Food Cops under Global Warming and Changing Water Availability

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Abstract

Much of food availability in the world depends on rain-fed crops, thus present and future changes in the water cycle (*e.g.* total amount, annual distribution and intensity of precipitation) may play a fundamental role in global food security. In particular, projecting further changes include increasing in temperature and changes in precipitation, with decreases in some dry regions at mid-latitudes and in the dry tropics (*e.g.*, the Mediterranean basin, western USA, southern Africa and north-eastern Brazil) that may intensify present limited water resources. Moreover, increases in the frequency and severity of heavy precipitation and extreme drought events are expected during the 21st century. Finally, sea-level rise is projected to extend areas of salinisation of groundwater and estuaries, resulting in a decrease of water availability for irrigation in coastal areas. All these projections, together with other external factors (increases in food demand, changes in human diet, etc.) may determine important impacts on food crops productions and the following food availability. This work aim to present a complete overview of the impacts that global warming and changing water availability will have on food crops and the adaptation strategies that may be used to cope with these.

Key words: Food crops, climate change, water availability, temperature

1. Introduction

Eight hundred million people are food-insecure, and 200 million children below 5 years of age are malnourished in the developing world. Trends for the near future are negative for developing countries, especially for sub-Saharan Africa, as world population will increase and degradation of lands will continue (Droogers *et al.*, 2001). Moreover, changes in diet patterns will represent another aspect that will have to be considered, since food demand of countries like China or India will increase not only for the population growth but also for raising in food calorie intake. Thus, producing enough food, and generating adequate income in the developing world to better feed the poor and reduce the number of those suffering will be a great challenge.

Irrigated agriculture has been an important contributor to the expansion of national and world food supplies since the 1960s, and is expected to play a major role in feeding the growing world population. However, irrigation accounts for about 72 percent of global and

90 percent of developing country water withdrawals, and water availability for irrigation may have to be reduced in many regions in favour of rapidly increasing non agricultural water uses in industry and households, as well as for environmental purposes. Thus, rainfed crops that currently account for 58 percent of world food production may play a significant role in meeting future food demand (Rosegrant *et al.*, 2002).

Further the competition for land and water, the role of both irrigated and rainfed crops in the future of global food production will be strongly affected by climate change. In particular, the recent IPCC report (IPCC, 2007) indicated small beneficial effects on crop yields in temperate region corresponding to local mean temperature increases of 1-3°C and associated CO_2 increase and rainfall changes; whilst in tropical regions predictions indicated negative yield impacts for the major cereals even with moderate temperature increases (1-2°C) (Easterling *et al.*, 2007).

This work aim to present a complete overview of the impacts that global warming and changing water availability will have on food crops and the adaptation strategies that may be used to cope with these.

2. Scenarios of climate change

Independent evidence from observations of the climate of the past century and a half strongly implies that the total global radiant energy forcing (gases and aerosols) is having a warming effect on the world. The global mean atmospheric temperature near the earth's surface has risen by 0.76ºC since 1850, when measurements began, and is now higher than at any time during at least the past two thousand years (Trenberth *et al.*, 2007). About three-quarters of the change observed since 1850 is attributed to human actions. These temperature rises already appear to be impacting on physical and biological systems with, for example, progressive earlier start to the growing season across the northern hemisphere (Rosenzweig *et al.*, 2007), widespread and rapid glacial melting and progressively earlier flowering of plants. In addition to these changes in temperature, there are trends in rainfall amounts and rainfall intensity (Trenberth *et al.*, 2007).

Future climate changes are highly uncertain. A selection of climate models, driven by a range of scenarios of human development, technology and environmental governance, projects the global mean temperature to rise a further 1.8°C (1.1°C – 2.9°C) to 4ºC (2.4°C – 6.4°C) during the 21st Century (Meehl *et al.*, 2007). The projected warming is not evenly distributed around the globe: continental areas warm more than the ocean and coastal areas, and the poles warm faster than equatorial areas. This is a large range, with about half of the variation in projected temperatures being due to uncertainties in the climate models, and the other half due to uncertainties regarding greenhouse gas emissions which are closely tied to social, economic and technological aspects of our future. The scenarios of emissions project atmospheric carbon dioxide concentrations to rise to between 550ppm and 960ppm during the 21st century (Nakićenović and Swart, 2000). This will have its own impacts on cropping systems as higher CO_2 concentrations makes plants more efficient in their use of water, light and nitrogen, increasing yields particularly in dry conditions but decreasing nitrogen contents of produce.

A warmer world will, on average, produce more rainfall, falling with greater intensity. However, for particular regions (*e.g.* Central America, southern Europe and Mediterranean Africa, southernmost Africa, the southern Andes in South, America and southern Australia), there may be substantial reductions in rainfall (Solomon *et al.*, 2007). The rainfall projections by the various climate models frequently differ in both sign and magnitude for given regions. The typical range of the changes is less than + 15%, which is approximately the amount by which evaporation will increase in a 3° C warmer world assuming symmetrical increases in day and night temperatures (Howden, 2002). The interannual variability of rainfall is likely to increase, leading to both more frequent droughts and more frequent floods (Solomon *et al.*, 2007).

3. Food crops responses

Biophysical processes of plants are strongly affected by environmental conditions. Thus, these are expected to react to specific environmental changes that are undergoing as a result of the increase in global greenhouse gases.

Enhanced CO_2

It is well known and demonstrated that plants, when exposed to increasing concentrations of CO_2, respond with an increase of the rate of photosynthesis (*e.g.* IPCC, 2001). Such increases in photosynthesis normally lead to larger and more vigorous plants and to higher yields of total dry matter (roots, shoots, leaves) and harvestable product as well. This behaviour is particular evident in C_3 plants (plants that use a 3-carbon compound in the first step of photosynthesis) that include most of the food crops (cereals, legumes, oil and root crops). C_4 plants (that have an additional 4-carbon compound step to capture CO_2), such as maize, sorghum, millet, and sugarcane, have a more efficient photosynthetic pathway than the C_3 plants under current CO_2 concentrations. C_4 plants also increase their photosynthesis with elevated atmospheric CO_2 concentration, but less markedly. However, both C_3 and C_4 plants respond to elevated CO_2 by partially closing their stomata. This reduces the loss of water from the interior of the leaf to the atmosphere (transpiration). As a result of these two responses, there is usually observed an increase in water-use efficiency with elevated CO_2.

Recent studies confirmed that the effects of elevated CO_2 on plant growth and yield depend on photosynthetic pathway, species, growth stage and management regime, such as water and nitrogen (N) applications (Kimball *et al.*, 2002; Ainsworth and Long, 2005). On average across several species and under unstressed conditions, recent data analyses find that, compared to current atmospheric CO_2 concentrations, crop yields increase at 550 ppm CO_2 in the range of 10-20% for C3 crops and 0-10% for C4 crops (Ainsworth *et al.*, 2004; Gifford, 2004; Long *et al.*, 2004).

Higher temperature

As reported in the IPCC, 2001 and IPCC, 2007 in mid- to high-latitudes crop producing areas may expand polewards, since global warming will extend the length of the potential growing season of indeterminate crops, allowing earlier planting or beginning of growth seasons in spring, and late ending of the growth seasons in autumn. Less severe winters will also allow more productive cultivars of winter annual and perennial crops to be grown. These potential expansions or shifts, however, may be reduced by other environmental (*e.g.* soil fertility) or physiological factors (*e.g.* adaptation to longer days). Whilst, in warmer, lower latitude regions, higher temperatures will increase respiration, evapotranspiration, determining less than optimal conditions for net growth. Another important effect of high temperature is accelerated physiological development, resulting in hastened maturation of determinate crops and reduced yield if there is no adaptation through change in crops to those with greater thermal time requirements (*e.g.* Easterling *et al.* 2007).

Moreover, short periods of high temperature can have significant impacts on crop yield through spikelet sterility or lowering grain number and grain size (Matsui *et al.* 1997; Ferris *et al.* 1999; Porter and Gawith 1999). High temperatures during grain-filling may also reduce grain quality through development of heat shock proteins such as beta-gliadins, which negatively impact on dough-making (*e.g.* Blumenthal *et al.* 1991).

Available water

Plant growth is strongly influenced by the availability of water. Changes in total seasonal precipitation or in its pattern of variability are both important. The occurrence of moisture stress during flowering, pollination, and grain-filling is harmful to most crops (*e.g.* grain, maize, soybean and wheat). Increased evaporation from the soil and increased transpiration from the plants will cause drought stress; resulting in an increased need for crop varieties with greater drought tolerance.

The demand for water for irrigation is projected to rise in a warmer climate, increasing the competition between agriculture and urban as well as industrial users of water (*e.g.* Doll 2002). Falling water tables and the resulting increase in the energy needed to pump water will make the practice of irrigation more expensive, and more water will be required per unit area under drier conditions with more greenhouse gas emissions generated. Peak irrigation demands are also likely to rise due to more severe heat waves. Additional investment for dams, reservoirs, canals, wells, pumps, and piping may be needed to develop irrigation networks in new locations or to maintain the existing irrigation systems. Finally, changes in soil water availability will alter soil salinisation processes in both irrigated and dryland cropping systems (*e.g.* van Ittersum *et al* 2003) with either beneficial or problematic outcomes possible depending on the system and climate changes. For example, dryland salinisation risk may be lessened by climate changes which involve lower rainfall (van Ittersum *et al.* 2003).

Interaction of CO_2 with temperature and precipitation

The impact of climate changes on cropping systems will be the result of the combined effect of CO_2 increases, temperature rises, changes in evaporation and changes in the mean, variability and intensity of rainfall.

Recent studies have confirmed that temperature and precipitation changes in future decades will modify, and often limit, direct CO_2 effects reducing grain number, size and quality (*e.g.* high temperature at flowering time) (Thomas *et al.*, 2003; Baker, 2004; Caldwell *et al.*, 2005) or increasing water demand (Xiao *et al.*, 2005). Thus, on the basis of the predicted changes in temperature and precipitation patterns, potentially large negative impacts are expected in developing regions, while only small changes in developed regions (Fischer *et al.*, 2002, 2005; Parry, 2004; Parry *et al.*, 2005).

Recent regional assessments, however, have shown the high uncertainty that underlies such findings, and thus the possibility for surprises, by projecting, in some cases, significant negative impacts in key producing regions of developed countries, even before the middle of this century (Olesen and Bindi, 2002; Reilly *et al.*, 2003). Moreover, specific new knowledges about the impact role of increases in the frequency of climate extremes, of irrigation water requirements, of new CO_2 stabilization scenarios have highlighted the possibility of different responses.

Climate variability. Extreme meteorological events, such as spells of high temperature, heavy storms, or droughts, can severely disrupt plant production. Similarly, frequent droughts not only reduce water supplies but also increase the amount of water needed for plant transpiration. Recent studies carried out on specific aspects of increased climate variability (*e.g.* increased heavy precipitation, increased flood, risks of soil erosion, water and soil salinisation, heat and frost stress during growing seasons) demonstrated that increased climate variability may have greater impacts on agriculture than changes in climate means alone (Howden *et al.* (2003; van Ittersum *et al.* 2003; Monirul and Mirza 2002; Rosenzweig *et al.* 2002; Nearing *et al.* 2004; Easterling *et al.* 2007).

Irrigation water requirements. Global irrigation requirements are expected to increase as demonstrated by Döll (2002) (+5% to +8% by 2070, without CO_2 effect) and Fischer *et al.* (2006) (+20% by 2080, with CO_2 effect), despite the positive effects of elevated CO_2 on crop water use efficiency. However, regional irrigation requirements may show different signs as demonstrated by recent regional studies on irrigated areas (higher irrigation requirements in North Africa, Abou-Hadid *et al.*, 2003; lower irrigation requirements in China, Tao *et al.*, 2003).

New CO_2 stabilization scenarios. Compared to the impacts of climate change on crop production by 2100 under business-as-usual scenarios, stabilisation at 550 ppm CO_2 may reduce significantly production loss (by -70% to –100%) and lower risks of hunger (–60% to –85%) (Arnell *et al.*, 2002; Tubiello and Fischer, 2006).

4. Adaptation strategies

The purpose of crop adaptation strategies is to manage potential risks related to climate change over the next decades (i.e. counter negative impacts or take advantage of positive ones). These adaptations can be thought of as being applicable at different temporal and spatial scales, *e.g.*, short term adjustments and long term adaptations, farm-level, regional or national policy level. Some of these adaptations are outlined below.

Temporal scale classification

Short-term adjustments. These adjustments to climate change are efforts to optimise production without major system changes. They are autonomous in the sense that no other sectors (*e.g.* policy, research, etc.) are needed in their development and implementation. Thus, short-term adjustment can be considered as the first defence tools against climate change through: a) the management of cropping systems for reducing yield losses (*e.g.* changes in crop varieties, in agronomic practices such as sowing/planting dates, in fertiliser and pesticide use; adoption of new tools for crop selection such as climate seasonal forecasts); b) the conservation of soil moisture for reducing drought stress and irrigation requirements (*e.g.* introduction of moisture conserving tillage methods such as minimum tillage, conservation tillage, stubble mulching etc.; management of irrigation in terms of amount and efficiency). Easterling *et al.*, 2007 synthesised the results from adaptation studies on wheat, rice and maize showing that on average these adaptations allowed to avoid damage caused by a temperature increase of up to 1.5 to 3°C in tropical regions and 4.5 to 5°C in temperate regions; while further warming than these ranges in either region exceeds adaptive capacity.

Long-term adaptations. Many long-term adaptations (planned adaptations), including major structural changes to overcome adversity caused by climate change, have been identified (Howden *et al.*, 2003; Kurukulasuriya and Rosenthal, 2003; Aggarwal *et al.*, 2004;Antle *et al.*, 2004; Easterling *et al.*, 2004). These include:

- Changes of land use to respond to the differential crop performance under climate change and to stabilise production. In this case crops with high inter-annual variability in production (*e.g.* wheat) may be substituted with crops with lower productivity but more stable yields (*e.g.* pasture).

- Crop breeding through the use of both traditional and biotechnology techniques to allow introduction of heat and drought resistant crop varieties. Collections of genetic resources in germ-plasm banks may be screened to find sources of resistance to changing diseases and insects, as well as tolerances to heat and water stress and better compatibility to new agricultural technologies. For example, crop varieties with higher "harvest index" will help maintain irrigation efficiency under conditions of reduced water supplies or enhanced demands. Genetic manipulation may also offer another possibility to adapt to stresses (heat, water, pest and disease, etc.) enhanced by climate change allowing the development of "designer-cultivars" much more rapidly than it is possible today. Species not previously used for agricultural purposes may be identified and others already identified may be quickly used.

- Crop substitution for the conservation of soil moisture. Some crops use a lower amount of water, are more water and heat resistant, so that they tolerate dry weather better than others do. For example, sorghum is more tolerant of hot and dry conditions than maize.

- New land field techniques (laser-levelling of fields, minimum tillage, chiselling compacted soils, stubble mulching, etc.) or new management strategies (*e.g.* irrigation scheduling and monitoring soil moisture status) to improve irrigation efficiency in agriculture. Moreover a wide array of techniques (such as inter-cropping, multi-cropping, relay cropping etc.) to improve water use efficiency.

- Changes in nutrient management to reflect the modified growth and yield of crops, but also changes in the turn-over of nutrients in soils, including losses. It may thus be necessary to revise standards of soil nitrogen mineralisation and the efficiency of use of animal manures and other organic fertilisers. There is a range of management options that will affect the utilisation of fertilisers and manure, including fertiliser placement and timing, reduced tillage and altered crop rotation management.

- Changes in farming systems to remain viable and competitive. Specialised farms, especially dairy farms and arable farms, will probably respond more to climate change than mixed farms. On mixed farms with both livestock and arable production there are more options for change, and thus a larger resilience to change in the environment.

Spatial scale classification

Farm level. There is a large range of farm level options for adapting to climate change. Key adaptations (Howden *et al.* 2003a) include:

- Further develop risk amelioration approaches (*e.g.* zero tillage and other minimum disturbance techniques, retaining residue, extending fallows, row spacing, planting density, staggering planting times, controlled traffic, erosion control infrastructure),
- More opportunistic cropping – more effectively taking into account environmental condition (*e.g.* soil moisture), climate (*e.g.* seasonal climate forecasting) and market conditions,
- Expand routine record keeping of weather, production, degradation, pest and diseases, weed invasion,
- Tools/training to access/interpret climate data and analyse alternative management options,
- Learning from farmers in currently more marginal areas,
- Selection of varieties with appropriate thermal time and vernalisation requirements, heat shock resistance, drought tolerance (i.e. 'Staygreen' varieties), high protein levels, resistance to new pests and diseases and perhaps that set flowers in hot/windy conditions,
- Improve seasonal and other climate forecasting and also develop warnings prior to planting of likelihood of very hot days and high erosion potential,

Regional level. Historically, there have been substantial and quite rapid changes in land management and land-use with climate variations in many parts of the globe (*e.g.* Meinig 1962; Meinke and Hammer 1997). The scope and scale of potential future climate changes suggests that significantly greater land-use change may happen in the future, particularly at the margins of current industry distributions. A key reason for problems that may arise from any negative climate changes may be either inappropriate policy or unrealistic expectations that encourage people to 'hang on' in extended dry periods, leading to substantial degradation of the soil and vegetation resources (McKeon and Hall 2000). One way to avoid such problems is to integrate climate change into regional planning (*e.g.* Olesen and Bindi 2002), however, there are significant issues in i) identifying climate change thresholds given the complexities of climate change interacting with the many ongoing issues (*e.g.* dryland salinisation, change in irrigation water allocation processes etc) and ii) the high levels of uncertainty inherent in climate change scenarios due to large ranges in greenhouse emissions (from uncertain socio-economic, political and technological developments) and fundamental uncertainty in the science of the global climate system. There are emerging approaches to deal with this uncertainty (*e.g.* Howden and Jones 2004) but these have yet to be applied to a regional context.

National level. The high levels of uncertainty in future climate changes suggest that rather than try to manage for a particular climate regime, we need more resilient agricultural systems (including socio-economic and cultural/institutional structures) to cope with a broad range of possible changes. There is a substantial body of both theory and practice on resilient systems (*e.g.* Gunderson *et al.* 1995). However, enhanced resilience usually comes with various types of costs or overheads such as building in redundancy, increasing enterprise diversity and moving away from systems that maximise efficiency of production at the cost of broader sustainability goals. One approach to developing more resilient agricultural regions is to develop an adaptive management strategy where policy is structured as a series of experiments that have formal learning and review processes. However, this could provide a serious challenge to some institutions that are based on precedent (and hence only look 'backwards' not 'forward'), have a short-term focus only and which are risk averse (*e.g.* Abel *et al.* 2002). Nevertheless, there is a large range of policy activities that could be undertaken which will enhance the capacity of agricultural systems to deal with a changing climate. These include (Howden *et al.* 2003a):

- Policy: linkages to existing initiatives to enhance resilience,
- Managing transitions: support during transitions to new systems,
- Communication: industry-specific and region-specific information,
- R&D and training: participatory approach to improve self-reliance and provide the knowledge base for adaptation,
- Model development and application: Systems modelling to integrate and extrapolate anticipated changes,
- Climate data and monitoring: to link into ongoing evaluation and adaptation,
- Seasonal climate forecasting: for incremental adaptation linked to other information,
- Breeding and selection: Support and ensure access to global gene pools,
- Pests, diseases and weeds: enhanced quarantine, sentinel monitoring, management,
- Water: trading systems that allow for climate variability and climate change, distribution systems, water management tools and technologies,
- Landuse change and diversification: risk assessments and support.

Whilst a range of technological and managerial options potentially may exist as indicated above, there has been little evaluation of how effective (i.e. costs/benefits) and widely adopted these adaptations may actually be. This will require:

- confidence that climate changes several years or decades into the future can be effectively predicted against a naturally high year to year variability in rainfall that characterises these systems,
- motivation to change to avoid risks or use opportunities,
- development of new technologies and demonstration of their benefits,
- protection against establishment failure of new practices during less favourable climate periods,

- monitoring of their costs and effects,
- alteration of transport and market infrastructure to support altered production.

6. Research gaps

Further research activities should be carried to reduce the uncertainties in assessing the impact of climate change on food crops availability and related adaptation strategies. Key research challenges for the next years include:

- the reduction of the uncertainty of the climate change scenarios and impact assessments,
- the role of changes in frequency and severity of extreme climate events on crop responses,
- the response to climate change of important crops for rural poor people, such as root crops, millet,
- the interactions among crops, weeds, pests and disease under a changing climate,
- the role of traditional and biotechnology techniques for coping with drought, heat and other climate related problems,
- the integrated impacts of climate change on cropping systems more than on single crops and on mixed farming systems more than on monoculture farms,
- the study of the rates of adaptation of new management strategies relative to rates of climate change for different farming systems and different cropping regions in order to evaluate their efficiency in mitigating negative impacts or exploring new options offered by climate change,
- the effects of climate change on specialised farming systems, which may be particularly sensitive and vulnerable to climate change,
- the development of integrated assessments using climatic and non-climatic conditions (economic, social, technological, environmental, institutional) to identify necessary changes in agriculture in a changing climate,
- the use of seasonal weather forecasts and methods for adapting such forecasts in farm management for adapting to climate change,
- the evaluation of how farmers perceive climatic related risks and how they respond, in both the short and long term.

7. Conclusions

The results of the studies performed in the last years indicated consistent increases in temperature and different patterns of precipitation with general increases in mid- to high-latitude and substantial reductions in rainfall for particular regions (e.g. Central America, southern Europe and Mediterranean Africa, southernmost Africa, the southern Andes in South, America and southern Australia). These changes in climate patterns are expected to affect all the components of the agricultural ecosystems (e.g. crop, soil, livestock, water, etc.). As regards food crops in particular, moderate warming may produce benefits for crop in mid- to high-latitude regions, while even slight warming may determine decreases yields in seasonally dry and low-latitude regions. Moreover, global irrigation requirements are expected to increase, despite the positive effects of elevated CO_2 on crop water use efficiency. Thus, adaptation strategies should be introduced to reduce negative effects and exploit possible positive effects of climate change. Among these, it seems that both autonomous adjustments (e.g. changes in crop species, cultivars and sowing dates) and planned adaptations (e.g. land allocation and farming system) should be considered. However, the differences in climate exposure, sensitivity, and adaptive capacity will affect in a different way food crops across world showing that developing countries will be more vulnerable than developed ones.

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