African Lessons on Climate Change Risks for Agriculture

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Annu. Rev. Nutr. 2013. 33:395–411

First published online as a Review in Advance on March 25, 2013

The *Annual Review of Nutrition* is online at http://nutr.annualreviews.org

This article's doi:
10.1146/annurev-nutr-071812-161121

Keywords

model, development, food security, adaptation, uncertainty, review

Abstract

Climate change impact assessments on agriculture are subject to large uncertainties, as demonstrated in the present review of recent studies for Africa. There are multiple reasons for differences in projections, including uncertainties in greenhouse gas emissions and patterns of climate change; assumptions on future management, aggregation, and spatial extent; and methodological differences. Still, all projections agree that climate change poses a significant risk to African agriculture. Most projections also see the possibility of increasing agricultural production under climate change, especially if suitable adaptation measures are assumed. Climate change is not the only projected pressure on African agriculture, which struggles to meet demand today and may need to feed an additional one billion individuals by 2050. Development strategies are urgently needed, but they will need to consider future climate change and its inherent uncertainties. Science needs to show how existing synergies between climate change adaptation and development can be exploited.

Contents

INTRODUCTION

Climate Change, Agriculture, and Human Nutrition

Climate change is caused by human activities, most importantly by emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (55). Although the general effect of the accumulation of GHGs in our atmosphere is clear—global warming—its impacts on human societies and ecosystems are less clear (*a*) because of the much larger diversity and complexity of the systems and (*b*) because impact assessments require much more detailed projections of climate change. Understanding the impacts of a two-degree warming on agricultural production, for example, requires detailed information on where, when, and how daily weather conditions will change. High temperatures during sensitive phenological stages, such as flowering, can be much more harmful to agricultural productivity than during other stages of plant growth (37, 128). Reductions in precipitation during the fallow period may have little impact, whereas an increase in precipitation may be devastating to agricultural production if it comes in the form of very intense rainfall or hail (108). Unfortunately, the uncertainty of climate projections increases with the level of detail. Although the global mean temperature increase for a given GHG emission scenario can be assessed with relatively little uncertainty, projections become drastically more diverse—and thus uncertain—for smaller regions, such as the Corn Belt in the United States or the rice fields in the Indo-Gangetic plains. The same principle holds for projections for shorter time periods: The uncertainty in climate change projection increases with shrinking time windows (49, 50).

Consequently, the uncertainties in climate projections and additional assumptions on more detailed aspects of climate strongly affect assessments of climate change impacts on agricultural production systems (94). Future agricultural production, however, will be affected not only by climate change. Human populations are increasing in many parts of the world, and the global population is projected to reach 9 billion or more by 2050; Africa's population may double by 2035 (84). Farmers will need to produce more food to feed the additional billions as well as produce different food types to meet the demands of individuals who are increasingly consuming more calories, more meat, and different and higher-quality food items as they become wealthier (7, 82, 120).

Agricultural production is closely linked to human nutrition and health. The historic rise in agricultural production and in food supply per capita (43) not only has led to a strong reduction of undernourished people between 1960 and 1990, but it also has strongly altered agricultural markets and health issues associated with food. While general reductions in food prices led to enhanced food security of poor consumers, the increase of prices of nutrient-rich products relative to that of staples and the increasing dominance of monoculture production systems led to reduced diet diversity and continuous micronutrient malnutrition for many poor people (103). For the wealthier population, the cheap supply of food advanced obesity and other diet-related diseases (60). Future climate change not only will affect agricultural productivity and associated supply and access to food but also will result in many indirect effects that are often related to nutrition and health (87). For example, the different responsiveness of crops to climate change (74) may lead to changes in diets, especially for the poor; malnutrition may lead to increased spread of transmittable diseases such as HIV (39); and diminished health of farmers and workers may reduce agricultural productivity (61).

Competition for Land and Water

Land and fresh water are the most basic resources in agricultural production, and they are already in short supply, at least in some areas of the world. The global competition for these resources has already begun and will intensify as food production needs to be increased, as yield levels stagnate in many parts of the world (43, 73), and as bioenergy becomes a new, potentially powerful player. Many projections of future energy supply foresee large shares of bioenergy, that is, energy from regrowing biomass (63, 70). Biomass not only takes up the most prominent GHG CO_2 during growth and can thus produce theoretically carbon-neutral energy, it also has great potential for negative emissions if combined with carbon capture and sequestration (CCS) techniques. With CCS, the CO_2 produced during the combustion of biomass is not emitted to the atmosphere but rather is extracted from the exhaust and stored in long-term reservoirs, such as depleted natural gas reserves (25). Already today, much of the maize produced globally is not consumed as food but instead is used as an energy source (e.g., 85). Although bioenergy is viewed as carbon neutral in theory, in reality it can have higher CO_2 emissions than conventional energy sources, particularly if indirect land-use change (25, 114) and other unwanted environmental effects (117) are considered. Nonetheless, biomass will be an important player in future energy supplies, especially if climate mitigation receives much-deserved and urgently needed high priority in political agendas (63).

Fertile land, however, is already scarce today (66), and any large-scale bioenergy production will require some sacrifices of other ecosystem services (14, 114). Food production will thus need to be increased by intensification rather than cropland expansion, especially in Africa (83), where current production levels are often far below the environmental potential (72, 98).

The Special Case of Africa

Climate change is very likely to lead to above-average warming in Africa (23). Because Africa is the continent with the highest share of undernourished people and very low levels of food security (42), any indication of negative impacts of climate change on agricultural productivity in Africa are of serious concern. Many studies of climate change impacts on African agriculture were collectively analyzed in the most recent Intergovernmental Panel on Climate Change (IPCC) assessment report (17, 55). The focus on one extreme and near-term projection, namely the possibility that rain-fed agriculture could be reduced by up to 50% by 2020, had fueled public debate on the credibility of such projections. The original statement in the IPCC Synthesis Report, "[b]y 2020, in some countries, yields from rain-fed agriculture could be reduced by up to 50%" (55), was later revised at the 35th IPCC plenary session in Geneva to "[b]y 2020, in some countries, yields from rain-fed agriculture could be reduced by up to 50%, as a consequence of climate variability and change" in order to better reflect the underlying report of Working Group II (17). More importantly, recent scientific literature on the topic (64, 94, 107) was found to support the more general statement of the IPCC

Fourth Assessment Report (AR4) that "[a]gricultural production… in many African countries is projected to be severely compromised."

Irrespective of that debate, it's worthwhile to review the available projections of climate change impacts on African agriculture and to carefully analyze them with respect to uncertainty and implications for decision makers. After all, agriculture contributes about 40% to the gross domestic product in most sub-Saharan African countries despite its poor performance. At the same time, it is very sensitive to variations in climate inter alia because of the low availability of irrigation infrastructure, degraded soils, and insufficient effort of farmers to adapt and improve production methods (9).

In the following sections, I lay out the mechanisms of projecting climate change impacts on agricultural productivity, review recent literature on assessments of climate change impacts on African agriculture, and discuss implications for African food security and future research needs.

STATE-OF-THE-ART IN CLIMATE IMPACT ASSESSMENTS FOR AGRICULTURE

Assessments of climate change impacts are especially challenging because they are subject to considerable uncertainties. Several laboratory and field experiments have demonstrated the importance of temperatures, precipitation and soil moisture, and atmospheric CO_2 concentrations (3–5, 52, 135), which are all projected to change significantly in the coming decades (55, 91). The knowledge gained in such experimental studies can be formalized in models, helping to structure the complex interactions, which can be purely conceptual or quantitative. Conceptual models describing the qualitative relationships between system properties often form the basis for hypotheses. Experimental trials have shown, for example, that high temperatures increase the maintenance costs of plants (65) and, above certain thresholds, reduce photosynthetic activity (57, 109).

Our hypothesis could thus be that Africa, hot already today, will suffer from yield losses under global warming. Such a hypothesis can then be tested with statistical analyses examining the relationship of temperature increases and yields and their significance (78, 112). Plant growth and crop productivity, however, are more complicated than formulated in our conceptual model so far because increases in temperature also affect many other processes in soils and plants, such as leaf senescence (8, 80) and the mineralization of soil organic matter, and thus the availability of nutrients (59, 131). Similarly, climate change not only contributes to rising temperatures but also affects precipitation and air moisture, cloud cover and radiation, and changes in diurnal cycles and seasonal patterns (104). In addition, rising atmospheric CO_2 concentrations drive climate change as well as stimulate photosynthetic activity in C_3 plants (such as wheat and soybean) and increase water-use efficiency in both C_3 and C_4 plants (such as maize and millet) (5).

Such complexity in drivers and plant response mechanisms limits the significance of simple statistical relationships that typically explain only small fractions of the observed variability in crop response (77). Process-based simulation models aim at quantifying the interaction of all relevant mechanisms at the process level, explicitly simulating processes in the soil (such as soil moisture or nutrient dynamics) and within plants (such as the opening of stomata or the stimulated growth of roots under water stress) and their interaction with the atmosphere (e.g., air moisture). In theory, such process-based models can be as complex as our understanding of the system but are limited by our ability to quantify and parameterize all of these detailed relationships. In practice, all process-based crop growth simulation models are mixtures of detailed descriptions of soil and plant growth processes and statistical relationships. In contrast to empirical models, they are not constrained to the model's training domain and can thus also be applied to novel environmental conditions as expected under climate change (20).

Econometric models, such as the Ricardian models of Mendelsohn & Dinar (89), are a subgroup of empirical models that aim at quantifying the effects of climate change on agricultural profitability in monetary terms rather than on crop yields in terms of biomass. Such models use empirical relationships of farmers' income and climate conditions to analyze climate change impacts on farmers or households in monetary terms.

Recent Climate Change Impact Assessments for African Agriculture

Climate change impacts on African agriculture are explored with empirical and process-based simulation models as well as econometric models. This suite of model types projects an extremely broad range of possible impacts on African agriculture (64, 94, 107). As summarized in **Figure 1**, the new literature emerged after the approval and publication of the IPCC AR4 confirmed (*a*) the risk of negative climate change impacts on African agriculture, (*b*) the high confidence in this finding (all studies indicate the possibility of reduced agricultural productivity under climate change), and (*c*) the large range of projected changes in productivity. Generally, the spread of projections increases with time in individual studies that cover several points in time (12, 45, 115, 119, 125) as well as across studies (**Figure 1**). Similarly, the range of projected impacts is often broader (74, 124) and generally covers more severe projections with decreasing spatial extent (74, 124, 125). This reflects the increasing uncertainty in climate projections with time and decreasing spatial scales (49, 50) as well as the importance of assumptions on future agricultural production systems. Although most studies analyze current production systems or assume little adaptation even in the more distant future, production systems could greatly benefit from adaptation and general development (e.g., 115). The indication of negative climate change impacts in the near future is especially alarming. Even though near-term projections are often not as severe as projections for the far- and mid-term future, implications for food security may be severe nonetheless because of the limited time to adapt.

Although Nelson et al. (96) comprehensively address agriculture in a broader context, including land-use change dynamics and shifts in agricultural technologies, other studies typically analyze agricultural systems in isolation. That is, any interaction with other sectors, such as the availability of fresh water, market access, or the development of infrastructure, is ignored. In fact, very little is known about impacts on whole value chains and the flexibility of consumers and markets. Econometric models are no exception to this, as they cannot account for changes in market structure owing to their empirical nature. In an increasingly globalized world, interregional trade may significantly alter demand patterns and conditions for agricultural production (83, 113). The implications of these alterations can be substantial, given that African productivity levels are very low (72, 98): Yield levels are 10% (Egypt) to 90% (Angola) below their environmental potential (98). The underlying reasons for these large yield gaps are mainly market access (98) and thus availability of fertilizers and pest control (86, 136). The lack of accounting for the interaction of African agriculture with other sectors and regions substantially limits the implications of these studies.

Although the range of projections may seem confusing, there is also broad consensus among the different studies in some important aspects, and some of the diversity that exists can be explained by differences in the studies' settings.

Reasons for Diversity in Projections

Climate data. The broad diversity in model projections limits comparability and general conclusions and has several underlying reasons. First, all climate change impact assessments inherit the uncertainties in GHG and aerosol emission trajectories (88, 91) and their effects on the climate system (104). Emission trajectories of GHGs and aerosols are typically model-supported translations of plausible

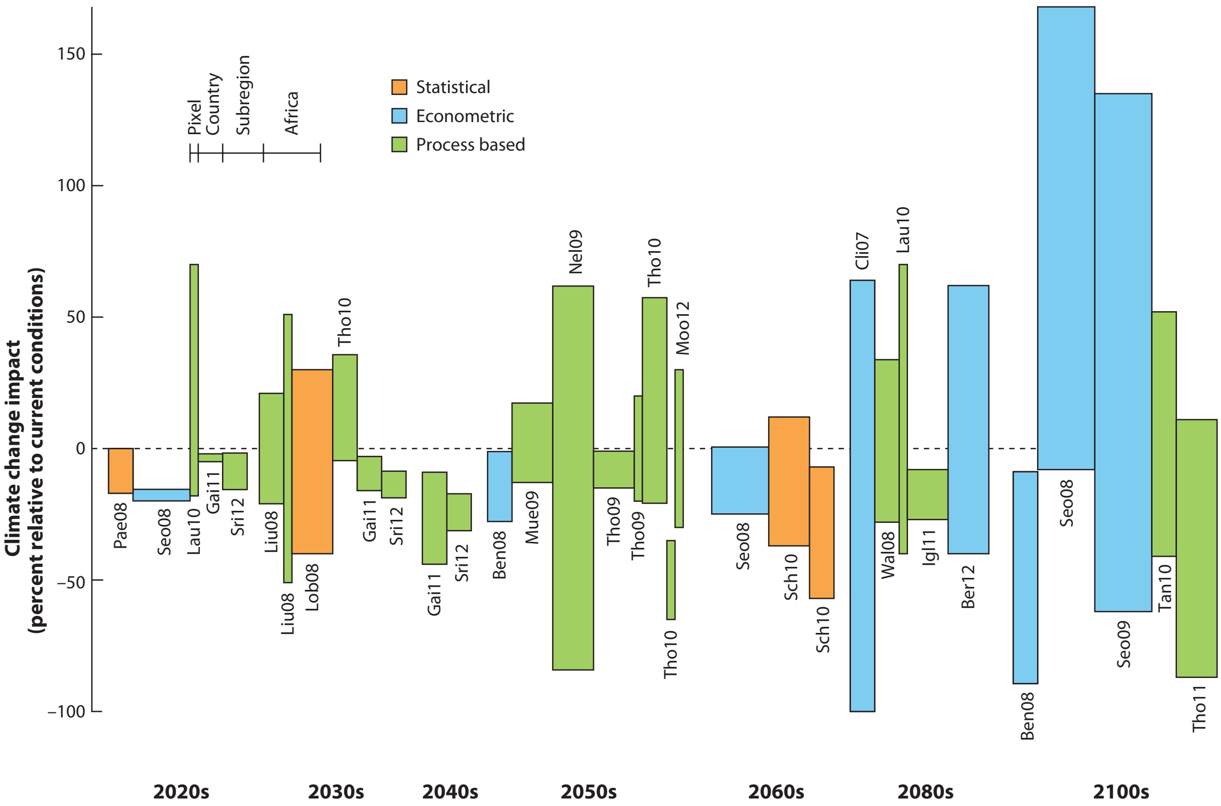

Figure 1

Climate change impacts on African agriculture as projected in recent literature, after the approval and publication of the International Panel on Climate Change Fourth Assessment Report (AR4). Impacts are expressed as percent changes relative to current conditions; bar width represents spatial scale of the assessment (pixel, country, subregion, Africa), color denotes the model type employed (statistical, *orange*; econometric, *blue*; process based, *green*). Bars are labeled with the first three letters of the first author's last name, and the two digits that follow represent the year of the report. The reference Ben08 (12) had already been assessed for the AR4 Working Group II report as Reference (11); Seo08 refers to the livestock sector only; Tho10 reports pixel-based results only for a random selection of strongly impacted pixels; Sch10 shows country data only for maize; Wal08 employs stylized scenarios that are representative for the climate in 2070–2100; Tan10 refers to northeast Ghana only; Gai11 and Sri12 refer to Upper Ouémé basin in the Republic of Benin only. References: Pae08 (100), Seo08 (115), Lau10 (67), Gai11 (45), Sri12 (119), Liu08 (74), Lob08 (77), Ben08 (12), Mue09 (93), Nel09 (96), Tho09 (124), Tho10 (125), Moo12 (90), Sch10 (112), Cli07 (26), Wal08 (134), Igl11 (54), Ber13 (13), Seo09 (116), Tan10 (122), Tho11 (126). Figure updated from (94).

and consistent scenarios of future societies. Most importantly, these scenarios comprise assumptions on population growth, economic development, and technological progress, which determine energy consumption and the sources of energy used (e.g., coal, nuclear, renewable) (91, 95). Even though these scenarios are developed with advanced and complex models, they are just scenarios. A scenario is different from a projection and certainly from a prediction because it does not try to project a system's behavior as a function of known or assumed drivers but merely creates plausible visions of alternative future states. This is necessary because many of the key assumptions, such as the development of new technologies (36), the willingness of societies to accept the risk of nuclear incidents, or the enforcement of future climate mitigation policies, cannot be predicted with much accuracy in the long term.

These socioeconomic scenarios form the basis for computing projections of radiative forcing, that is, the GHGs and aerosols, such as "representative concentration pathways" (91, 129). Such scenarios of GHG and aerosol emissions or of their atmospheric concentrations are implemented by general circulation models or earth system models to simulate the climatic response (104). Even though these models are based on well-established physical principles and are able to reproduce historic climate patterns and trends, there is considerable uncertainty (i.e., disagreement between models) with respect to the spatial patterns of changes in temperature, precipitation, and other climate variables (104). For Africa, it is very likely that temperature increases will be above average, but there is less certainty with respect to the patterns of precipitation change (23). Generally, the uncertainty of climate projections for a specific emission scenario increases with shrinking spatial or temporal extent (49, 50). As such, impact assessments for smaller spatial domains are already burdened with higher uncertainty with respect to the driving climate data. This is partially reflected in the results, where the spread of model projections of climate change impacts on African agriculture is typically broader for smaller spatial domains (74, 124). Most climate change impact assessments analyze only very small samples of climate projections that seem to be selected at random (94), and much of the range of possible climate change scenarios is not available from general circulation models (51). Also, climate data are often provided at coarse spatial grids and sometimes also at aggregated temporal resolution (e.g., monthly), so data need to be downscaled, adding another source of uncertainty (46).

Complexity in plant and soil processes. Second, owing to the incomplete understanding and the reduced complexity of the plant and soil mechanisms in models used to assess climate change impacts on agriculture, it remains unclear which of the multiple counteracting mechanisms will be dominant under changed climatic conditions. This shortcoming has recently been criticized (106), and two consolidated research community efforts, the Agricultural Model Intercomparison and Improvement Project (AgMIP; **http://www.agmip.org**) (105) and the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP; **http://www.isi-mip.org**), have been set up to improve impact models' capabilities. In addition, uncertainties exist that are related to model types. Statistical models, in both biophysical as well as econometric analyses, are generally unsuitable for extrapolation to conditions outside their training domain. Because climate change is projected to lead to novel climatic and weather conditions in the future (20, 48), the suitability of statistical models in such analyses is limited. Although statistical models that describe the biophysical agricultural productivity as a function of climate conditions typically have little explanatory power (77), econometric models are also strongly constrained by the availability of suitable data (116). Process-based models, on the other hand, are subject to overtuning (22) and often lack good parameterization of spatially explicit crop varieties and management options, especially if applied for larger spatial domains (93, 96).

Smart or dumb farmer assumptions. Third, models strongly differ in their assumptions on adaptation to changing conditions. Although classical climate change impact studies investigate the effect of changed climatic conditions on current agricultural systems and management intensities, some make assumptions on autonomous adaptation, such as adjustments in sowing dates and selection of cultivars (93). Adaptation efforts that are often easy to implement, such as the adaptation of sowing dates, can greatly affect climate change impacts (41, 67). Impact assessments often assume fixed or historically observed sowing dates, which is also problematic for the baseline simulation in regions with strong variation in rainy seasons (68). Simulations that simply use the most productive cropping period from systematic sowing date variation in their simulations may overestimate the ability of farmers to shift production periods (e.g., 121), whereas simulations that internally compute sowing dates as a function of the farmers' past climate experience do not necessarily match the actual cropping periods, especially in regions with low seasonality or multiple cropping systems (133). Econometric approaches, which describe statistical relationships between climatic factors and farm or household income, show that climate change can be strongly beneficial to the income of farmers if combined with adaptation measures (115, 118).

Aggregation. Climate change impacts are reported at very different levels of aggregation, ranging from individual cells in gridded simulations to aggregations for the entire continent. The level of aggregation strongly affects the range of reported impacts. Climate change will affect Africa inhomogenously, with some likelihood of further drying in the Mediterranean region and in southern Africa during winter, whereas East Africa will likely see general increases in precipitation (23). This will affect agricultural production systems as well as the increase in temperatures, which very likely will be above average global warming (23). Warming will be beneficial to agriculture only in small mountainous regions with current temperature limitations. In all other regions, warming is likely to be detrimental both directly, in plants with low temperature optima such as wheat, and indirectly, through increased water vapor pressure deficit in the atmosphere. If averaged across regions with different climate change signals, the reported average will conceal this gradient. Similarly, crops and cropping systems have very different sensitivities to changes in temperatures, precipitation, and CO_2 fertilization. Temperate cereals (such as wheat) with low temperature optima for photosynthesis are projected to experience strong reductions in yield, whereas some tropical crops with high heat tolerance (such as millet) could actually benefit from global warming (74, 96). There is a similar large diversity in production systems that also cover different production seasons (33, 132) and may thus experience different seasonal climate change signals. As such, climate change impacts reported at larger spatial aggregation units indicate that impacts are likely to be more severe and also more positive in individual subregions (74, 124, 125).

Robust Conclusions in Spite of Large Uncertainties

The limited comparability of climate impact studies on agriculture and the broad diversity of projected impacts seem to question the value of these assessments. As almost anything seems possible in African agriculture, ranging from complete loss (26, 56) to more than doubling of agricultural productivity (115, 116), science seems to offer little guidance here. However, this impression is wrong. The overall conclusions from such a broad range of studies are very robust not in spite of but rather because of the diversity of settings analyzed, and they have clear implications for decision making.

Most importantly, the diversity in projected climate change impacts on agriculture must not be misused as an excuse for inaction. On the contrary, it is a very strong incentive to act, if additional incentives to improve African agricultural productivity are needed. The most important and very robust conclusion from the wealth of analyses is that negative impacts of climate change on African agriculture cannot be ruled out. All quantitative studies reviewed here (see **Figure 1**) as well as those addressing climate change impacts in qualitative terms only (10, 15, 20, 44, 56, 71, 76, 77, 79) agree that climate change is a threat to African agriculture. That is, every single study covers at least one setting that sees declining agricultural productivity; many of these are severe (**Figure 1**). The risk of negative climate change impacts on African agriculture is so robust that it cannot be challenged by methodological differences in the assessments, which often are enormous (92, 107).

Equally important, 16 out of 21 quantitative assessments also project increasing agricultural productivity under climate change. Consequently, there is much opportunity to limit negative impacts on African agriculture or even to enhance productivity—but opportunities need to be seized. Most important are climate mitigation measures, as scenarios with lower radiative forcing see impacts that are significantly reduced in comparison to high radiative forcing scenarios (107). Adaptation measures also yield much potential to reduce negative impacts of climate change, and even more so if they are extended to measures that enhance agricultural productivity irrespective of climate change. A variety of options that require little or no technical support are available and have successfully demonstrated their potential in Africa (e.g., 35). This is of particular interest for development measures and policies. Given that African agriculture struggles to meet the current demand for food as reflected by the strong dependence on food aid (2, 43), various synergies between development aid and climate change mitigation as well as adaptation are possible (101, 110).

Even though there is still no comprehensive assessment of climate change impacts on African agricultural production systems, the current literature supplies a sufficiently complete picture of the general nature of impacts to be expected. Although impacts will certainly vary greatly across Africa, some regions are at risk to experience substantial reductions in or even complete loss of agricultural productivity (26, 56), whereas other regions could benefit from climate change, in particular if it comprises substantial increases in precipitation in semiarid regions. Model projections also reflect that impacts will vary by crop and farm type. That is, some crops are more susceptible to warming (e.g., wheat) than others (e.g., millet), and larger or irrigated farms typically have a greater ability to buffer against negative impacts from climate change (12).

RESEARCH GAPS AND FUTURE DIRECTIONS

It is clear that climate change poses a significant threat to current African agriculture. Farmers, regional decision makers, national governments, international organizations, and the public need to be concerned. African farmers and societies need strong assistance in transforming current production systems to ones that are less exposed and more flexible. But our understanding of how this could be achieved is actually very limited. It is clear that many of the prerequisites for such a transformation are of institutional, governmental, and cultural dimensions (38), which is in great contrast to the climate change impact assessments that focus almost exclusively on the biophysical mechanics of crop production or the economics of existing farming systems.

From Biomass to Nutrition

Generally, the reduction of crop yields in food-insecure regions is likely to increase undernutrition and its effects on population health, such as stunting (75). Although changes to agricultural production in terms of metric tons and calories are certainly an important aspect in the food security discussion, very little information is available on climate change–driven alterations of chemical composition of agricultural products. Changes in calorie production, if reported, are typically based on a fixed translation scheme of simulated changes in carbon or biomass to calories (e.g., 93), whereas changes in protein content or other nutritional values typically are not addressed. There is, however, generally a trade-off between the quantity and quality of storage organs (102), but the impact of climate change on this trade-off has been largely unexplored so far. Nonetheless, there are indications that climate change will affect the chemical composition of crop plants, especially in combination with the driving increase in atmospheric CO_2 concentrations (29, 123). This may also affect pesticide use, as altered chemical composition changes the susceptibility of crops to insect damage (31, 137). The role of CO_2 fertilization for agricultural productivity and crop quality is a major source of uncertainty in impact assessments and requires additional scientific attention (69, 81, 127). It has been demonstrated that increasing atmospheric CO_2 concentrations lead to higher carbon assimilation rates in photosynthesis as well as to higher water-use efficiencies, but it remains uncertain to what extent this will be achievable in larger regions because higher assimilation rates can support additional plant growth only if sufficient nutrients can be acquired by the plant, and higher rates may reduce crop quality or even nitrogen assimilation (16).

Although climate change is likely to have little effect on nutritional diseases of affluence [unless wealth is diminished under climate change (e.g., 1)], it has much greater potential to negatively affect the poor. Agricultural markets and food prices have responded to increasing food production in the past and are projected to respond to future climate change (97). Similar to the effects of the Green Revolution (103), shifts in the relative price levels of staple crops and nutrient-dense crops may affect dietary patterns, especially of poor people. Production systems that are more diverse may prove to be less susceptible to climate change (132) and could contribute to the diversification of diets, but market orientation and increased trade could lead to proliferation of monoculture production systems and associated less-diverse diets (103). Agricultural production in poorer economies is also subject to the health status of the labor force (61) and could be significantly affected by climate-driven changes in health, such as the spread of malaria (18, 47), and other infectious disease burden, such as HIV/AIDS (34).

Accounting for More Climatic and Nonclimatic Drivers

Consequently, agricultural production is analyzed in a manner that is much too isolated, and field-scale processes are often simulated to approximate agricultural production systems. Consequently, simulated production systems are likely not representative for future African production systems. The assumption in many studies that African agricultural production systems will not change in the future is very unrealistic even under an assumed absence of climate change. Given current food security problems (58) and projected changes in population (84) and dietary habits (7), as well as large unexplored agricultural potentials (72, 98), African agriculture is bound to see significant changes in the near and more distant future. These changes will also be driven by changes in other world regions through international trade (82, 96, 97, 113). Although agronomic measures to increase productivity have been identified, their implementation has failed, mainly for institutional reasons (38). Large investors have recently started to act, securing vast areas of fertile land in Africa. These investors, such as multinational companies and foreign governments, secure rights to use large parts of the fertile land in many developing countries through long-term binding contracts. In return they often provide resources that are lacking, such as irrigation techniques, fertilizers, and pesticides, to increase land productivity. This “land grabbing” phenomenon is not necessarily beneficial for local farmers, who typically are not involved in the contract negotiations (27), but it may possibly spark agricultural development in Africa more efficiently than did the foreign development assistance of previous decades. Given the high risk of foreign exploitation of African agricultural resources at the expense of local farmers and residents, facilitated by weak governance (30), land grabbing needs to be carefully watched and regulated (28, 32, 130). Besides forced changes in land access, climate change may also directly affect migration of African people (62). It is being debated whether social unrest can be related to climate change and declining food production (6, 19, 21, 53, 99, 111), which also would imply changed pressures on land and agricultural production systems.

Some aspects of climate change, in particular the role of weather extremes (10, 48, 76, 80) or droughts in main growing seasons (44, 71), are likely underestimated in current assessments, as are indirect climate change impacts. Sea level rise, for example, threatens some of the most productive areas in Africa, such as the Nile Delta, with cropland inundation, erosion, and salinization (40).

From Classical Climate Change Impact Assessments Toward Decision Support

Most scientific research that has tried to assess the impact of future climate change on African agriculture shows little agreement in the absolute numbers but consensus in the topline conclusion: African agriculture is at risk to be severely compromised by future climate change. Therefore, strategies need to be developed for increasing resilience to climate change in African agriculture (24). Beyond this point, there is little information to be taken from the sketchy sampling of possible future climate change scenarios and agricultural production systems because of the large uncertainties in both drivers (e.g., climate change patterns, atmospheric CO_2 concentrations) and system response (e.g., technologies and management, land use change). Therefore, such classical climate change impact assessments are of little value for decision making, although they contribute to the scientific understanding and thus provide great academic value. However, we need to investigate future research issues differently. Given current food security problems in Africa, we first need to develop visions of acceptable or even desirable African futures, including futures for agriculture. From there, we need to explore how these visions can be achieved and whether the implementation plan is climate proof; that is, the plan needs to account for uncertainties in future climate conditions.

Climate change is not the only worry for African agriculture and not necessarily the most pressing one (45). Focusing on climate change adaptation in isolation, without considering nonclimatic drivers of change such as population growth, land degradation, or globalization of markets, will not provide helpful information to decision makers. Similarly, any development strategy that ignores the risk of severe alterations of livelihoods and agricultural production systems through climate change will be of little informational value. Strategies need to be established for development and climate change adaptation in an integrated way; both require full attention today.

CONCLUSIONS

Despite large efforts, several of the major sources of uncertainty in climate change impact assessments on agriculture in Africa are not likely to see major advances in the near future. Consequently, climate change impact assessments on agriculture in Africa and elsewhere will remain inherently uncertain. These uncertainties, however, will not constrain science or decision support if model projections are interpreted in a meaningful manner. Because the purpose of model simulations with such large uncertainties in drivers (e.g., climate, management, adaptation options) certainly cannot be to predict future conditions in agricultural productivity, their value is twofold: Agricultural impact models and the scenario analyses conducted with them facilitate a better scientific understanding of the complex interaction of processes in agricultural systems, and this increasing understanding of the mechanisms and our ability to formulize it in models are the best tools to assess possible future conditions. Any indication of severe risk to food security should be of major concern to all of us. Scientists will strive to reduce uncertainties, but decisions will have to be made on the basis of indications of risks. African agriculture needs to change to achieve successful economic development and to reduce vulnerability to future climate change impacts. Both targets need to be analyzed in combination, and both require attention today.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

LITERATURE CITED

1. Aaheim A, Amundsen H, Dokken T, Wei TY. 2012. Impacts and adaptation to climate change in European economies. *Glob. Environ. Change* 22:959–68
2. Abdulai A, Barrett CB, Hoddinott J. 2005. Does food aid really have disincentive effects? New evidence from sub-Saharan Africa. *World Dev.* 33:1689–704
3. Ainsworth EA. 2008. Rice production in a changing climate: a meta-analysis of responses to elevated carbon dioxide and elevated ozone concentration. *Glob. Change Biol.* 14:1642–50
4. Ainsworth EA, Davey PA, Bernacchi CJ, Dermody OC, Heaton EA, et al. 2002. A meta-analysis of elevated [CO_2] effects on soybean (*Glycine max*) physiology, growth and yield. *Glob. Change Biol.* 8:695–709
5. Ainsworth EA, Long SP. 2005. What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytol.* 165:351–71
6. Aldhous P. 2010. Civil war in Africa has no link to climate change. *New Sci.* 207:11
7. Alexandratos N, Bruinsma J, Bödeker G, Schmidhuber J, Broca S, et al. 2006. World agriculture: towards 2030/2050. *Interim Rep.*, *Prospects for Food, Nutr., Agric. Major Commod. Groups*. Glob. Perspect. Stud. Unit, Food Agric. Organ., Rome, Italy
8. Asseng S, Foster I, Turner NC. 2011. The impact of temperature variability on wheat yields. *Glob. Change Biol.* 17:997–1012
9. Barrios S, Ouattara B, Strobl E. 2008. The impact of climatic change on agricultural production: Is it different for Africa? *Food Policy* 33:287–98
10. Battisti DS, Naylor RL. 2009. Historical warnings of future food insecurity with unprecedented seasonal heat. *Science* 323:240–44
11. Benhin JKA. 2006. Climate change and South African agriculture: impacts and adaptation options. *Rep. CEEPA Discuss. Pap. No. 21*, Cent. Environ. Econ. Policy in Africa, Univ. Pretoria
12. Benhin JKA. 2008. South African crop farming and climate change: an economic assessment of impacts. *Glob. Environ. Change* 18:666–78
13. Berg A, de Noblet-Ducoudré N, Sultan B, Lengaigne M, Guimberteau M. 2013. Projections of climate change impacts on potential C4 crop productivity over tropical regions. *Agric. Forest Meteorol.* 170:89–102
14. Beringer T, Lucht W, Schaphoff S. 2011. Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *Glob. Change Biol. Bioenergy* 3:299–312
15. Blignaut J, Ueckermann L, Aronson J. 2009. Agriculture production's sensitivity to changes in climate in South Africa. *S. Afr. J. Sci.* 105:61–68
16. Bloom AJ, Burger M, Asensio JSR, Cousins AB. 2010. Carbon dioxide enrichment inhibits nitrate assimilation in wheat and *Arabidopsis*. *Science* 328:899–903
17. Boko M, Niang I, Nyong A, Vogel C, Githeko A, et al. 2007. Africa. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson, pp. 433–67. Cambridge, UK: Cambridge Univ. Press
18. Bomblies A. 2012. Modeling the role of rainfall patterns in seasonal malaria transmission. *Clim. Change* 112:673–85
19. Buhaug H. 2010. Climate not to blame for African civil wars. *Proc. Natl. Acad. Sci. USA* 107:16477–82
20. Burke MB, Lobell DB, Guarino L. 2009. Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. *Glob. Environ. Change* 19:317–25
21. Burke MB, Miguel E, Satyanath S, Dykema JA, Lobell DB. 2009. Warming increases the risk of civil war in Africa. *Proc. Natl. Acad. Sci. USA* 106:20670–74
22. Challinor A, Wheeler T, Garforth C, Craufurd P, Kassam A. 2007. Assessing the vulnerability of food crop systems in Africa to climate change. *Clim. Change* 83:381–99
23. Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, et al. 2007. Regional climate projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor, HL Miller, pp. 847–940. Cambridge, UK/New York: Cambridge Univ. Press

24. Chuku CA, Okoye C. 2009. Increasing resilience and reducing vulnerability in sub-Saharan African agriculture: strategies for risk coping and management. *Afr. J. Agric. Res.* 4:1524–35
25. Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, et al. 2011. Bioenergy. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, ed. O Edenhofer, R Pichs-Madruga, Y Sokona, K Seyboth, P Matschoss, S Kadner, T Zwickel, P Eickemeier, G Hansen, S Schlömer, C von Stechow, pp. 214–332. Cambridge, UK/New York: Cambridge Univ. Press
26. Cline WR. 2007. *Global Warming and Agriculture. Impact Estimates by Country.* Washington, DC: Cent. Global Dev., Peterson Inst. Intl. Econ.
27. Cotula L, Vermeulen S, Leonard R, Keeley J. 2009. *Land Grab or Development Opportunity? Agricultural Investment and International Land Deals in Africa*. London/Rome, Italy: IIED/FAO/IFAD. 130 pp.
28. Cotula L, Vermeulen S, Mathieu P, Toulmin C. 2011. Agricultural investment and international land deals: evidence from a multi-country study in Africa. *Food Secur.* 3:99–113
29. DaMatta FM, Grandis A, Arenque BC, Buckeridge MS. 2010. Impacts of climate changes on crop physiology and food quality. *Food Res. Int.* 43:1814–23
30. Deininger K, Byerlee D. 2011. *Rising Global Investment in Farmland: Can It Yield Sustainable and Equitable Benefits?* Washington, DC: World Bank
31. Dermody O, O'Neill BF, Zangerl AR, Berenbaum MR, DeLucia EH. 2008. Effects of elevated CO_2 and O_3 on leaf damage and insect abundance in a soybean agroecosystem. *Arthropod-Plant Interact.* 2:125–35
32. De Schutter O. 2011. How not to think of land-grabbing: three critiques of large-scale investments in farmland. *J. Peasant Stud.* 38:249–79
33. Dinar A, Benhin J, Hassan R, Mendelsohn R. 2008. *Climate Change and Agriculture in Africa: Impact Assessment and Adaptation Strategies*. London: Earthscan Clim.
34. Drimie S, Gillespie S. 2010. Adaptation to climate change in Southern Africa: factoring in AIDS. *Environ. Sci. Policy* 13:778–84
35. Ebi K, Padgham J, Doumbia M, Kergna A, Smith J, et al. 2011. Smallholders adaptation to climate change in Mali. *Clim. Change* 108:423–36
36. Edenhofer O, Bauer N, Kriegler E. 2005. The impact of technological change on climate protection and welfare: insights from the model MIND. *Ecol. Econ.* 54:277–92
37. Edreira JIR, Carpici EB, Sammarro D, Otegui ME. 2011. Heat stress effects around flowering on kernel set of temperate and tropical maize hybrids. *Field Crops Res.* 123:62–73
38. Ejeta G. 2010. African Green Revolution needn't be a mirage. *Science* 327:831–32
39. Ellington SR, King CC, Kourtis AP. 2011. Host factors that influence mother-to-child transmission of HIV-1: genetics, coinfections, behavior and nutrition. *Future Virol.* 6:1451–69
40. El-Nahry AH, Doluschitz R. 2010. Climate change and its impacts on the coastal zone of the Nile Delta, Egypt. *Environ. Earth Sci.* 59:1497–506
41. Folberth C, Gaiser T, Abbaspour KC, Schulin R, Yang H. 2012. Regionalization of a large-scale crop growth model for sub-Saharan Africa: model setup, evaluation, and estimation of maize yields. *Agric. Ecosyst. Environ.* 151:21–33
42. Food Agric. Organ. 2010. *The State of Food Insecurity in the World.* Rome, Italy: Food Agric. Organ.
43. Food Agric. Organ. 2011. FAOSTAT data. Rome, Italy: Food Agric. Organ. **http://faostat.fao.org/**
44. Funk C, Dettinger MD, Michaelsen JC, Verdin JP, Brown ME, et al. 2008. Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development. *Proc. Natl. Acad. Sci. USA* 105:11081–86
45. Gaiser T, Judex M, Igué AM, Paeth H, Hiepe C. 2011. Future productivity of fallow systems in sub-Saharan Africa: Is the effect of demographic pressure and fallow reduction more significant than climate change? *Agric. Forest Meteorol.* 151:1120–30
46. Giorgi F. 2006. Regional climate modeling: status and perspectives. *J. Phys. IV* 139:101–18
47. Grasso M, Manera M, Chiabai A, Markandya A. 2012. The health effects of climate change: a survey of recent quantitative research. *Int. J. Environ. Res. Public Health* 9:1523–47
48. Hansen J, Sato M, Ruedy R. 2012. Perception of climate change. *Proc. Natl. Acad. Sci. USA* 109:E2415–23
49. Hawkins E, Sutton R. 2009. The potential to narrow uncertainty in regional climate predictions. *Bull. Am. Meteorol. Soc.* 90:1095–107

50. Hawkins E, Sutton R. 2011. The potential to narrow uncertainty in projections of regional precipitation change. *Clim. Dyn.* 37:407–18
51. Heinke J, Ostberg S, Schaphoff S, Frieler K, Müller C, et al. 2012. A new dataset for systematic assessments of climate change impacts as a function of global warming. *Geosci. Model Dev. Discuss.* 5:3533–72
52. Hillel D, Rosenzweig C. 2010. *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation*. London: Imperial Coll. Press. 440 pp.
53. Hsiang SM, Meng KC, Cane MA. 2011. Civil conflicts are associated with the global climate. *Nature* 476:438–41
54. Iglesias A, Quiroga S, Diz A. 2011. Looking into the future of agriculture in a changing climate. *Eur. Rev. Agric. Econ.* 38:427–47
55. Intergov. Panel Clim. Change (IPCC). 2007. *Climate Change 2007: Synthesis Report*. Geneva, Switz.: IPCC
56. Jones PG, Thornton PK. 2009. Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environ. Sci. Policy* 12:427–37
57. June T, Evans JR, Farquhar GD. 2004. A simple new equation for the reversible temperature dependence of photosynthetic electron transport: a study on soybean leaf. *Funct. Plant Biol.* 31:275–83
58. Kates RW, Dasgupta P. 2007. African poverty: a grand challenge for sustainability science. *Proc. Natl. Acad. Sci. USA* 104:16747–50
59. Katterer T, Reichstein M, Andren O, Lomander A. 1998. Temperature dependence of organic matter decomposition: a critical review using literature data analyzed with different models. *Biol. Fertil. Soils* 27:258–62
60. Kearney J. 2010. Food consumption trends and drivers. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 365:2793–807
61. Kinabo J, Mamiro P, Nyaruhucha C, Kaarhus R, Temu AE, et al. 2011. Quality of human capital for agricultural production in rural areas of Morogoro and Iringa regions, Tanzania. *Afr. J. Agric. Res.* 6:6296–302
62. Kniveton DR, Smith CD, Black R. 2012. Emerging migration flows in a changing climate in dryland Africa. *Nat. Clim. Change* 2:444–47
63. Knopf B, Luderer G, Edenhofer O. 2011. Exploring the feasibility of low stabilization targets. *Wiley Interdiscip. Rev. Clim. Change* 2:617–26
64. Knox J, Hess T, Daccache A, Wheeler T. 2012. Climate change impacts on crop productivity in Africa and South Asia. *Environ. Res. Lett.* 7:034032
65. Kruse J, Rennenberg H, Adams MA. 2011. Steps towards a mechanistic understanding of respiratory temperature responses. *New Phytol.* 189:659–77
66. Lambin EF, Meyfroidt P. 2011. Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl. Acad. Sci. USA* 108:3465–72
67. Laux P, Jacket G, Tingem RM, Kunstmann H. 2010. Impact of climate change on agricultural productivity under rainfed conditions in Cameroon—a method to improve attainable crop yields by planting date adaptations. *Agric. Forest Meteorol.* 150:1258–71
68. Laux P, Kunstmann H, Bardossy A. 2008. Predicting the regional onset of the rainy season in West Africa. *Int. J. Climatol.* 28:329–42
69. Leakey ADB, Ainsworth EA, Bernacchi CJ, Rogers A, Long SP, Ort DR. 2009. Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *J. Exp. Bot.* 60:2859–76
70. Leimbach M, Bauer N, Baumstark L, Edenhofer O. 2010. Mitigation costs in a globalized world: climate policy analysis with REMIND-R. *Environ. Model. Assess.* 15:155–73
71. Li YP, Ye W, Wang M, Yan XD. 2009. Climate change and drought: a risk assessment of crop-yield impacts. *Clim. Res.* 39:31–46
72. Licker R, Johnston M, Foley JA, Barford C, Kucharik CJ, et al. 2010. Mind the gap: How do climate and agricultural management explain the "yield gap" of croplands around the world? *Glob. Ecol. Biogeogr.* 19:769–82
73. Lin M, Huybers P. 2012. Reckoning wheat yield trends. *Environ. Res. Lett.* 7:024016

74. Liu JG, Fritz S, van Wesenbeeck CFA, Fuchs M, You LZ, et al. 2008. A spatially explicit assessment of current and future hotspots of hunger in sub-Saharan Africa in the context of global change. *Glob. Planet. Change* 64:222–35
75. Lloyd SJ, Kovats RS, Chalabi Z. 2011. Climate change, crop yields, and undernutrition: development of a model to quantify the impact of climate scenarios on child undernutrition. *Environ. Health Perspect.* 119:1817–23
76. Lobell DB, Banziger M, Magorokosho C, Vivek B. 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nat. Clim. Change* 1:42–45
77. Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL. 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science* 319:607–10
78. Lobell DB, Field CB. 2007. Global scale climate-crop yield relationships and the impacts of recent warming. *Environ. Res. Lett.* 2:014002
79. Lobell DB, Schlenker W, Costa-Roberts J. 2011. Climate trends and global crop production since 1980. *Science* 333:616–20
80. Lobell DB, Sibley A, Ortiz-Monasterio JI. 2012. Extreme heat effects on wheat senescence in India. *Nat. Clim. Change* 2:186–89
81. Long SP, Ainsworth EA, Leakey ADB, Nosberger J, Ort DR. 2006. Food for thought: lower-than-expected crop yield stimulation with rising CO_2 concentrations. *Science* 312:1918–21
82. Lotze-Campen H, Müller C, Bondeau A, Rost S, Popp A, Lucht W. 2008. Global food demand, productivity growth and the scarcity of land and water resources: a spatially explicit mathematical programming approach. *Agric. Econ.* 39:325–38
83. Lotze-Campen H, Popp A, Beringer T, Müller C, Bondeau A, et al. 2010. Scenarios of global bioenergy production: the trade-offs between agricultural expansion, intensification and trade. *Ecol. Model.* 221:2188–96
84. Lutz W, Samir KC. 2010. Dimensions of global population projections: What do we know about future population trends and structures? *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 365:2779–91
85. Malcolm SA, Aillery M, Weinberg M. 2009. *Ethanol and a Changing Agricultural Landscape*. Washington, DC: U.S. Dep. Agric., Econ. Res. Serv.
86. Markelova H, Meinzen-Dick R, Hellin J, Dohrn S. 2009. Collective action for smallholder market access. *Food Policy* 34:1–7
87. McMichael AJ, Lindgren E. 2011. Climate change: present and future risks to health, and necessary responses. *J. Intern. Med.* 270:401–13
88. Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, et al. 2009. Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* 458:1158–62
89. Mendelsohn R, Dinar A. 2003. Climate, water and agriculture. *Land Econ.* 79:328–41
90. Moore N, Alagarswamy G, Pijanowski B, Thornton P, Lofgren B, et al. 2012. East African food security as influenced by future climate change and land use change at local to regional scales. *Clim. Change* 110:823–44
91. Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, et al. 2010. The next generation of scenarios for climate change research and assessment. *Nature* 463:747–56
92. Müller C. 2011. Agriculture: harvesting from uncertainties. *Nat. Clim. Change* 1:253–54
93. Müller C, Bondeau A, Popp A, Waha K, Fader M. 2009. *Climate Change Impacts on Agricultural Yields*. Washington, DC: World Bank
94. Müller C, Cramer W, Hare WL, Lotze-Campen H. 2011. Climate change risks for African agriculture. *Proc. Natl. Acad. Sci. USA* 108:4313–15
95. Nakicenovic N, Swart R, eds. 2000. *Special Report on Emission Scenarios*. Cambridge, UK: Cambridge Univ. Press. 599 pp.
96. Nelson GC, Rosegrant MW, Koo J, Robertson R, Sulser T, et al. 2009. *Climate Change—Impact on Agriculture and Costs of Adaptation.* Washington, DC: Intl. Food Policy Res. Inst.
97. Nelson GC, Rosegrant MW, Palazzo A, Gray I, Ingersoll C, et al. 2010. *Food Security, Farming, and Climate Change to 2050*. Washington, DC: Intl. Food Policy Res. Inst. 155 pp.
98. Neumann K, Verburg P, Stehfest E, Müller C. 2010. A global analysis of the intensification potential for grain production. *Agric. Syst.* 103:316–26

99. O'Loughlin J, Witmer FDW, Linke AM, Laing A, Gettelman A, Dudhia J. 2012. Climate variability and conflict risk in East Africa, 1990–2009. *Proc. Natl. Acad. Sci. USA* 109:18344–49
100. Paeth H, Capo-Chichi A, Endlicher W. 2008. Climate change and food security in tropical West Africa—a dynamic-statistical modelling approach. *Erdkunde* 62:101–15
101. Palm CA, Smukler SM, Sullivan CC, Mutuo PK, Nyadzi GI, Walsh MG. 2010. Identifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa. *Proc. Natl. Acad. Sci. USA* 107:19661–66
102. Parry MAJ, Hawkesford MJ. 2010. Food security: increasing yield and improving resource use efficiency. *Proc. Nutr. Soc.* 69:592–600
103. Pingali PL. 2012. Green Revolution: impacts, limits, and the path ahead. *Proc. Natl. Acad. Sci. USA* 109:12302–8
104. Randall DA, Wood RA, Bony S, Colman R, Fichefet T, et al. 2007. Climate models and their evaluation. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor, HL Miller, pp. 589–662. Cambridge, UK/New York: Cambridge Univ. Press
105. Rosenzweig C, Jones JW, Hatfield JL, Ruane AC, Boote KJ, et al. 2012. The Agricultural Model Intercomparison and Improvement Project (AgMIP): protocols and pilot studies. *Agric. For. Meteorol.* 170:166–82
106. Rötter RP, Carter TR, Olesen JE, Porter JR. 2011. Crop-climate models need an overhaul. *Nat. Clim. Change* 1:175–77
107. Roudier P, Sultan B, Quirion P, Berg A. 2011. The impact of future climate change on West African crop yields: What does the recent literature say? *Glob. Environ. Change* 21:1073–83
108. Saa Requejo A, García Moreno R, Díaz Alvarez MC, Burgaz F, Tarquis M. 2011. Analysis of hail damages and temperature series for peninsular Spain. *Nat. Hazards Earth Syst. Sci.* 11:3415–22
109. Salvucci ME, Crafts-Brandner SJ. 2004. Inhibition of photosynthesis by heat stress: the activation state of Rubisco as a limiting factor in photosynthesis. *Physiol. Plant.* 120:179–86
110. Sanchez PA. 2000. Linking climate change research with food security and poverty reduction in the tropics. *Agric. Ecosyst. Environ.* 82:371–83
111. Scheffran J, Brzoska M, Kominek J, Link PM, Schilling J. 2012. Climate change and violent conflict. *Science* 336:869–71
112. Schlenker W, Lobell DB. 2010. Robust negative impacts of climate change on African agriculture. *Environ. Res. Lett.* 5:014010
113. Schmitz C, Biewald A, Lotze-Campen H, Popp A, Dietrich JP, et al. 2012. Trading more food: implications for land use, greenhouse gas emissions, and the food system. *Glob. Environ. Change* 22:189–209
114. Searchinger T, Heimlich R, Houghton RA, Dong FX, Elobeid A, et al. 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319:1238–40
115. Seo SN, Mendelsohn R. 2008. Measuring impacts and adaptations to climate change: a structural Ricardian model of African livestock management. *Agric. Econ.* 38:151–65
116. Seo SN, Mendelsohn R, Dinar A, Hassan R, Kurukulasuriya P. 2009. A Ricardian analysis of the distribution of climate change impacts on agriculture across agro-ecological zones in Africa. *Environ. Resour. Econ.* 43:313–32
117. Smith KA, Searchinger TD. 2012. Crop-based biofuels and associated environmental concerns. *GCB Bioenergy* 4:479–84
118. Sonneveld B, Keyzer M, Adegbola P, Pande S. 2012. The impact of climate change on crop production in West Africa: an assessment for the Oueme River Basin in Benin. *Water Resour. Manag.* 26:553–79
119. Srivastava AK, Gaiser T, Paeth H, Ewert F. 2012. The impact of climate change on yam (*Dioscorea alata*) yield in the savanna zone of West Africa. *Agric. Ecosyst. Environ.* 153:57–64
120. Stehfest E, Bouwman L, van Vuuren DP, den Elzen MGJ, Eickhout B, Kabat P. 2009. Climate benefits of changing diet. *Clim. Change* 95:83–102
121. Stehfest E, Heistermann M, Priess JA, Ojima DS, Alcamo J. 2007. Simulation of global crop production with the ecosystem model DayCent. *Ecol. Model.* 209:203–19

122. Tan ZX, Tieszen LL, Liu SG, Tachie-Obeng E. 2010. Modeling to evaluate the response of savanna-derived cropland to warming-drying stress and nitrogen fertilizers. *Clim. Change* 100:703–15
123. Taub DR, Miller B, Allen H. 2008. Effects of elevated CO_2 on the protein concentration of food crops: a meta-analysis. *Glob. Change Biol.* 14:565–75
124. Thornton PK, Jones PG, Alagarswamy G, Andresen J. 2009. Spatial variation of crop yield response to climate change in East Africa. *Glob. Environ. Change* 19:54–65
125. Thornton PK, Jones PG, Alagarswamy G, Andresen J, Herrero M. 2010. Adapting to climate change: agricultural system and household impacts in East Africa. *Agric. Syst.* 103:73–82
126. Thornton PK, Jones PG, Ericksen PJ, Challinor AJ. 2011. Agriculture and food systems in sub-Saharan Africa in a 4°C+ world. *Philos. Trans. R. Soc. A* 369:117–36
127. Tubiello FN, Amthor JS, Boote KJ, Donatelli M, Easterling W, et al. 2007. Crop response to elevated CO_2 and world food supply: a comment on "Food for Thought..." by Long et al., *Science* 312:1918–1921, 2006. *Eur. J. Agron.* 26:215–23
128. Ugarte C, Calderini DF, Slafer GA. 2007. Grain weight and grain number responsiveness to pre-anthesis temperature in wheat, barley and triticale. *Field Crops Res.* 100:240–48
129. van Vuuren D, Edmonds J, Kainuma M, Riahi K, Thomson A, et al. 2011. The representative concentration pathways: an overview. *Clim. Change* 109:5–31
130. von Braun J, Meinzen-Dick R. 2009. *"Land Grabbing" by Foreign Investors in Developing Countries: Risks and Opportunities*. Washington, DC: Intl. Food Policy Res. Inst.
131. von Lutzow M, Kogel-Knabner I. 2009. Temperature sensitivity of soil organic matter decomposition: What do we know? *Biol. Fertil. Soils* 46:1–15
132. Waha K, Müller C, Bondeau A, Dietrich J, Kurukulasuriya P, et al. 2013. Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa. *Glob. Environ. Change* 23:130–43
133. Waha K, van Bussel LGJ, Müller C, Bondeau A. 2012. Climate-driven simulation of global crop sowing dates. *Glob. Ecol. Biogeogr.* 21:247–59
134. Walker NJ, Schulze RE. 2008. Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. *Agric. Ecosyst. Environ.* 124:114–24
135. Wang D, Heckathorn SA, Wang XZ, Philpott SM. 2012. A meta-analysis of plant physiological and growth responses to temperature and elevated CO_2. *Oecologia* 169:1–13
136. Wichelns D. 2003. Policy recommendations to enhance farm-level use of fertilizer and irrigation water in sub-Saharan Africa. *J. Sustain. Agric.* 23:53–77
137. Zavala JA, Casteel CL, DeLucia EH, Berenbaum MR. 2008. Anthropogenic increase in carbon dioxide compromises plant defense against invasive insects. *Proc. Natl. Acad. Sci. USA* 105:5129–33

Annual Review of Nutrition

Volume 33, 2013

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Errata

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