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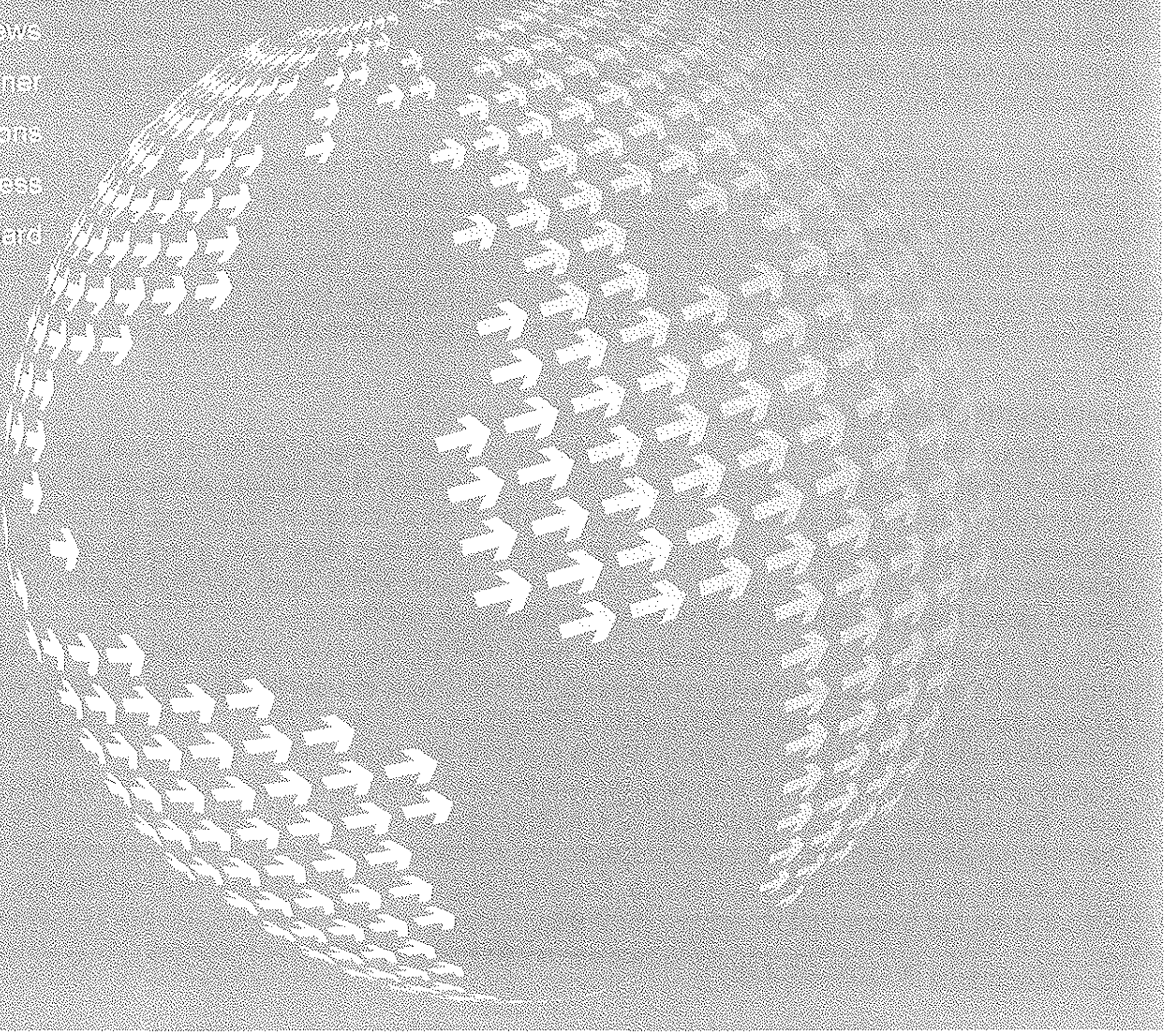

Climate change, crop yields, and the future

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Introduction

There is growing realization of the immense challenge of feeding the growing human population this century (FAO 2009, Beddington 2010, Godfray et al. 2010). Among the many reasons for this is concern that climate change will affect agricultural productivity, livelihoods, and development prospects (Bloem et al. 2010). In January 2008, the head of the World Food Programme commented "we could now be facing a perfect storm of challenges, including climate change and increasingly severe droughts and floods, soaring food prices and the tightest supplies in recent history" (Sheeran 2008). However, even more environmental and social problems are emerging. These will inevitably interact with climate change. Without extraordinary social and technological improvements, including a Green Revolution for Africa (Ejeta 2010) global nutrition and health appear likely will be inevitable casualties of the future.

Central to these developing problems is a re-awakening of concern about a crucial and disconcerting prospect: limits to growth (Meadows et al. 1972, Turner 2008, Hall and Day 2009, Leder and Shapiro 2009, Butler 2009a, 2009b). This debate is most obviously manifested by the rising price of energy. The likelihood of approaching "peak oil" has recently been given added credibility by a paper co-written by David King, recent Chief Scientific Adviser to the UK Government (Owen et al. in press). Also uncomfortably near are "peak phosphorus" (Cordell et al. 2009) and projected shortages of fifteen elements known collectively as rare Earths, essential for a growing number of electronic devices (Stone, 2009). These scarcities are accelerated by a still growing human population, mainly in the low-income countries. Perversely, the poorest populations in low-income countries contribute little on a per-capita basis to resource demand, yet their limited human and institutional resources make them particularly vulnerable to global stresses. These populations also need to be fed, and many are likely to receive even more inadequate nutrition in future. In turn, via several causal pathways, this is likely to increase the risk of insurgency and political instability, outcomes understood, predicted and feared since the birth of the Food and Agricultural Organization of the United Nations (FAO). Consequently, there is a slowly growing awareness of the dependency of modern agriculture upon cheap and abundant energy, vital for transport, for the manufacture of nitrogenous fertilizer and pesticides (White and Grossman 2010).

At the time that Sheeran warned of a perfect storm, the price of energy, fertilizer and food was rising sharply (von Braun 2008, Piesse and Thirtle 2009) but the global financial crisis had not yet started. As that crisis strengthened, it forced another 100 million into undernourishment, leading to an estimated 1.02 billion in this state by early 2010 (FAO 2009). This catastrophe makes achievement of the Millennium Development Goal on Hunger and the even more ambitious World Food Summit target, set in 1996, seem unachievable (Butler 2009a, FAO 2009), a failure so severe that it is likely to undermine credibility in internationally set targets.

How might climate change impact on food security?

The impact of climate change on food security has been modeled for at least two decades (Adams et al. 1990). Consistent over this period has been the prediction that climate change will bring benefits and harms to agriculture and food security, especially in the short to medium term (e.g. to 2100). Models beyond 2100 are rare, if they exist at all. If they do, the intrusion of sea level rise, likely by then to be at least a metre (Hansen 2007, Allison et al. 2009) on densely populated fertile land, combined with extreme weather effects would seem likely to result in overwhelmingly negative effects.

Over a shorter period, warmer weather is predicted to allow expansion of croplands to sparsely populated regions of Canada, Scandinavia and Russia, where crops are currently limited due to short growing seasons (Rosenzweig and Parry 1994; Parry et al. 1999, Easterling et al, 2007). At the best case, such new areas for cultivation will compensate for areas which are forecast to decline in productivity, such as many parts of the tropics (Fischer et al. 2001). Farming innovation and adaptations (for example earlier planting) will also reduce the negative impact, particularly in mid and higher latitudes (Cassman et al, in press). However, even if warmer temperatures expand agricultural zones poleward, much of the soil then subject to agriculture is likely to be acidic or in other ways sub-fertile, requiring large fossil-fuel intensive investments, including of fertilizer. It thus does not follow that increased crop production from high latitudes will easily compensate for the forecast reduction in crops in tropical regions. This task is made even harder by the possibility of increased rural impoverishment in densely populated South Asia, where many agro-climatic models forecast cereal declines by 2080, some by as much as 22% (Tubiello and Fischer 2007). Few if any models forecast improvement.

Most obviously, climate change will affect agricultural production by altering temperature and precipitation patterns (Zhang et al. 2007, Schmidhuber and Tubiello 2007). Climate change has long been predicted to alter the intensity and distribution of rainfall (Milly et al. 2002). Recent evidence suggests that the rainfall models are conservative. That is, the changes in rainfall intensity may exceed the model's predictions (Allan and Soden 2008). Limited observational data also suggest that moist regions are becoming wetter and dry regions drier (Allan and Soden 2008). Anecdotal evidence from 2009 is consistent with this sobering finding, including from the slow moving Taiwanese typhoon Morakot and the twin typhoons, Ketsarna and Parma, which soon after displaced over 400,000 people in the northern Philippines. Only a few weeks later, a severe drought in the Indian states of Karnataka and Andhra Pradesh was broken by rains, judged as the greatest in a century. At least one million people became temporarily homeless.

Unfortunately, however, the paucity of high quality agricultural, health and meteorological data in these low-income areas make the attribution and measurement of adverse agricultural effects due to climate change extremely difficult. On the other hand, such patterns are consistent with climate change predictions, and undoubtedly cause local adverse effects to food supplies and food security, especially for the poor.

Changes in average rainfall may poorly reflect growing conditions; for example increased rainfall intensity combined with longer dry spells could maintain average rainfall, yet be unfavorable for agriculture, especially for crops (Rosenzweig et al. 2002). Altered precipitation patterns are also likely to lead to increased agricultural variability, reducing livelihood security for landless agricultural laborers, and thus worsening food security. Such vulnerable populations face a double jeopardy – less income in conditions of tightened food supply at increased prices (Schmidhuber and Tubiello 2007).

Carbon fertilization

The carbon fertilization effect (CFE) refers to evidence and theory that because carbon dioxide (CO_2) is essential for photosynthesis, increased levels of this key greenhouse gas will partially offset harm to crop growth due to other climate change consequences. While there is consensus that the CFE exists, doubts persist concerning its strength and importance, especially for C4 plants such as maize, sorghum and sugar cane, where the effect may only occur during drought (Leakey et al. 2008). This controversy arises because of a discrepancy in the earlier, enclosed studies and the more recent open air studies, called Free Air Carbon Enrichment (FACE) (Long 2006; Tubiello et al. 2007). This debate remains unsettled, and unsettling. However, it is possible that there may be systematic differences in the genetic structure of the crops used in the newer studies, for example there may be less down regulation in the presence of increased CO_2 in the older plants. Were this the case, then both sets of observations could be correct, but if so, there may still be a risk that dominant modern strains of plants might be less able to take advantage of higher CO_2. Lower amounts of soil nitrogen, due to higher energy prices and hence more expensive fertilizer, might also impede the full benefit of the CFE.

Increased CO_2 may even cause harm for some crops, including cassava, a staple food today for about 750 million people, most of whom are poor (see more on this in the Burns paper in this issue). Increased CO_2 may also favor some important insect pests (Zavala et al. 2008).

Other agricultural impacts of climate change

The likely effect of climate change upon crops, livestock and fisheries is more complicated than the average temperature during the growing season or the winter, important for pest control and some perennial crops, such as stone fruits. Apart from changes in rainfall intensity, frequency and reliability, also to be considered are altered patterns of winds, hailstorms, forest fires, and other extreme weather events, such as cyclones and hurricanes. Sea level rise is already harming food production in some low-lying islands (Keim 2010), while warmer temperatures are reducing nutrient mixing and fishery productivity in LakeTanganyika (Tierney et al. 2010). Despite warming, the pattern and even frequency of frosts may change, for example by reduced seasonal rainfall and cloudiness. Indeed, increased frosts have been reported in autumn in parts of southern Australia (due to reduced rainfall and clearer skies at that time), though probably not at a time when crops are vulnerable (Murphy and Timbal 2008).

Large-scale risks, such as weakening in the Indian monsoon (Zickfeld et al. 2005), intensification of the El Niño Southern Oscillation or of other ocean currents and atmospheric oscillations may also occur. Tropospheric ozone is not only an important greenhouse gas, but is also increasingly recognized as having a substantial adverse effects on both current and future crop growth, (Ashmore et al. 2006). It too is currently excluded from agro-climate models.

Other likely effects of climate change upon agriculture include altered crop and animal diseases, such as the expansion of the midge transmitted viral disease, blue tongue, a growing problem for livestock in Europe (Purse et al. 2005). Milder winters are predicted to expand the range of some important pests, such as the corn earworm (Diffenbaugh et al. 2008). The Vietnamese Minister of Agriculture recently warned of increasing plant diseases, a warm winter (harmful to seedlings) and drought, all factors likely to reduce the 2010 rice harvest in the Red River Delta, one of Vietnam's main food bowls (ProMed 2010). It is plausible this is contributed to by climate change.

Ideally, models which try to forecast the effect of climate change on agriculture should consider the soil characteristics of areas which may in future be climatically suitable for crops. Complex effects from climate change upon irrigation are also likely, not only from changed rainfall, but from accelerated glacial melting and reduced summer river flow, including to many of the great rivers springing from central Asia (Kehrwald et al. 2008). Climate change is also predicted to have complex and largely adverse effects on marine fisheries, in the short run by changing the pattern of ocean currents, and in the longer run by increasing ocean acidity. Also in the long run, climate change, unless rapidly mitigated, will lead to sea level rise of a metre or more by 2100, with likely catastrophic impacts for fertile low lying shorelines, including many parts of coastal Bangladesh (Inman 2009) and the Mekong and Nile deltas.

Modeling

The plethora of effects of climate change upon global and regional agriculture thus presents a huge modeling challenge. Models simulate agricultural conditions to reflect altered average temperatures, rainfall and the CFE. Some incorporate models of world trade. Table 1 lists some of the main modeling studies reviewed for this paper.

These modeled studies consistently predict a change in the location of growing areas, with agricultural expansion to areas formerly too cool to consistently grow crops, such as northern Canada and Scandinavia. They also consistently forecast a decline in agricultural productivity in hot regions. An early modeling study noted several limitations, including soil quality in new areas, as well as changes in weeds, pests and diseases, and on altered climatic variability (Adams et al. 1990). Indeed, in vast regions that are likely to become more climatically suitable for crops, such as in the boreal forests of Russia, soil quality is known to be poor (Dronin and Kirilenko 2008). Twenty years later, few if any of these excluded factors are well simulated.

Models omit many factors likely to impact on future food production. These can be classified into climate and non-climatic related effects, (see tables 2 and 3). There are three main reasons that agro-climate models omit both classes of effects. Firstly, few, if any such models are designed to simulate future food security, but only to consider the impact of climate change upon future agricultural food supplies. Few if any agro-climatic modeling teams are likely to feel empowered or motivated to incorporate any comprehensive list of extra-climatic factors. Secondly, many of the climatic factors, such as a sea level rise of 50cm, or a weakening of the Indian monsoon, are either decades away or highly uncertain. It is not surprising that early modelers have focused on temperature and rainfall. Finally, the sheer number of such effects presents a daunting, perhaps intractable computational challenge. Nevertheless, in aggregate, both classes of omitted factors are likely to be negative, particularly from the second half of this century.

One of the most detailed modeling studies to date was recently published by the International Food Policy Research Institute (Nelson et al. 2009). It combines economic, population and trade figures with a sophisticated climate model of two scenarios, incorporating temperature and rainfall for both irrigated and rain fed crops. The models also account for increased water demand caused by higher temperatures. Results are presented with and without a CFE. Other limitations of models, as discussed here above, are not included. The findings of this analysis are sobering, yet also likely to be optimistic.

In developing countries, and in the absence of a strong CFE, the model reports declining yields for most crops, with irrigated wheat and rice especially harmed. On average, yields in developed countries are affected less than those in developing countries.

In China, some crops fare reasonably well, due to the large temperature ranges present in that country.

South Asia, however, is particularly affected, and shows the greatest yield decline for almost all crops. Sub-Saharan Africa sees mixed results, with little change in maize yields but large negative effects on rain fed wheat. The Latin American and Caribbean region also shows mixed yield effects.

The IFPRI study presents an analysis of the number of malnourished children globally under 5 years of age of in 2050. It finds that this increases by about 25 million compared to scenarios without climate change, or by about 20% (from 113 to 138 million). In reality, the increase in the prevalence of undernutrition will be higher, because this result refers only to the cohort of children born between 2045 and 2050. Many children born before (and after) these dates will also be malnourished (due to climate change), and many will still be alive (in, say 2050).

The adverse consequences of undernutrition in the first years of life are often irreversible (Victora et al. 2008). Such effects include reduced cognitive capacity, with a lesser capacity to benefit from schooling, even if available and less productive lives as adults. Thus, for the period 2020-2060, at least 100 million additional malnourished children and young adults are likely to be growing up, due to climate change, with millions more succumbing to diseases which have malnutrition as an underlying cause.

Another problem is disguised in the IFPRI model. The report predicts that without climate change the number of malnourished children will fall by 30% between 2000 and 2050, from 147 to 114 million, with a particularly strong decline in South Asia, from 77 to 42 million. These figures are implausible. In India, for example, undernutrition remains a very serious problem, despite many years now of high economic growth (Black et al. 2008). It is clear that the benefits of that growth remain extremely unequally shared, especially in the north and north east. The influence of Maoists (Naxalites) in India is growing, substantially fuelled by the high prevalence of poverty and undernourishment (Chakravarti 2008). In much of the highly fertile irrigated grain belt of parts of north-west India, aquifers are seriously depleted (Rodell et al. 2009). Even without climate change, yields are at risk. Finally, relatively high population growth persists in northern India, especially among the poor. This impedes economic development (Bryant et al. 2009) and adds to the absolute number of undernourished children. In Pakistan, similar problems are likely; indeed the current breakdown in governance in much of Pakistan is arguably in part caused by poor nutrition, consistent with concerns long held by food and development workers, such as Sir John Orr, the first director of the FAO.

Such baseline models, devised before the global financial crisis and the oil shock of 2008, arguably reflect a worldview which is more optimistic than reality. Between 2007 and late 2009 the number of undernourished increased by over 100 million, due not to climate change but to other factors (Butler 2009a). There is thus an urgent need to develop models which are more realistic.

Conclusions and recommendation

The future is rushing nearer, and the daunting task of decarbonising the global energy system, necessary to slow climate change has barely commenced. While the documented effects of climate change on agriculture to date are mixed, few if any studies have looked carefully at the recent effect on agriculture of climate change effects in low-income countries. In any case, these effects seem likely to soon become overwhelmingly negative, especially for poor populations in South Asia and sub-Saharan Africa. Without dramatic and rapid technological breakthroughs, the problem of climate change will soon be exacerbated by a rising price of oil and phosphorus (Butler, 2009b).

Low-income populations can look for support, but by no means "rescue" by high income populations. Low income countries need better and fairer governance, more education, and to accelerate their demographic transitions (Bryant et al. 2009). Their contribution to climate change is still small, and it is rational for them to rely upon fossil fuels for development, which are cheaper. High income countries need to reduce their emphasis on adaptation, which may prove ineffectual if the current policy trajectories persist. Instead, they must awaken to the urgency posed by climate change, limits to growth and their interaction with global security. Alliances perhaps may strengthen between philanthropists and activists in developing countries, in order to facilitate technological "leapfrogging" and to improve the other social and environmental needed to promote resilience, well-being and the endurance of global civilization.

Finally, there is an urgent need to need to develop agro-climatic models which are more realistic. Such models should try to better integrate knowledge from the social and physical sciences, and to also incorporate a range of extra-climatic factors, such as soil quality and the likely price of fertilizer.

If this tasks proves too computationally intense, then perhaps modelers could explicitly list major factors which are excluded, with an estimation of their likely collective direction and importance. Such caveats would reduce excessively optimistic or uncritical interpretation of models, especially by policy makers.

Study (year)	Scale	CFE	Temp	Rain	Farming adaptation	Other
Adams et al (1990)	US	optimistic	yes	yes		no
Rosenzweig and Parry, (1994)	global	optimistic/no effect	yes	yes		no
IPCC (1996)	global		yes	yes	yes	no
Fischer et al, (2001)	global	optimistic	yes	yes		no
Rosenzweig et al, 2002	US		yes	yes		
Fischer et al, (2005)	global	optimistic	yes	yes		socio-economic, world trade
Thornton et al, 2007	Africa		yes	yes		no
Tubiello & Fischer (2007)	global		yes	yes		no
Easterling et al (2007)	global	Varying strength	yes	yes	yes	
Nelson et al (2009)	global	Optimistic/no effect	yes	yes		

Table 1. This is an incomplete list of key reviews and studies of models of the effect of climate change upon agriculture. All studies consider average temperature, average rainfall and the carbon fertilization effect. Several studies comment explicitly on limitations, such as soil quality, which are excluded from the models.

Climate change effect	Modeled?	Likely food security effect	Timing of effect
Temperature	yes	varies	1950 on
Rainfall	partially	varies	1990 on
Rainfall intensity and distribution	no	varies	2000 on
Irrigation	partially	mostly harmful	1990 on
Glacial melting	no	harmful	2050 on
Carbon fertilization effect (CFE)	yes (earlier studies more optimistic)	beneficial	1950 on
CFE on pests	no	adverse	Uncertain
CFE harm for cassava	no	adverse	Future
Conflict	no	adverse	2050 on
Extreme weather events	no	adverse	Increasing
Fishery effects	no	adverse	2050 on
Frost frequency	no	uncertain	current
Governance disruption	no	adverse	2050 on
Gulf stream weakens	no	adverse	2100 on
Monsoon changes	no	adverse	uncertain
Population dislocation	no	adverse	2050 on
Sea level rise	no	adverse	2050 on
Soil quality	no	adverse	2050 on
Tropospheric ozone	no (not with CC)	adverse	2000 on

Table 2. This is an incomplete list of likely effects of climate change upon agriculture. The impression of whether an effect is modeled derives mainly from the studies referred to in table 1. The timings are approximate and indicative; they refer to substantial effects likely to occur from the date listed. The word "on" (in the timing column) indicates not only the start of an effect, but that the effect is likely to then intensify, because climate change is likely to increase in effect for many decades. The soil effect is important in the future as warmer temperatures allow new areas to be cultivated. Some models do exist for tropospheric ozone, but not for its interaction with climate change.

Non-climate change effect	Modelled?	Direction of agricultural effect	Timing
Conflict (regional)	no	harmful	current
Desalinization (cheap)	no	beneficial	uncertain
Ecosystem decline	no	harmful	1970 on
Energy price increase	no	adverse	2020 on
Fertilizer (N) scarcity	no	adverse	2020 on
Fertilizer (P) scarcity	no	adverse	2050 on
Genetically modified organisms	no	probably beneficial	2020 on
Groundwater depletion	no	harmful	2000 on
Institutional failure	no	harmful	Africa, already
Institutional failure	no	harmful	parts of Asia
Yield increase	yes	beneficial	current
Yield plateau	no	harmful	uncertain

Table 3. This is an incomplete list of predictable non-climatic effects upon agriculture. The timings are approximate and indicative; they refer to substantial effects likely to occur from the date listed. The word "on" indicates not only the start of an effect, but that the effect is likely to then intensify, because climate change is likely to increase in effect. The soil effect is important in the future as warmer temperatures allow new areas to be cultivated. Many non-climatic constraints are also likely to apply to future agriculture, including yield limits, a rising cost of fertilizer and transport costs, and in some places impaired governance. Ecosystem decline is widespread, and is likely to already be harming food production. However, there is little specific literature about this.

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