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Introduction: food crops in a changing climate

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Changes in both the mean and the variability of climate, whether naturally forced, or due to human activities, pose a threat to crop production globally. This paper summarizes discussions of this issue at a meeting of the Royal Society in April 2005. Recent advances in understanding the sensitivity of crops to weather, climate and the levels of particular gases in the atmosphere indicate that the impact of these factors on crop yields and quality may be more severe than previously thought. There is increasing information on the importance to crop yields of extremes of temperature and rainfall at key stages of crop development. Agriculture will itself impact on the climate system and a greater understanding of these feedbacks is needed. Complex models are required to perform simulations of climate variability and change, together with predictions of how crops will respond to different climate variables. Variability of climate, such as that associated with El Niño events, has large impacts on crop production. If skilful predictions of the probability of such events occurring can be made a season or more in advance, then agricultural and other societal responses can be made. The development of strategies to adapt to variations in the current climate may also build resilience to changes in future climate. Africa will be the part of the world that is most vulnerable to climate variability and change, but knowledge of how to use climate information and the regional impacts of climate variability and change in Africa is rudimentary. In order to develop appropriate adaptation strategies globally, predictions about changes in the quantity and quality of food crops need to be considered in the context of the entire food chain from production to distribution, access and utilization. Recommendations for future research priorities are given.

Keywords: climate variability; climate change; crops; agriculture; seasonal forecasting

1. INTRODUCTION

Climate change is likely to impact agriculture and food security across the globe. A large fraction of the world's food is grown as rainfed annual crops in the tropics, where climate variability plays an important role in determining productivity. Asia alone has more land under cultivation than all of the industrialized nations taken together (FAO 2002). Although crops grown at mid-latitudes may be less sensitive to climate variability under current climates, crop production in some of these areas will become more risky under future climates as, for example, competition for water resources increases, and the frequency of extreme temperatures changes. Globally, all societies will be vulnerable to changes in food production, quality and supply under climate change along with their consequent socio-economic pressures.

This paper presents a summary of the key issues and challenges that emerged from a Discussion Meeting on food crops in a changing climate that was held at the Royal Society on 26th and 27th April 2005. The proceedings of the meeting are reported in the 16 papers of this journal issue.

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One contribution of 17 to a Discussion Meeting Issue 'Food crops in a changing climate'.

2. EXTENT OF CURRENT KNOWLEDGE

Climate prediction involves the use of increasingly complex earth system models that represent the interactions between the atmosphere, ocean, biosphere and cryosphere, and addresses the concept of climate as a high-dimensional chaotic system in which the outcome of any prediction system should be viewed in the context of a forecast probability distribution. The simulations of past and present climate are able to reproduce much of the observed behaviour, though significant improvements in the models are still required. Predictions for months or seasons ahead are now starting to be used in a number of applications (Palmer *et al.* 2005).

The same climate models that are used for seasonal forecasting can provide information on changes in the statistics of weather which will be vital in estimating the impacts of climate change on food crops. As the resolution of climate models increases, the detail in the spatial and temporal distributions of key surface variables for crops (e.g. rainfall, temperature, soil moisture) will also increase. Pushing these models to higher and higher resolutions is a major driver for research and one that poses particular demands on both the climate and computational scientist. Access to significantly increased levels of computer power will be vital.

In crop science, there have been substantial advances in the understanding of the physiology of crops and their sensitivity to various aspects of weather and climate. The dependence of yields on the seasonal mean climate is well documented across a range of crops, and their response functions are now known to be far from linear. Increasingly, emergent is the importance of the sensitivity of crops to drought and periods of heat stress at particular stages of development. This suggests that there are thresholds above which crops become highly vulnerable to climate and weather (Challinor *et al.* 2005; Porter & Semenov 2005). More controversially, the response of crops to changes in atmospheric composition has produced conflicting evidence, with the benefits of carbon dioxide (CO_2) fertilization being less than previously thought and potentially being counteracted by the damaging effects of increases in surface ozone (Long *et al.* 2005). An advantage of elevated CO_2 is more efficient water use by the plant, particularly for C_3 crops; this is an important aspect of the response of cropping systems to climate change, since many regions will become increasingly water limited. Overall, C_3 crops, such as rice, wheat and soybean, are much more sensitive to atmospheric CO_2 and surface ozone concentrations than C_4 crops, such as maize, sugarcane and sorghum.

Crop prediction methodologies range from statistical methods, based on past associations between crop production and climate, to dynamic methods, which attempt to represent the physiology of the crop. The former methods have limitations for climate change studies because the statistical relationships that are valid today may not be valid in a changed climate, and because these methods are less amenable as test beds for adaptation strategies. The latter methods can be highly sophisticated and have the capability of capturing nonlinear behaviour and the impacts of weather variations on crop performance, as well as enabling testing of adaptation strategies such as more tolerant varieties and changes in management. However, they tend to be tuned at the local or plot level, which has so far restricted their use in larger-scale assessments. There is an increasing body of research exploring methods of bridging the scale gap between process based crop models and climate prediction systems (Baron *et al.* 2005; Challinor *et al.* 2005; Hansen 2005).

Currently, the direct use of climate model output within crop prediction systems is limited. Assessments of the impacts of climate change on crops reflect the disparity of scale between crop and climate models. Climate models are typically run at horizontal scales in excess of 100 km, whereas crop models are usually developed at the plot of field scale of a kilometre or less, although crop models designed to operate at scales of tens of kilometres have recently been developed. So far, the few studies that have attempted to provide a global assessment of food supply have necessarily used simple representations of the effects of climate on crops. They suggest that food crop production will increase slightly at high latitudes under moderate climate change, but then decrease towards the end of this century (Fischer *et al.* 2005; Parry & Livermore 2005). In contrast, crop production is predicted to decline across the tropics even under moderate climate change. There is little account of the effects of sub-seasonal variability in climate in these studies and the impacts of weather thresholds are entirely absent; both factors are likely to reduce crop yields further. In contrast, studies that use detailed, dynamic crop models over small regions may be compromised by the validity of the climate and weather inputs on those spatial scales. Advances are now being made in integrating crop and climate modelling that have the potential to improve assessments of the impacts of climate change on crops by addressing in a more consistent manner the issues of the spatial and temporal scales on which the two systems interact (Baron *et al.* 2005; Challinor *et al.* 2005; Hansen 2005). Furthermore, there is emerging evidence that major land use changes have already had detrimental effects on the local climate (Betts 2005), reinforcing the need for a fully integrated approach to crop–climate prediction.

Seasonal forecasting of crop yields is more mature than climate change prediction. In some regions (e.g. Queensland, Australia), the development of operational seasonal forecasting systems for agriculture provides important links with users (Stone & Meinke 2005). These have enabled the establishment of decision support systems, which engage with farmers and agricultural advisory bodies, and encourage the analysis of risk associated with a range of crop management options. Seasonal forecasting is also playing an increasingly key role in famine early warning systems (FEWS), particularly for Africa (Verdin *et al.* 2005). In parts of the world, where climate variability is large and cropping systems are already vulnerable, there is evidence that the effective use of seasonal forecasts and the associated development of sustainable adaptive strategies may help build resilience to climate change.

3. LIMITATIONS AND UNCERTAINTIES IN CURRENT KNOWLEDGE

(a) *Crops and atmospheric composition*

Many uncertainties in our knowledge and understanding of the interface between atmospheric composition and crops still exist. Until recently, research indicated that the positive impacts of CO_2 enrichment would most likely compensate for the negative impacts of rising mean temperatures (which shorten the growing season of most annual crops, and so reduce yields of current varieties). These conclusions were largely based on studies of crops grown in field chambers or in controlled environments that showed that the yield of C_3 crops (such as rice, soybean and wheat) increased by 24–43% with doubled CO_2. However, a new analysis based on a small number of studies of crops grown in near-field conditions suggest that the benefits of CO_2 enrichment may be less than this, in the range of 8–15% (Long *et al.* 2005). Realizing the benefits of CO_2 fertilization also depends on water and nitrogen availability and hence on the optimal management of the crop (Erda *et al.* 2005).

The possible decline in air quality with increased levels of surface ozone could have serious detrimental effects on crop growth. C_3 crops are particularly sensitive; initial estimates suggest that the loss of yield is currently *ca* 5%, rising to potentially *ca* 30% in 2050

(Long *et al.* 2005), but further studies are needed to confirm these estimates. Countries such as China, where ozone levels are predicted to rise dramatically, may be seriously affected (Erda *et al.* 2005). Overall, the impacts of changes in atmospheric composition may be more damaging than previously estimated, and more research is urgently needed so that these effects can be included in crop prediction models. In particular, there are, to date, no field experiments quantifying the impacts of increased CO_2 and ozone levels in the tropics, where most of the world's food is produced.

The adaptation of food systems to climate change will in turn also influence atmospheric composition through emissions of methane from, for example, rice paddies, and nitrous oxide from the use of synthetic fertilizers. Since these are important greenhouse gases, it is disturbing that the agricultural emissions of methane and nitrous oxide are projected to rise by up to 60% by 2030 (see Gregory *et al.* 2005). As well as being a potent greenhouse gas, nitrous oxide is also involved in stratospheric ozone depletion.

(b) *Crops and water resources*

It is, generally, accepted that the availability of water for agriculture will be a key issue for crop production in the coming decades. There is a focus worldwide on how to improve the efficiency of water use for crop production. However, water availability for crops depends on processes across a range of spatial scales, and its assessment requires the integration of information from crop, climate and hydrological models. For example, for irrigated crop production, large-scale changes in rainfall will influence the water that is available from stream-flow or groundwater sources.

Higher CO_2 levels improve the water usage efficiency of most crops. Plant transpiration is reduced under higher CO_2 and the crop loses less water. These changes in transpiration can alter the hydrological balance over land and affect the local climate, particularly where there may be large-scale changes in land use associated with extensification of agriculture (Betts 2005). Reduced transpiration over a sufficiently large region could lead to reduced precipitation there as well. This highlights the inherent links between crops, climate and the water cycle, and suggests the need for fully integrated crop–climate modelling approaches to take careful account of hydrology (Betts 2005; Huntingford *et al.* 2005).

Climate models still have substantial regional biases, particularly in their representation of the spatial and temporal scales of rainfall. The *distribution* of rainfall through the growing seasonal is critical for many crops, particularly in the semi-arid Tropics. These variations in rainfall, generally associated with dominant weather patterns, are currently poorly simulated in climate prediction models.

(c) *Effects of extreme events on crops*

Most previous climate studies of extreme events have focused only on the occurrence and magnitude of individual extreme values: the number of days per year with maximum temperature exceeding a threshold, and the annual maximum one-day precipitation total, for example. More detailed information, however, is often critical for determining the impacts of extreme events. For example, preceding conditions affect the likelihood that heavy rainfall will cause a flood; clustering of intense weather systems magnifies potential damage; the spatial extent and temporal evolution of droughts is crucial for water-resource management; and the timing of heat- and water-stress during the life cycle of crops is a key determinant of yield. Extended dry spells and hot spells may be more prevalent in west Africa under climate change, putting cropping systems at risk (Huntingford *et al.* 2005).

Important climate thresholds for food crops include episodes of high temperatures that coincide with critical phases of the crop cycle. These high-temperature episodes can lead to dramatic reductions in yield, in some cases in excess of 50%; for example, temperatures greater than 30 °C lasting for more than 8 h lead to reduced grain-set in wheat (Porter & Semenov 2005). Experimental studies have led research in this field and these are beginning to be understood in terms of simple physiology. Quantitative methods to simulate and predict the impacts of high-temperature episodes are being developed and combined with the probabilistic simulation methods in order to enable the assessment of the impacts of climate extremes on crop yields (Challinor *et al.* 2005).

Climate change scenarios suggest that critical temperature thresholds for food crops will be exceeded with increasing frequency in the future. For some crops, these critical temperatures, particularly at anthesis (flowering), are reasonably well known (e.g. temperatures greater than 35 °C for more than 1 h leads to pollen sterility in rice), but for others they are not well characterized. In general, the reproductive limits for most crops are narrow, with temperatures in the mid-30 °C representing the threshold for successful grain set (Porter & Semenov 2005).

(d) *Influence of climate on crop quality*

As well as yield, changes in crop quality can have a major impact on food systems and their vulnerability to climate variability and change. Grain quality of wheat (e.g. protein content) is highly susceptible to current variations in climate and affects the type of foods that can be produced through, for example, gluten levels and related dough strength (Porter & Semenov 2005). Other examples of the effects of climate on crop quality include pests and diseases, such as dangerous levels of mycotoxin contamination of groundnuts. Relatively little is known about the potential impact of climate change on crop quality.

(e) *Coupling crop, water and climate models*

The interaction between climate, crops, and the land and water use changes associated with agricultural practices has been largely neglected until recently (Betts 2005; Osborne 2005). A large fraction of the land surface in the tropics is used for growing crops (e.g. 94% of land in south Asia is used for crop cultivation; FAO 2002) and this may have implications for predictions of both the local climate and crop productivity. Some initial research has been conducted with a process-based crop model operating as an interactive part of the climate model's land surface scheme and has demonstrated the feasibility of this fully coupled methodology (Osborne 2005). This combined system allows the simulated weather to affect crop development on a sub-daily basis (important for assessing threshold behaviour as outlined in §3*c*). Equally, it allows the developing crop in turn to influence the land–atmosphere system.

The coupled crop–climate modelling system will enable investigation of the impact of different scenarios of changes in agricultural land use on land–atmosphere interactions and on local climate. Furthermore, it can be used to provide a consistent framework for assessing the effects of crops on the carbon and nitrogen cycles, the response of the latter being largely unknown. The impacts of changes in atmospheric composition noted in §3*a* can also be addressed more completely; potential nonlinearities in the feedbacks between atmospheric composition, climate and crops are currently unknown, but could potentially be very serious.

Early results have demonstrated changes in the water cycle, particularly the balance between fast and slow runoff, associated with land use change (Betts 2005). There is also the potential for changes in evapotranspiration under climate change (see §3*b*). The existence of these, and other nonlinear interactive processes, has consequences for future directions in research: it is likely that a prediction system which considers the coupling between crops, water resources and climate will be considered essential.

(f) *Understanding socio-economic responses*

It is important to consider the complete food chain from production to distribution, access and utilization (Gregory *et al.* 2005). This requires an appreciation of the intimate relationship between climate, socio-economic and environmental factors, and an understanding of major economic sectors and the embedding of agricultural systems within national economies.

There is a complex web of policy and decision making along the value chain from farm to market to industry to consumer (Gregory *et al.* 2005). There have been rapid changes worldwide in food systems associated with urbanization and the dominance of supermarket chains. These may radically alter the relationship between food production and food security, with lifestyles and preferences driving consumption and demand; countries such as India and China are already showing trends towards a western-style diet with increased consumption of meat. Adapting to climate change may be as much to do with improving infrastructures for food distribution as with changing agricultural practices.

The relentless pressures of increasing populations on land and water use are major factors in determining future scenarios for food security and are likely to be key factors in risks of famine. There is a gradual decline in 'carry over' food stocks with implications for food security (Haile 2005). Understanding and assessing the vulnerability of populations requires engagement across a wide range of disciplines with the recognition that risk is multi-dimensional. Rapidly changing socio-economic factors can lead to increased sensitivity to climate shocks; for example, the high incidence of HIV and increasing levels of poverty in Africa increase the exposure of the population and its inability to cope with climatic stress. Simulation methods that integrate climate and human behaviour provide a novel approach to understanding adaptation options for climate variability and change (Bharwani *et al.* 2005).

(g) *Quantification of uncertainty*

The physical, biological and socio-economic processes described so far determine the response of food systems to climate variability and change. Each of these processes has its own associated uncertainties. To date only a very limited range of these uncertainties has been sampled. Recently, studies have begun to include more comprehensive estimates of physical and biological uncertainty (Challinor *et al.* 2005).

4. RECOMMENDATIONS FOR FUTURE RESEARCH PRIORITIES

A range of future research priorities emerge from the considerations outlined in §3 and from discussion during the meeting.

(a) *Cross-disciplinary research*

A more integrated approach to the impacts of climate change on food production, water availability and water quality is needed. Specifically:

- (i) natural and social sciences need to work together if workable solutions to adapting to climate variability and change are to be found. The Intergovernmental Panel for Climate Change (IPCC) is a good attempt to achieve this synthesis *a posteriori*, but it needs to occur also at earlier stages in the research process;
- (ii) fully integrated crop – climate modelling is currently in its infancy but offers huge potential. Its further development and extension to include the water cycle is a priority for research;
- (iii) it is vital that studies quantify the uncertainty due to physical, biological and socio-economic processes in order to provide firmly based and useful information on agricultural climate change impacts.

(b) *Agricultural research*

- (i) More studies of the effects of rising levels of CO_2 and ozone on crops under field conditions are needed. These should be carried out in countries where crop vulnerability is potentially high, and should cover a range of the major food crops.
- (ii) The importance of developing adaptation options for agriculture that do not exacerbate climate and other environmental changes is crucial.
- (iii) Defining critical temperatures, and their timing within the growing cycle, across all major crops is crucial for providing more confident assessments of future global food

production. High-temperature events are likely to be one of the major impacts of climate change and, hence probabilities of their occurrence must be included in future assessments.

(iv) Cultivars need to be developed that are more resistant to extreme weather and growing conditions in terms of both yield and quality. This requires consideration of the complete biological system, which includes pests, diseases, toxins, protein content, etc.

(c) *Climate modelling*

(i) There is an urgent need to improve the skill of the hydrological cycle in climate model simulations. It is increasingly argued that this will not be achieved unless the climate models are run at much higher resolution, close to that used in numerical weather prediction, necessitating a substantial increase in computer power. Such an increase in spatial resolution is entirely consistent with the provision of high resolution fully interactive crop – climate simulations (see §4*a*).

(ii) Improved understanding of how local weather patterns will change with global warming should be a major area of research. Different crops will have different weather sensitivities that will need to be taken into account when considering the impact of these changes. This information can inform the development of drought resistant varieties of staple annual crops such as wheat and maize (see §4*b*).

5. FEEDING AFRICA, NOW AND IN THE FUTURE

Of the developing world, Africa is the most vulnerable to climate variability and change. Its widely dispersed population is heavily dependent on rainfed agriculture, with one third currently at risk from widespread hunger and malnutrition. This is a situation that is likely to worsen as climate change begins to bite. Africa is consistently predicted to be among the worst hit areas across a range of future climate change scenarios. Some seriously damaging trends in the weather, such as the steep decline in rainfall in the first part of the growing season for Ethiopia in the past 10 years, have been identified (Verdin *et al.* 2005).

Understanding the early impacts of climate change is essential; a focus on climate variability over the next few decades could bring with it tangible human benefits and ensure that advice is given with lead times that makes intervention possible. For example, FEWS have inspired the creative use of satellite monitoring, modelling and geospatial methods (Verdin *et al.* 2005). It is clear that predictability on the seasonal time-scale could be capitalized upon far more than it is currently, leading to the saving of not just lives, but livelihoods. There is a gap between development and relief activities that leaves each looking to the other for disaster preparedness. These benefits could be realized by mobilizing the recommendations of the Commission for Africa (Commission for Africa 2005).

Current knowledge of the regional impacts of climate change in Africa is at a rudimentary level and needs to be advanced substantially and quickly if further and more extreme environmental and consequent human disasters in Africa are to be averted. Weather events are critical to many aspects of African society and the ability to forecast accurately on time-scales of days, weeks and seasons is vital in enabling mitigation and adaptation to save lives and promote economic development. The advances made in weather and climate forecasting in the UK and other developed countries have not yet been transferred to Africa because of the lack of infrastructure and resources both in the UK but particularly in Africa. The UK possesses world-leading expertise in climate change science, in assessment of the socio-economic impacts of climate change and in weather and climate forecasting. This expertise needs to be mobilized and coordinated to focus on Africa in conjunction with African scientists and the development community. The use of local scientists to evaluate the current performance of climate simulations and of monthly and seasonal forecasts in their regions is important as this experience will help them to develop as critical users of climate information and results. The feedback to the UK experts will also be invaluable for future modelling.

The global weather and climate observational networks that underpin weather forecast skill and monitor climate change are severely deficient in Africa with little current prospect of improvement. African scientists have the knowledge and more importantly the local expertise to undertake this monitoring but lack the technology required. Accurate monitoring of both temperature and rainfall will be crucial. In some semi-arid regions crops are already near their thermal maximum and will soon become vulnerable to heat stress as outlined in §3*d*. Changes in rainfall patterns and distribution through the seasonal cycle are likely to have serious consequences. It is the responsibility of the developed world to assist the developing world by transfer of this technology.

Although great progress has been made in predicting whether annual crops are likely to fail, networks for making decisions about how to minimize the negative impacts of weather-induced food shortages are not using this valuable information to deliver timely humanitarian aid before a crisis has arisen. Since the 1980s, the number of food emergencies has tripled as a result of this lack of preparedness (Haile 2005).

It has to be recognized that poverty is the principal cause of increasing food insecurity in Africa, along with frequent and extreme weather and climate variability. Africa is now in a critical situation with respect to drought because of population increase, disease (particularly malaria and HIV) and conflicts. Africa has very little resilience to cope with a widespread drought now, let alone in the next 50–100 years. Furthermore, in many regions of Africa, such as sub-Saharan Africa, the options for employing traditional coping strategies are declining as a result of land degradation and increasing vulnerability to climate variability and change.

Many parts of Africa are marginal in terms of agriculture and it is in these regions that progress is slowest and poverty is most persistent. Escaping the poverty trap is a major challenge for development and cannot be achieved without coherent national and international policies and without proper recognition of the roles science, technology and innovation play in development. Currently, natural climate variability is one of many factors already pushing people below the poverty trap threshold (Bharwani *et al.* 2005). Farmers on the brink of poverty will not want to take a risk based on advice (such as to grow an alternative crop) and may make a decision that pushes them below the poverty level. One innovative approach, Acute Hunger Insurance, aims at avoiding responses by farmers that exacerbate the problems of climate variability and change, and links emergency aid with developmental support (Haile 2005).

The development of innovative solutions and adaptive strategies that deliver long-term, sustainable livelihoods for rural Africa are essential. These should be delivered within a framework that promotes capacity building within Africa. Specifically, the following recommendations, which build on and reiterate the proposals of the Commission for Africa (2005), are made on the basis of the above discussion.

(i) A programme of research and model development in climate prediction and crop science is urgently needed that will assess more completely the risks and impacts of climate change in Africa. Regional models need to be cognisant of the scales at which decision makers (local and national) work.

(ii) Resources need to be found to support weather and climate related observational networks if an accurate and reliable picture of the current and future climate of Africa is to be built-up in order to mitigate as many of the predicted problems as possible.

(iii) Investment in people and capacity building in Africa is crucial. This can be achieved by providing effective knowledge transfer mechanisms and opportunities for training of African scientists by the developed world. Specific possibilities include institutional partnerships and studentship programmes.

(iv) There is evidence that in Africa, where climate variability is significant and cropping systems are already vulnerable, the effective use of seasonal forecasts and the development of sustainable adaptive strategies may build resilience to climate change. More emphasis should be placed on improving the use of seasonal forecasting, and more research on bridging the gap to climate change by focusing on the next 5–20 years should be encouraged.

(v) All actions need to take a global perspective. Global population growth is leading to a gradual decline in food stocks; shifting climatic patterns may lead to questions of what will happen to current 'bread baskets' and what is being done to prepare new 'bread baskets'.

6. CONCLUDING REMARKS

A number of key issues and recommendations which emerged from the Royal Society Discussion Meeting have been highlighted in this paper. All of these issues have clear cross-disciplinary and societal relevance. Research is beginning to map out the range of complex socio-economic, physical and biological interactions that determine the vulnerability of food systems and livelihoods to climate change. It is increasingly clear that adaptation to climate change is necessary, and that in some regions of the globe, particularly Africa, adaptation options are few and vulnerability is high. If we are to strengthen our knowledge in this important area, it is imperative that forums continue to be found for truly interdisciplinary dialogue and research. Furthermore, it is clear that the dialogue with the range of stakeholders is essential in guiding the nature of the information provided from scientists and in steering the research agenda in the future.

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REFERENCES

Baron, C., Sultan, B., Balme, M., Sarr, B., Teaore, S., Lebel, T., Janicot, S. & Dingkuhn, M. 2005 From GCM grid cell to agricultural plot: scale issues affecting modelling of climate impact. *Phil. Trans. R. Soc. B* **360**, 2095–2108. (doi:10.1098/rstb.2005.1741.)

Betts, R. 2005 Integrated approaches to climate–crop modelling: needs and challenges. *Phil. Trans. R. Soc. B* **360**, 2049–2065. (doi:10.1098/rstb.2005.1739.)

Bharwani, S., Bithell, M., Downing, T. E., New, M., Washington, R. & Ziervogel, G. 2005 Multi-agent modelling of climate outlooks and food security on a community garden scheme in Limpopo, South Africa. *Phil. Trans. R. Soc. B* **360**, 2183–2194. (doi:10.1098/rstb.2005.1742.)

Challinor, A. J., Wheeler, T. R., Slingo, J. M. & Hemming, D. 2005 Quantification of physical and biological uncertainty in the simulation of the yield of a tropical crop using present-day and doubled CO_2 climates. *Phil. Trans. R. Soc. B* **360**, 2085–2094. (doi:10.1098/rstb.2005.1740.)

Commission for Africa 2005 Our common interest. Report of the Commission for Africa. www.commissionforafrica.org.

Erda, L., Wei, X., Hui, J., Yinlong, X., Yue, L., Liping, B. & Liyong, X. 2005 Climate change impacts on crop yield and quality with CO_2 fertilization in China. *Phil. Trans. R. Soc. B* **360**, 2149–2154. (doi:10.1098/rstb.2005.1743.)

FAO 2002 World agriculture: towards 2015/2030, available online at http://www.fao.org/docrep/004/y3557e/y3557e00.htm.

Fischer, G., Shah, M., Tubiello, F. N. & van Velhuizen, H. 2005 Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. *Phil. Trans. R. Soc. B* **360**, 2067–2083. (doi:10.1098/rstb.2005.1744.)

Gregory, P. J., Ingram, J. S. I. & Brklacich, M. 2005 Climate change and food security. *Phil. Trans. R. Soc. B* **360**, 2139–2148. (doi:10.1098/rstb.2005.1745.)

Haile, M. 2005 Weather patterns, food security and humanitarian response in sub-Saharan Africa. *Phil. Trans. R. Soc. B* **360**, 2169–2182. (doi:10.1098/rstb.2005.1746.)

Hansen, J. W. 2005 Integrating seasonal climate prediction and agricultural models for insights into agricultural practice. *Phil. Trans. R. Soc. B* **360**, 2037–2047. (doi:10.1098/rstb.2005.1747.)

Huntingford, C., Lambert, F. H., Gash, J. H. C., Taylor, C. M. & Challinor, A. J. 2005 Aspects of climate change prediction relevant to crop productivity. *Phil. Trans. R. Soc. B* **360**, 1999–2009. (doi:10.1098/rstb.2005.1748.)

Long, S. P., Ainsworth, E. A., Leakey, A. D. B. & Morgan, P. B. 2005 Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. *Phil. Trans. R. Soc. B* **360**, 2011–2020. (doi:10.1098/rstb.2005.1749.)

Osborne, T. M. 2005 Towards an integrated approach to simulating crop–climate inter-actions. Ph.D. thesis, University of Reading.

Palmer, T. N., Doblas-Reyes, F. J., Hagedorn, R. & Weisheimer, A. 2005 Probabilistic prediction of climate using multi-model ensembles: from basics to applications. *Phil. Trans. R. Soc. B* **360**, 1991–1998. (doi:10.1098/rstb.2005.1750.)

Parry, M., Rosenzweig, C. & Livermore, M. 2005 Climate change, global food supply and risk of hunger. *Phil. Trans. R. Soc. B* **360**, 2125–2138. (doi:10.1098/rstb.2005.1751.)

Porter, J. R. & Semenov, M. A. 2005 Crop responses to climatic variation. *Phil. Trans. R. Soc. B* **360**, 2021–2035. (doi:10.1098/rstb.2005.1752.)

Stone, R. C. & Meinke, H. 2005 Operational seasonal forecasting of crop performance. *Phil. Trans. R. Soc. B* **360**, 2109–2124. (doi:10.1098/rstb.2005.1753.)

Verdin, J., Funk, C., Senay, G. & Choularton, R. 2005 Climate science and famine early warning. *Phil. Trans. R. Soc. B* **360**, 2155–2168. (doi:10.1098/rstb.2005.1754.)