production sector is catering increasingly to globalized diets. Retailing through supermarkets is growing at 20 per cent per annum in some countries, and this growth is likely to continue over the next few decades as urban consumers demand more processed foods, shifting agricultural production systems from on-farm production towards agribusiness chains [6].

Several projections suggest that global cereal and livestock production may need to increase by between 60 and 100 per cent to 2050, depending on the scenario, because of the increasing demand and changing patterns of demand [7]. In sub-Saharan Africa (SSA), this will require considerable investments in agricultural research and technology and in infrastructural development [6]. Agricultural growth rates for SSA declined in the 2000s [8] and food insecurity is still a concern, as the prevalence of malnourishment has only dropped from 34 to 30 per cent in two decades [9]. Agriculture is still an economic mainstay of many SSA countries, employing about 60 per cent of the workforce and contributing an average of 30 per cent of gross domestic product [10]. Although the efforts of the agricultural research and development communities over the last 40 years have led to successes in improving yields, increasing incomes and contributing to food security, these successes have not been automatic and they have not occurred everywhere [11]. Rural communities and households continue to demonstrate tremendous adaptive capacity in the face of economic and social change, but this capacity needs appropriate social, institutional and political support [12].

Even more challenging, the necessary increases in food production will have to occur at the same time as the climate is changing and as climate variability increases. Potential impacts of climate change on agricultural production in SSA have been assessed in several modelling studies, using methods grounded in an understanding of both crop and climate science (see the review by Challinor *et al.* [13]). The inherent complexity of the climate–crop system, together with fundamental limits to climate predictability, mean that predicted ranges for major crops depend strongly on the methods and models used [14]. However, as in the current climate, these broad trends are likely to mask local differences caused by spatial variability in climate. The regional distribution of hungry people will change, with particularly large negative effects in SSA owing to the impact of declines in crop yields on both food availability and access [15].

The challenges for agricultural development are already considerable, and there is now general concern that climate change and increasing climate variability will compound these in vulnerable areas. The interactions of climate with other drivers of change in agricultural and food systems, and on broader development trends, are only incompletely understood, but the impacts on human health and nutrition and on water resources and other ecosystems goods and services may be locally severe. In this paper, we outline how the impacts of a changing climate in a world that warms by 4°C or more will diminish the options available for agricultural production and livelihoods in SSA. Many of the production trends and food security goals that SSA still needs to achieve will be compromised, as current crop and livestock varieties and agricultural practices will be inadequate. Food security will become more difficult to achieve as commodity prices increase and local production shortfalls become the norm. Although adaptation strategies for agricultural production and food security exist, and indeed rural communities have been adapting to climatic variability for centuries, the institutional and policy support needed to successfully implement such adaptation on the scale that SSA requires in a 4°C+ world would probably be very substantial [16]. We stress that planning for and implementing successful adaptation strategies with local communities and households are key to maintaining options for food security and agricultural growth in SSA, although exactly what constitutes a successful adaptation option is a key research question. Many issues pertaining to the role of livelihood diversification out of or in to different forms of agriculture need to be explored, and more attention needs to be given to empowering local communities so that they have greater control over their adaptation choices and livelihood pathways.

2. Impacts on agricultural production

(*a*) *Projected changes in growing season length and crop and pasture yields*

As noted above, several modelling studies have assessed the potential impacts of climate change on agricultural production in SSA, although the projected ranges of shifts in yields for the major crops vary widely [13,14]. Many of these studies have estimated yield impacts in response to the Special Report on Emissions Scenarios (SRES) greenhouse-gas emission scenarios [17]. The multi-model means of surface warming (relative to 1980–1999) for the SRES scenarios A2, A1B and B1 from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment show increases of about 1–2°C to the 2050s and about 1.5–3°C for the 2080s [18].

Multiple model simulations are needed in order to sample the inherent uncertainties in the projection of climate and agricultural production. Climate models are computationally expensive to run, and so choices must be made regarding the complexity, spatial resolution, simulation length and ensemble size of the simulations [19]. An emphasis on complexity allows simulation of coupled mechanisms such as the carbon cycle and feedbacks between agricultural land management and climate. In addition to improving skill, greater spatial resolution increases relevance to regional planning. Greater ensemble size improves the sampling of probabilities. Thus, assessments of a 4°C+ world are contingent on the choice of focus: studies that focus primarily on ensembles and uncertainty may fail to demonstrate consensus, while other studies may find a more clear consensus emerging.

Here, to examine some of the likely effects on agricultural production in SSA of warming of 4°C or more, we carried out some downscaling and simulation runs using climate projections from AR4 climate model runs assembled by New *et al.* available at www.geog.ox.ac.uk/~clivar/ClimateAtlas/4deg.html. We used an ensemble mean of the three AR4 emissions scenarios (A2, A1B and B1) and the 14 general circulation models (GCMs) for which data were provided, and anomalies were scaled to a global temperature increase of +5°C. The climate differences were downloaded at a resolution of 1° latitude–longitude. There are several ways to increase the spatial resolution of climate model outputs, all of which have their own strengths and weaknesses, recently reviewed by Wilby *et al.* [20]. Here, we were also concerned to increase the temporal resolution of climate model outputs, from monthly means of key variables to characteristic daily data that could then be used to drive crop models. Accordingly, as in previous work, we used historical gridded climate data from WorldClim [21], aggregated to 10 arc-minutes to speed the analysis, which we took to be representative of current climatic conditions. We produced a grid file for Africa of climate normals for future conditions at 10 arc-minutes by interpolation using inverse square distance weighting, one of the methods that [20] refer to as 'unintelligent downscaling'. To increase the temporal resolution of the climate model outputs, we generated the daily data needed (maximum and minimum temperature, rainfall and solar radiation) for each grid cell using MarkSim, a third-order Markov rainfall generator [22] that we use as a GCM downscaler, as it uses elements of both stochastic downscaling and weather typing on top of basic difference interpolation. MarkSim generates daily rainfall records using a third-order Markov process to predict the occurrence of a rain day. It is able to simulate the observed variance of rainfall by way of stochastic resampling of the relevant Markov process parameters. MarkSim is fitted to a calibration dataset of over 10 000 weather stations worldwide, clustered into some 700 climate clusters, using monthly values of precipitation and maximum and minimum temperatures. All weather stations in the dataset have at least 12 years of daily data, and a few have 100 years or more. Some of the parameters of the MarkSim model are calculated by regression from the cluster most representative of the climate point to be simulated, whether that climate is historical or projected into the future. More details of the methods used are given in Jones *et al.* [23].

We carried out two sets of analyses. First, we estimated the average length of growing period (LGP) for each pixel in SSA. LGP is an indicator of the adequacy of conditions for crop growth, and is the period (or periods—some parts of SSA have more than one well-defined growing season per year) during the year when both moisture availability and temperature are conducive to crop growth. LGP was calculated on a daily basis using methods outlined in Jones [24], ignoring intervening drought periods, and is thus a proxy for the number of grazing days, but not necessarily of cropping success. Percentage changes in LGP between now and the 2090s are shown in figure 1*a*, for areas with at least 40 days LGP under current conditions. Much of the cropping and rangeland area of SSA is projected

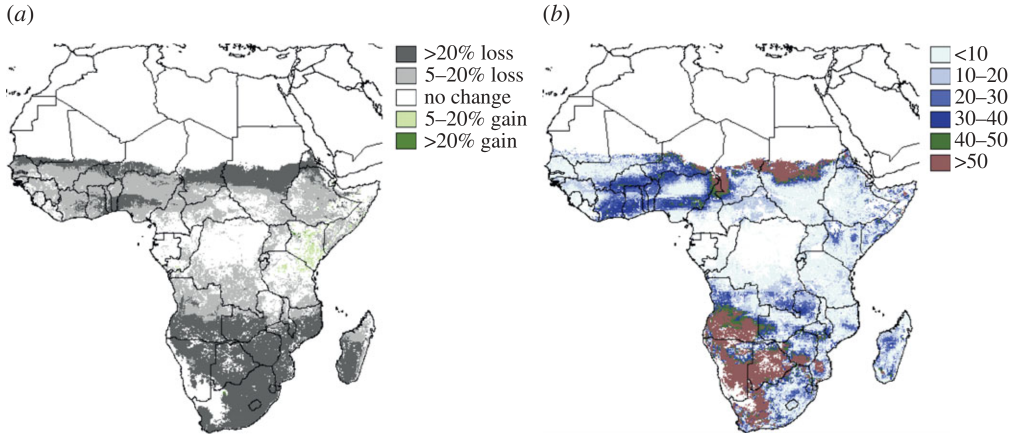

Figure 1. Length of growing period in the 2090s compared with the present. (*a*) Mean percentage change for an ensemble of 14 GCMs. (*b*) Coefficient of variation (%) of the change in length of growing period for an ensemble of 14 GCMs. See text for details.

to undergo some loss in growing season length, and most of Africa in southern latitudes may see losses of at least 20 per cent. Parts of East Africa may see moderate increases in growing period, on the other hand.

There are several sources of uncertainty attached to such estimates, including the uncertainties associated with the downscaling techniques used, and the uncertainties associated with the use of different combinations of GCM and emissions scenario. To assess the latter, we estimated the standard deviation of the mean estimate of change in LGP for each pixel from the 75th percentile of the ensemble distribution (14 climate models and three emissions scenarios). These are mapped as the coefficients of variation in figure 1*b*, and represent the variability of estimates of LGP primarily in relation to the different climate models (there are only limited differences between the three emissions scenarios in the first half of the current century). This variability among the climate models is relatively small for large areas of central and eastern SSA (20% or less), higher (to 40%) for the crop and agro-pastoral lands of West Africa and parts of southern Africa, and highest (greater than 50%) in arid and semi-arid rangelands in south-west Africa and the central desert margins in the north, where LGP is short and highly variable anyway. These results highlight both the reasonable consensus among the climate models for shifts in conditions in East Africa and the lack of consensus as to changes in agricultural conditions in some of the higher-rainfall areas of West Africa in particular.

We also calculated the primary season failure rate and reliable crop growing days per year; for methods see Jones & Thornton [25]. Results are not shown here, but season failure rates increase for all of SSA except for central Africa; in southern Africa they increase to the point where nearly all rain-fed agriculture below latitude 15°S is likely to fail one year in two. These trends are in accord with previous analyses [26], only here the effects are considerably greater.

In the second analysis, we ran crop simulations for conditions in this 5°C warmer world, for maize, *Phaseolus* bean, and an ‘indicator’ pasture species, *Brachiaria decumbens*, a cultivated forage grass widely used for feeding to cattle

Table 1. Simulated yields (the pixel-weighted averages of 30 independent replications) in four regions of sub-Saharan Africa, for three crops grown on cropland and pastureland as defined by Ramankutty *et al.* [29], under current conditions and in the 2090s. Regions are defined as follows: Central: Cameroon, Central African Republic, Chad, DR of Congo, Congo, Equatorial Guinea, Gabon. East: Burundi, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Somalia, Sudan, Tanzania, Uganda. Southern: Angola, Botswana, Lesotho, Madagascar, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia, Zimbabwe. West: Benin, Burkina Faso, Cote d'Ivoire, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo.

	2000s yield (kg ha^{-1})	2090s +5°C yield (kg ha^{-1})[a]	mean % change in production[a]	CV of change in production %[b]
maize				
central	744	612	−13	23
east	954	689	−19	7
southern	748	612	−16	22
west	764	536	−23	23
mean	806	612	−24	19
beans				
central	666	175	−69	58
east	685	263	−47	6
southern	716	220	−68	48
west	487	63	−87	47
mean	639	182	−71	34
B. decumbens				
central	1493	1311	−4	3
east	1745	1570	+9	7
southern	1384	1344	+11	18
west	1498	1437	−6	27
mean	1525	1422	−7	15

[a]Simulated from the ensemble mean climate of all applicable GCMs and the three AR4 SRES scenarios.
[b]Coefficient of variation ($100\sigma/\mu$) estimated from the simulated yields using the 75th percentile of the ensemble climate distribution for all GCMs and scenarios.

in the tropics and subtropics. Runs were done using the models in the decision support system for agrotechnology transfer (DSSAT; [27]) using similar methods as those described in Thornton *et al.* [28]. We ran 30-year replicated simulations for all pixels classified as cropland and pastureland in the dataset of Ramankutty *et al.* [29]. Average yields for the three crops are shown in table 1 on a regional basis for current conditions and for the 2090s with a 5°C temperature increase. These results show clearly that the increases in LGP projected for parts of East Africa will not translate into increased agricultural productivity; maize production is projected to decline by 19 per cent and bean production by 47 per cent, all other things (such as area sown) being equal, with little or no change for the pasture grass. These simulated changes take only limited account of shifts in weather variability; a substantial portion of this region that is currently cropped already experiences season failure rates of 25 per cent or more, and these areas will increase in size substantially in the future. Table 1 includes an estimate of the coefficient of variation in the change in production for these three crops, again calculated from the 75th percentile of the ensemble climate distribution for all climate models and scenarios. In general, this variability is high, indicating that yield changes are heavily dependent on choice of climate model and emissions scenario used, except for yield changes in East Africa (and pasture yields in central Africa), which appear to be remarkably robust.

(*b*) *Other impacts affecting food production*

Other studies indicate some of the additional impacts that may be experienced in a warmer world, which will increase challenges for food production and food security. Regarding water resources, by 2025 it is projected that 64 per cent of the world's population will live in water-stressed basins, compared with 38 per cent today [30]. Large increases in non-irrigation water demands will occur over the next 50 years, these increases being concentrated in developing countries. In a 4°C+ world, 15 per cent of the world's population (more than 1 billion people) may be exposed to increased water resources stress by 2080, and 50 per cent of flood-prone people may be exposed to increased flood hazard [31]. There are also likely to be substantial changes in land suitability for agriculture in a 4°C+ world: by the end of the century, 15 per cent of the land globally that is currently suitable for cultivation would become unsuitable, although this is more than balanced by an extra 20 per cent of land that is currently too cold to support cultivation becoming suitable [31]. But there is no balance in the situation for Africa: in East and southern Africa, Arnell [31] estimates that about 35 per cent of current cropland will become unsuitable for cultivation. These stresses will add to the difficulties of adopting new varieties or increasing agricultural productivity, as water and land availability are key limiting factors.

Over the long term, future disease trends are likely to be heavily modified by climate change, although there are no *a priori* reasons for expecting that disease risks will automatically increase in general, given that multiple interacting factors determine infection risk and exposure [32]. Nevertheless, climate change will increasingly make major public health risks more difficult to control, especially in developing countries [33]. Future trends in human, livestock and crop diseases will be affected by various drivers, including shifts in the spatial and temporal distribution of some disease vectors, such as ticks and mosquitoes, caused by changes in climate and climate variability, changes in human population distributions and age structures, and changes in the development and application of different technologies for combating infectious diseases. There is considerable heterogeneity in the disease issues associated with different regions, and the future outlook is complicated [34]. Hunger and conflict may be widespread in a 4°C+ world, and it is these processes and their consequences, rather than more direct impacts of climate change and changes in climate variability, that may become the dominant influences on health in the future [33].

Increasing frequency and severity of droughts and extreme weather events, sea-level rise and other impacts that are at least partially attributable to climate change, such as shifts in disease risks and the narrowing of livelihood options, are likely to bring about large-scale population movements during the current century. Many of the vulnerable regions are densely populated. It is not easy to disentangle the environmental drivers of migration from other drivers and thus to set apart 'climate migrants' from other migrants, but enormous migration pressures are likely to result in a 4°C+ world [35]. Wide-ranging policies would be needed to adapt to these greater migratory pressures, and in many cases, migration would need to be encouraged, not avoided, and the most vulnerable enabled to move [35].

3. Adaptation to maintain options for agricultural growth and food security

The impacts described above of a 4°C+ warming in SSA will require quite radical shifts in agriculture systems, rural livelihood strategies and food security strategies and policies. In this section, we discuss some of the potential for and constraints to adaptation in relation to crop varieties and species, livestock breeds, cropping patterns, changes in rural livelihood strategies and changes in food security interventions and policy. Our intent is a realistic evaluation of the steps needed for proactive adaptation to the additional stresses that climate change will bring to food systems in SSA. We acknowledge the many successes that local farmers have had in adapting to change [36–38] in modern times in spite of policies and economic trends that are not in their favour. We caution, however, that they also pay a price at times, as their capacity to manage multiple stresses is limited, and often economic pressures outweigh climatic stresses [39–41]. This is in many cases because of the lack of political and institutional power that vulnerable communities have throughout SSA. We also recognize the success stories in agricultural development, such as those highlighted in the recent book *Millions fed* [11], which demonstrates what can occur when institutional support is sufficient for innovation by farmers and researchers to succeed. However, proactive adaptation to a 4°C+ world will require much more concerted effort at all levels to manage quite radical shifts. In addition, when food security is considered as the outcome of food systems, which expand beyond agricultural production to include markets, trade and distribution networks, for example, the evaluation of successful adaptation becomes more difficult. Food security has not decreased much in SSA in the recent past, and over the last 3 years price shocks have combined with economic recession to increase the numbers of food-insecure [42]. The idea that there may well be limits to adaptation, beyond which action will not reduce vulnerability (or may even increase it for some), and/or that the necessary actions are not able to be implemented because of political or other constraints, becomes real in the case of agriculture and food security in SSA [43,44]. We return to this notion below.

For crops, changes in management practices and strengthening of seed systems are two key approaches to adapting agricultural systems in SSA [14]. While local seed systems can be resilient to climatic stresses [45], the challenge for the future is to improve access to the varieties that will be needed as climate changes and to adapt farming systems to new climatic, land and water constraints. As emphasized by experts on local adaptation, these new practices must build upon strategies and farming practices that local communities and farmers already use [39,40,46,47]. For livestock, there are several approaches, including movement of feed resources and/or of livestock over what may be large distances, where this is feasible, as mobility has been demonstrated as the key strategy that pastoralists rely on to maintain their herds during periods of drought [38]. A new approach is livestock insurance schemes that are weather-indexed, so that policy holders are paid in response to 'trigger events' such as abnormal rainfall or high local animal mortality rates. Index-based livestock insurance schemes based on satellite imagery are currently being piloted in several areas of drought-prone northern Kenya via novel public–private partnerships [48]. However, these schemes are themselves highly vulnerable to climate change, as increases in the frequency and severity of droughts could make them unviable. An approach that has been used by pastoralists in the past to deal with the vagaries of climate is to change the mix of livestock species and/or breeds, sometimes on a temporary basis [49,50], and indeed recent anecdotal information suggests that in parts of East Africa herders are switching from cattle and sheep to camels and goats. As for certain crops, some livestock species and breeds are better able to deal with dry and drought conditions than others, and there may be considerable potential in some areas for pastoralists and agropastoralists to adapt to a changing climate in this way.

(*a*) *Constraints to local adaptation*

Good practice in adaptation is constrained by a number of factors, and these will become much more critical in a 4°C+ world. First, there are inherent limits to the predictability of both climate and its impacts; and there is variability in the methods and assumptions used by any single study to assess probable impacts. Thus, not only is our knowledge of the future necessarily imprecise, but also the degree of precision claimed by different studies varies considerably, making such studies not directly comparable. Challinor *et al.* [14] discuss this in more detail, citing an example where the simulated responses of maize in Africa to a doubling of carbon dioxide can be as narrow as −14 to −12 per cent, or as broad as −98 to +16 per cent. Thus adaptation occurs in the context of uncertainty, and if that uncertainty is too great then it may be difficult to assess appropriate adaptation options. Uncertainty about the future can never be banished entirely, of course, and adaptation decisions will be taken in any case, but uncertainty may substantially raise the costs of being able to accommodate fully possible future events with different characteristics [51]. Experience with use of seasonal forecasts to make short-term crop choices or provide insurance to households and farmers suggests that uncertainty about even three months ahead can be difficult for decision makers to incorporate [52], although continued research on this is a promising way forward. Such research highlights the limits to scientific advances alone in fostering adaptation; any new technologies or information advances are only successful to the extent that they meet farmers' needs and contexts.

Second, adopting new varieties or different crop and livestock management techniques requires farmers to take on new risks and explore new markets, and also requires access to credit and technical support. The ability of many smallholder farmers in SSA to obtain access to such support mechanisms is already low [53,54]; the need to adapt to climate change may provide a stimulus to increase such support, but it can be achieved only with considerable institutional and political commitments [55,56]. Currently many farmers rely on a host of off-farm diversification strategies to support their own agricultural activities and ensure a household income [57]. If a changing climate increases the risks associated with agriculture, it is not clear how farmers will adjust the balance of on- and off-farm activities. As a 4°C+ warming will affect not only what can be grown but also where, as land suitability shifts, existing successful technological packages and systems may not be that useful. By 2050, temperature increases may result in about a quarter of African countries experiencing climatic conditions over substantial parts of their existing cropped areas for which there are no current analogues [58]. In places where no historical analogues exist, then pressures on farming systems, livelihoods, agricultural technology and supporting mechanisms may become intense, as smallholders become increasingly alienated from their realm of experience. In this case, the notable trend of economic diversification into non-farm activities would most probably increase even more, as rural residents made the logical choice to seek less climate-sensitive activities [59], although these choices may not lead to greater food security [60].

Many authors have argued for vulnerability-led approaches to adaptation, so as to contextualize how climate change affects livelihoods, and to explain that successful adaptation depends upon not only exposure and sensitivity to climate change, but also adaptive capacity and an enabling institutional and policy environment [61–63]. Emphasizing vulnerability as a social and political phenomenon also cautions against an over-reliance on research-led solutions alone. Although many studies in developing country contexts emphasize the importance of supporting local-level, grassroots adaptation, lessons from decades of agricultural development interventions have shown the need for higher-level institutional and policy support as well [59,64,65]; thus local adaptive capacity requires higher-level enabling support. For example, the recent collections of success stories in agricultural development and food security achievement compiled by the International Food Policy Research Institute (IFPRI) and the Food and Agriculture Organization (FAO) are explicit in describing the necessary enabling conditions, such as access to markets for new crops, national policy that prioritizes food security, agricultural extension and so on [11]. In a 4°C+ world, successful adaptation will require a huge investment in policy and technology.

The constraints described above can combine to produce particularly pronounced problems when it comes to any particular adaptation option. For example, the number of crop varieties cultivated by farmers has declined over time because of an increasing focus on high-yielding varieties, necessitated by the need for increased production and enabled by the globalization of trade, a phenomenon referred to as 'genetic erosion' (e.g. [66]). A changing climate will further constrain the number of varieties that can be used, since many may not be suited to the new environment. Thus, the options for adaptation through a change in cultivar diminish over time.

Increasing yields is, of course, not the only adaptation option. Expansion of cropped land can also be used to maintain production. However, climate change may heavily modify land suitability. In relatively large areas of SSA that are currently classified as mixed rain-fed arid–semiarid systems, cropping may become increasingly risky and marginal, perhaps leading to increased dependence on livestock keeping or increasing diversification into non-agricultural activities and migration to urban areas. Such areas may, to all intents and purposes, 'flip' from a mixed system to a predominantly rangeland-based system: some 730 000 km^2 of SSA may be at risk of such flipping [25], of which about 16 per cent is located in areas within 3 h travel time of a population centre with more than 250 000 people (a proxy for 'good accessibility to markets'). We recalculated the size of the transition areas that may flip from mixed rain-fed arid–semiarid to rangeland-based arid–semiarid systems using the climate data outlined in §2*a* above. In a 5°C+ world, the transition zone increases in size to some 1.2 million km^2 (about 5% of the land area of SSA). Moreover, with such warming, the proportion of this transition zone that is in areas of high accessibility increases to about 50 per cent. Such conditions would mean considerable loss of cropland in SSA (cropping would become too risky in about 35% of the mixed rain-fed arid–semiarid systems); and increasing amounts of this land would be in the hinterlands of large urban areas with already high population densities.

Such changes in the agricultural landscape and crop geography will require significant adjustments in livelihood strategies and agricultural growth pathways. As already discussed, decades of work on agricultural development has shown that farmers need support to switch strategies, and the evidence suggests that there are no historical analogues for the growing conditions in a 4°C+ world in which globalization has changed the structure of food systems [8,67]. Although the recent increased investment by the World Bank, the Bill & Melinda Gates Foundation and other donors in the long-neglected agricultural sector are timely and welcome, the engagement of these groups with the reality of a changing climate is only just beginning, as evidenced by the 2010 World Development Report on 'Development and Climate Change' and the launch in 2010 of the new Challenge Programme on Climate Change, Agriculture and Food Security (www.ccafs.org).

(*b*) *The adaptive capacity of food systems*

As patterns of agricultural production will change profoundly in a 4°C+ world, the question of how food security will be affected, and whether food systems can adapt sufficiently to avoid increased food insecurity, raises a host of issues. Food security depends upon much more than just local agricultural production, as access to food is often the major reason why poor households suffer from hunger [42,68]. Access is a function of both income and price of food, as well as of the ability of markets and distribution networks to allocate food equitably (from the household to the international level; [69]). In Africa, progressive climate change will increase the probability of failed agricultural seasons owing not only to long-term shifts in temperature and precipitation but also to the probably increased frequency of droughts and floods [70]. Thus increases in transitory food insecurity episodes can be expected. The lessons gathered from 30 years of food security analyses and interventions demonstrate the following:

— Repeated droughts erode the assets of poor and marginal farmers, and relief interventions struggle to protect such households effectively from food insecurity and poverty [71,72]. Food aid as a long-term strategy is not wise [73]; both food- and cash-based transfer or safety net programmes are difficult to design and implement on a broad scale, particularly in response to seasonal shocks [74,75].

— The responses of national governments to protect food security in the face of supply and price shocks are not always successful, particularly over the long term [76,77]. The domestic interventions of multiple national governments are partially blamed for exacerbating the impacts of the 2007–2008 food price increases.

As we saw in 2007–2008, crop failures in major exporting countries such as Australia, when occurring at the same time as other food system disruptions such as speculation, increased demand for agricultural commodities and low grain reserves, can lead to widespread, global food price increases [78]. As climate change is a global phenomenon, we can expect more price shocks in the future. The evidence about a country's 'adaptive capacity' in the face of the 2008 price shocks is sobering, as many reverted to domestic price controls, export bans or import tariffs, and globally food aid was in short supply. Food insecurity persists not only because of economic imbalances between rich and poor, but also due to power imbalances, between governments as well as between communities. This manifests itself not only in political negotiations such as the Doha Round of the World Trade Organization (WTO) but also in differential capacity of markets and national policies to accommodate food price shocks [79–81]. The lesson from this is that there is still much learning to do concerning how to implement risk management and agricultural growth strategies for SSA at the necessary scale. The IPCC's Fourth Assessment Report [15] assumes that regional shortfalls in SSA can be ameliorated with imports from global markets; the experience of 2008 underscores the difficulties that such an 'adaptation' strategy will face in reality.

(*c*) *Diminishing technical options for adaptation*

Constraints to adaptation at the local level (§3*a* above), together with the indications above that the adaptive capacity of food systems is also limited, lead to a reduction in the number of adaptation options as climate moves further from the current coping range. While, at first glance, globalization may appear to offer a mechanism for smoothing out geographical differences and thus stabilizing food supply, it is far from clear that this is the case. If options are reduced across the globe, then we cannot rely on redistribution of resources via trade as an adaptive mechanism. Simulation results for maize in the USA [82] are one indication that this may indeed be the case, with existing varieties showing an overall decreasing crop production under scenarios of climate change. Although there were some regional variations, the results of that study indicated that adaptation to climate change for maize yields would require either increased tolerance of maximum summer temperatures in existing maize varieties or a change in the maize varieties grown. Similar projections have been made for a range of crops across the globe. Spring wheat crop failures in China have been projected to increase with (both local and global) mean temperature, owing to an increasing occurrence of extremes of heat and drought [83]. This suggests that here too the options for adaptation are decreasing. Quantifying climate uncertainty is an important aspect of such assessments: using one regional climate scenario across India, and quantifying uncertainty in the response of crops to elevated CO_2, Challinor [83] found significant potential for adaptation of groundnut cultivation to climate change in India. However, a subsequent, fuller account of uncertainty in climate demonstrated that this potential will not necessarily maintain current yields [84].

Comprehensive analyses of adaptation options are difficult to make, partly owing to the complexity of any adaptive system. Even when only one option is considered, such as a change in crop variety, insufficient data may be available for analysis. Germplasm databanks provide an invaluable source of information for matching crops to future climates. Making use of one such dataset—the multi-location International Wheat Information System held at the International Maize and Wheat Improvement Center CIMMYT—we examined the response of 2711 varieties of spring wheat to increases in mean temperature. We used observed current crop durations with proscribed changes in mean temperature in order to calculate future crop durations. We chose the northern USA as the study region, since the current mean growing season temperature in this region is around 21°C, thus permitting the assumption that the optimum temperature for development is greater than any season-mean temperature and allowing us to use the methods of Challinor *et al.* [84, eqn (3)] to calculate duration. At +2°C of local warming, 87 per cent of the 2711 varieties examined, and all of the top five most common varieties, could be used to result in a crop duration similar to that of the current climate. This can be interpreted as a successful adaptation to mean warming. At +4°C, however, the proportion fell to 54 per cent of all varieties, and only two of the top five.

While the above analysis is relatively simple, assessing only crop response to mean temperature, it does illustrate the way in which adaptation options diminish as climate changes. Furthermore, we have seen that diminishing options in one region of the globe result in diminishing options elsewhere. Thus, the options available for adaptation to climate change for SSA, whether domestic or foreign, are likely to decrease. What is unclear is at what point those options become too few for successful adaptation across a region. This is a major question, given the many problems that continue to plague African food systems. It may be that critical thresholds are already being reached because of economic and policy failures. While understanding of physical thresholds in the Earth system is increasing [85], as yet we have little understanding of socio-economic and cultural thresholds. Understanding and quantifying the critical thresholds in global food systems and how these play out in SSA in particular is an urgent research issue.

4. Conclusions

The prognosis for agriculture and food security in SSA in a 4°C+ world is bleak. Already today, the number of people at risk from hunger has never been higher: it increased from 300 million in 1990 to 700 million in 2007, and it is estimated that it may exceed 1 billion in 2010 [42]. The cost of achieving the food security Millennium Development Goal in a +2°C world is around $40–60 billion per year, and without this investment, serious damage from climate change will not be avoided [86]. Currently, the prospects for such levels of sustained investment are not that bright. Croppers and livestock keepers in SSA have in the past shown themselves to be highly adaptable to short- and long-term variations in climate [14], but the kind of changes that would occur in a 4°C+ world would be way beyond anything experienced in recent times. There are many options that could be effective in helping farmers adapt even to medium levels of warming, given substantial investments in technologies, institution building and infrastructural development, for example, but it is not difficult to envisage a situation where the adaptive capacity and resilience of hundreds of millions of people in SSA could simply be overwhelmed by events.

At the moment, it seems unlikely that international climate policies will succeed in confining global warming to +2°C; even this will require unprecedented collective will and collective action [16]. What can realistically be done in relation to food security in SSA in the short to medium term? We highlight four things. First, we can assist the adaptation that is already inevitable by identifying, encouraging and helping to implement proactive adaptation to keep the number of options high for smallholders. Households' capacity to adapt in the face of increasing external stresses is largely governed by flexibility in livelihood options, and there is increasing evidence that generally it is the poorer households that can gain the most from implementing options for coping with and managing risk [87]. A wide variety of prospective options exist, from the effective use of climate information to paying smallholders for ecosystem goods and services to increase household income. Some of these options are likely to be robust, even given the uncertainties that exist concerning future patterns of climate change. But the lessons of the recent past teach us that the difficulty of implementing many of these options in SSA should not be underestimated: massive investment and increases in agricultural productivity will be necessary if economic development is to succeed in Africa in the coming decades [88].

Second, we need to go 'back to basics' in collecting data and information. Difficult though it may be for many people to accept in the second decade of the twenty-first century, the fact is that land-based observation and data collection systems in SSA have been in decline for decades. This affects the most basic data: weather data, land-use data, and crop and livestock distribution data, for example. For instance, estimates of the cropland extent in Africa range from about 1 to more than 6 million km^2, the value depending on choice of satellite-derived product [89]. The uncertainty in such basic information ('where are crops grown and how much of them is there?') adds considerable difficulty to the quantification and evaluation of impacts and adaptation options. There is much technology that is being brought to bear on data issues: remote sensing of weather information, validation of different land-use products using Wikis and Google Earth (see www.geo-wiki.org) and dissemination of market information using mobile phone technology in East Africa, to name just a few. But many of these things need to complement land-based observations, not substitute for them. A similar situation exists with respect to germplasm data. Specific information on the response of crops to weather and climate is often not collected, but it could be with relatively modest additional effort.

Third, concerted action is needed to maintain and exploit global stocks of crop germplasm and livestock genes. Preservation of genetic resources will have a key role to play in helping croppers and livestock keepers adapt to climate change and the shifts in disease prevalence and severity that may occur as a result. Genetic diversity is already being seriously affected by global change. Genetic erosion of crops has been mostly associated with the introduction of modern cultivars, and its continuing threat may be highest for crops for which there are currently no breeding programmes [90]. Breeding efforts for such crops could thus be critically important. For livestock, about 16 per cent of the nearly 4000 breeds recorded in the twentieth century had become extinct by 2000, and a fifth of reported breeds are now classified as at risk [91]. Using germplasm in SSA will need technical, economic and policy support. Revitalizing agricultural extension services, whether private or in the public sector, is key: no farmers will grow crops or raise livestock they do not know, are not able to sell, and are not used to eating.

Fourth, the social, economic and political processes that contribute to vulnerability and food insecurity must be addressed with even greater vigour. Food insecurity has received renewed policy attention since 2008, when several high-level meetings on food security were held in response to the food price crisis. Political reforms have been proposed, and countries have made commitments to better food system governance and increased investment in smallholder agriculture. In addition, the momentum for supporting community-based and local adaptation is building in communities of practice; however, this requires higher-level policy and institutional support to ensure that local-level adaptation is enabled and communities are empowered.

The agricultural landscape of SSA is likely to undergo considerable change in the coming decades as a result of several different drivers. Food systems will have to adapt to ensure food security for the extra billion people who will be populating the African continent by 2050, and this will require broad and integrated (yet locally context-specific) institutional and policy responses. It would not be wise to bank on limiting climate change to +2°C, and we should be prepared for more. Some places may see sustainable intensification of production, where this is possible, others may see shifts in crop and livestock production, and some of the drylands are likely to need sustainable extensification as cropping becomes ever riskier. Keeping smallholders' options open is key, and a substantial part of this will lie in much better understanding of the limits to adaptation and the thresholds beyond which much more radical action will be needed, if food security is to be achieved in SSA.

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