Global environmental change and future crop production

Peter J. Gregory[1] and John S.I. Ingram[2]

[1]Department of Soil Science, The University of Reading, PO Box 233, Whiteknights, Reading, RG6 6DW, UK. www.reading.ac.uk/soil Email p.j.gregory@reading.ac.uk
[2]GECAFS International Project Office, CEH-Wallingford, Maclean Building, Wallingford, OX10 8BB, UK. www.gecafs.org Email jsii@ceh.ac.uk

Abstract

Global environmental change (GEC) is a consequence of a range of human activities and includes elements such as increasing concentrations of gases in the atmosphere, climate variation and change, rising sea level, loss of biodiversity, and changes in water and nitrogen cycling. Crop production is both affected by and contributes to GEC.

Estimates of future global crop production show that most of the required increases in production will come about by greater intensification with substantial extensification only in limited areas. Production systems demonstrate a spectrum of intensification practices that can be characterised by different methods of site preparation and pest control, and inputs of germplasm, nutrients and water. Collectively, intensification has contributed to GEC particularly through changes to the nitrogen cycle and increasing atmospheric concentrations of gases contributing to global warming. The environmental consequences of the increased production may occur either on- or off-site or both, and will vary regionally depending on whether intensification or extensification is the main pathway for achieving the increases.

Changes in extremes of weather associated with increased climate variability in the short term, and in mean values of temperature and rainfall associated with climate change in the long term, contribute to the uncertainties introduced by GEC. In Australia, average annual temperatures are predicted to be 0.4 to 2.0 ?C higher over most of the continent by 2030 with generally lower rainfall in winter and spring (-10 % to +5 %). Projected decreases are greater in the south-west (-20 % to +5 %). Crop models incorporating doubling of atmospheric [CO_2] to 700 ppm show a yield response for wheat of +15 % to +25 % as mean temperature increases in the range 0 to 4 ?C, but this response decreases to a range of +4 % to -8 % if rainfall simultaneously decreases by 20 %. Adaptation of crop production to cope with GEC and the feedback of the adapted production systems to GEC have been much less studied and is research that is needed for goals of both production and sustainability. The real challenge, then, is to develop crop production systems that are more productive and more environmentally benign.

Key Words

Crop productivity, greenhouse gases, human population

Introduction

The growth in human population over the past two centuries (from about one billion in 1825 to about six billion today) together with an increased consumption of resources has led to marked environmental changes on a global scale (1). Global environmental change (GEC) is evident through a range of interacting factors such as increasing concentrations of gases in the atmosphere, climate variation and change, rising sea level, loss of biodiversity, and changes in cycling of water and nitrogen. Some of these phenomena manifest at a global level due to rapid global mixing (e.g. changes in atmospheric CO_2 concentrations) while others are more local issues but which occur in so many places as to constitute a global phenomenon (e.g. application of N fertilisers). Despite widespread concern about the implications of these changes (2), there has been very little concerted action to change patterns of human behaviour so that, for example, global atmospheric CO_2 concentrations continue to increase and are now well outside the range experienced in recent inter-glacial periods.

A topic of particular societal concern is that of GEC and food production. The last decade or so has seen greatly increased understanding of the impacts of global change (especially increasing atmospheric CO_2 concentrations and increasing temperatures) on components of production systems (e.g. 3), and hence what this may mean for human concerns such as food security (e.g. 4). However, the increasing human demand for food and forest products is in itself a major cause of global change contributing substantially to changes in land use and the increase of greenhouse gases in the atmosphere. For example, agricultural production systems have been estimated to account for about 18.4% of annual CO_2-equivalent gas emissions in Australia of which methane from livestock production accounts for just over 60% and nitrous oxide emissions from agricultural soils accounts for about 18%(5). Similarly, human intervention in the global nitrogen cycle has now become so pronounced that more nitrogen is "fixed" in fertilisers and legumes in agricultural systems than is fixed by natural processes (6). The enhanced losses of N from agricultural land to adjacent areas such as watercourses can have major impacts on ecosystem services (7).

Increasingly, though, research is being undertaken to understand what can be done to "cope" with GEC. Given that global change is happening, albeit with different aspects manifesting themselves at different rates, farmers and other land managers will undoubtedly adapt to the changing conditions. Production systems will need to be developed to be buffered against the deleterious aspects of global change, but also to exploit the beneficial aspects. Adaptation research will need to deliver a range of appropriate strategies as the nature of global change becomes clearer for given regions of the world. For all systems, these strategies must draw in part on the impacts research referred to above.

The objectives of this paper are: (i) to outline the major interactions between GEC and crop production systems; (ii) to examine aspects of environmental change and crop production in Australia; and (iii) to suggest future areas in which research is required.

Global changes in crop production

Demand for crop products

Projected increases in the global human population together with an improved diet indicate that current production of agricultural products will need to increase substantially over the next few decades (8,9). Associated with this increase will be substantial increase of the urban population especially in the developing world where urban populations are expected to double in the next 20 years. Rising per capita incomes of this urbanised population will result in significant increases in the demand for food crops, meat and forest products (10,11). Given the close association of population and grain production, and allowing for changes in diet towards greater consumption of meat, it is possible to estimate the required grain production (wheat, rice and maize together supply about 60% of the total carbohydrate) to feed the additional human population. Annual population growth of 80 million requires an annual increase in grain production of about 26 million tonnes; more if allowance is made for rising affluence (12). Cereal production has increased from 740 Mt in 1950 to about 1,900 Mt in 1995 and will have to increase by another 690 Mt to meet projected demand in 2020 (13). The increased demand is not only for direct human consumption but also to meet the projected 1.4% p.a. increase in cereal feed for livestock production over the next two decades.

Extensification and intensification

Past increases in agricultural production have occurred as a result of both extensification (altering natural ecosystems to generate products) and intensification (producing more of the desired products per unit area of land already used for agriculture). Where other economic activities allow, purchasing food from elsewhere can enhance food supply locally. Globally, no one means will be adopted and different regions will increase production in different ways (10). About 3 billion ha of the world's land is suitable for arable agriculture and 1.2 to 1.5 billion ha of the most productive land is already cultivated (14). Most of the potentially available land is presently under tropical forests. Cultivation of more of this land is undesirable with respect to biodiversity conservation, greenhouse gas emissions and regional climate and hydrological changes, and would incur high costs to provide the necessary infrastructure. In general, then, further extensification of agriculture will likely provide only a small fraction of the increased production needed. Typically new areas of crop land will only contribute 7.4% (51 Mha) to cereal production on a global basis by 2020. Estimated contributions of extensification to crop production range from 47% in sub-Saharan Africa to 18% in South Asia (10).

Intensification will thus be the dominant means for increasing production. This will be achieved largely by increased yields per area rather than increased number of crops grown in a seasonal cycle. For instance, average cereal yield has already increased from 1.15 t/ha in 1951 to 2.8 t/ha in 1995 and is projected to be about 4.2 t/ha in 2020. Simultaneously per capita arable land area has declined from 0.24 ha in 1951 to 0.13 ha in 1993 (13,14).

From a biophysical perspective, intensification (expressed as increasing production per ha of farmers' field) has been achieved by using several management options either singly or in combination (15). The major options lie in the degree of land preparation, the choice of germplasm (crop species or cultivar) and the time of sowing of the crop, the use of appropriate nutrients to enhance growth, the use of irrigation where water is available and the method of pest and weed control. For much of agricultural history, the number of options was limited and intensification occurred by the gradual adoption of individual new means of management. For example, many soils of Australia are P-deficient and the adoption of P fertilisers between 1900 and 1950 raised average wheat yields from 0.49 t/ha to 0.86 t/ha with subsequent introduction of legume leys and new varieties increasing this further to 1.3 t/ha (16). Current production systems now occupy a continuous spectrum of intensification, characterised by different levels of inputs and crop management practices. For convenience, three types of intensification can be specified each with characteristic features (Table 1). Productivity may however vary widely within a given type. For example, at Type II intensity, yields of wheat in eastern England may reach 11.5 t/ha, close to the current physiological limits of the crop whereas yields in Western Australia are typically about 1.2 t/ha.

Environmental consequences of increased crop production

The environmental consequences of producing more food will vary regionally and depend substantially on whether intensification or extensification is the main pathway for achieving the increases. Different factors operate at different temporal and spatial scales and their effects may be realised both on and off the site of production (17). While all production systems increasingly play a significant role in enhancing global change and other aspects of environmental degradation (7) it is the increased production per unit area discussed above that lies at the heart of many environmental concerns. All three intensification strategies result in some detrimental environmental consequences, but their nature and magnitude differ markedly between types and particularly in whether the major consequences are on- or off-site (15). Key issues are: (i) the emission of green-house gases (especially CO_2) and changes in other climate forcing factors (e.g. albedo); (ii) the impacts on soils; (iii) the impacts on water courses and aquifers; and (iv) the destruction of habitats leading to reduced biodiversity and the loss of species (18).

Table 1. Types of intensification of crop production systems (from 15).

Intensification type	Type I: Low external inputs, "pre-green revolution"	Type II: High external inputs, "green revolution"	Type III: Improved efficiency of inputs, "doubly-green revolution"
Main objective	Minimising food shortage	Maximising food production	Maximising profit and other land functions

Rural population density	Increasing	High	Reduced
Access to market and technology	Low	High	High
Environmental concern	Medium	Low	High
Land efficiency	Increasing/Declining	High	Reduced
Labour/energy efficiency	High or Declining	Low	Reduced
Capital efficiency	No capital	Low or Medium	High
Fallow/time	Declining	Zero	Increasing
Technological package	Zero or limited	High	Reduced (minimum tillage, IPM, manure etc.)
Credit, land tenure	Zero	High	High
“Mining” agriculture	Yes or No	Yes	No
Example	Sub- Saharan Africa	Indo-Gangetic plain	South-American “success” stories

Impacts of climate change on crop production in Australia

Most attention in Australia on GEC has focussed on the issues of climate variation and climate change. Issues of nutrient runoff and degradation of water quality are locally important (e.g. leaching of P from sandy soils in Western Australia into coastal estuaries (19), and leaching of nitrate into groundwater from intensive agricultural areas in Queensland (20)), but the susceptibility of the crop production industry in Australia to natural climatic variability leads inevitably to climate as a focus. The Australian wheat industry is very sensitive to climate through both its direct effects on yield and via its indirect effects and interactions with sowing date, choice of cultivar, spatial extent of planting, and crop management. Wheat production has progressively extended into more arid areas and into the wetter margins as technologies have improved although future cropping may be restricted through increasing dryland salinisation (up to 22% of current cultivated area potentially affected). To these existing uncertainties will be added the additional complicating factor of GEC.

Climate variation and change

Analysis of climate records over the last century shows that, for the country as a whole, annual mean temperature increased by about 0.7 ?C between 1910 and 1999 (most of this occurred after 1950) while annual mean rainfall increased only slightly (21). However, the increases have not been uniform across the country. However, the increases have not been uniform across the country. For temperature, both mean maximum and minimum temperatures showed a similar increase in the NW and SW quadrants of Australia but only minimum temperatures showed an increase in NE and SE Australia. For rainfall, NE and SW quadrants showed little or no trend since 1900 while in NW Australia the increase was about 0.8 mm per year and in SE Australia about 1 mm per year. There was much variability between years (most in NE Australia and least in the SW) and in many parts of the country there is evidence of cycles of wet and dry years. Figure 1 shows such a cycle at Horsham, Victoria with a periodicity of about seven years. This natural variability is at the heart of many practical problems of dryland agriculture where uncertainty dominates and seasonal weather forecasts may assist with crop management decisions (22).

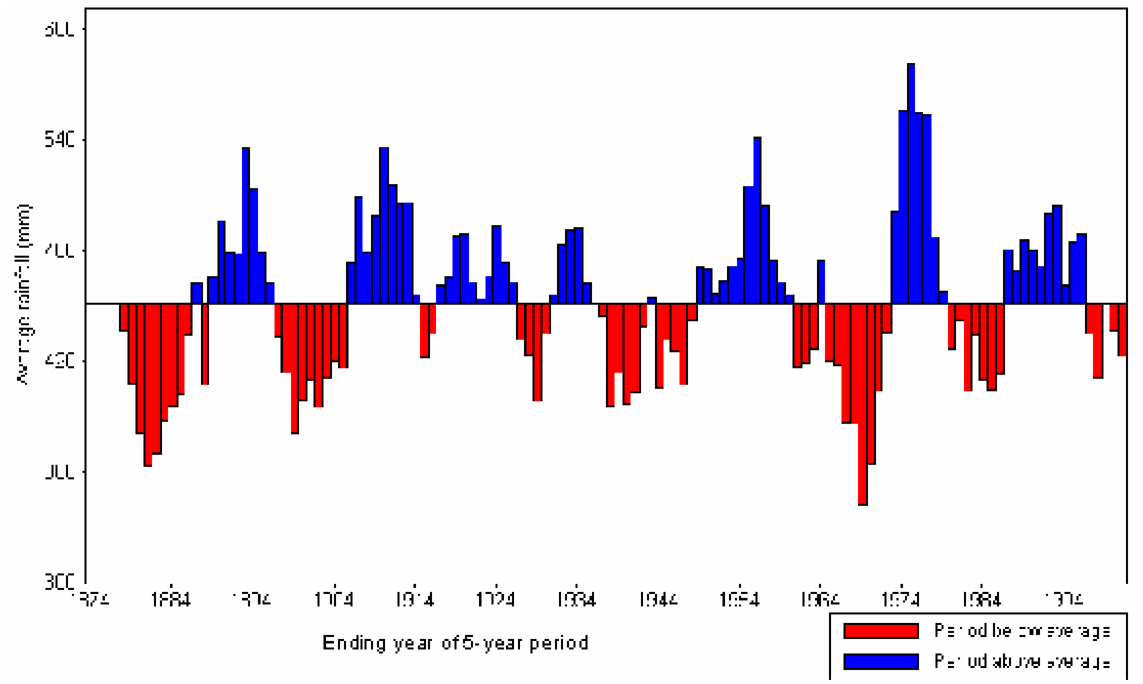

Figure 1. The 5-year moving average rainfall (January to December) at Horsham, Victoria. The long-term average is 451 mm. Source: Australian Rainman.

Modelled projections of future Australian temperature and rainfall have taken account of the increased atmospheric [CO_2] and that of other greenhouse gases (23). The conditions in individual years are strongly affected by natural climatic variability so cannot be predicted. The simulations show that by 2030, annual average temperature will be 0.4 to 2.0 ?C higher over most of Australia and by 2070 1.0 to 6.0 ?C higher. The model output indicates that changes in daily minimum and maximum temperatures will be similar to the change in mean temperature. This contrasts with the greater increase in minimum than maximum temperature found in the last century that was commented on earlier. Projected annual rainfall shows a decrease in the SW (-20 to +5% in 2030 and -60 to +10% by 2070) and in parts of the SE. In much of eastern Australia, projected ranges are -10 to +10% by 2030 and -35 to +35% by 2070. In winter and spring most areas will be drier (-10 to +5% by 2030 and -35 to +10% by 2070).

Climate change and yields

Considerable progress has been made internationally in both the measurement and modelling of the effects of climate and atmospheric [CO_2] change on the growth of crops. For example, experiments at Maricopa, Arizona, USA showed that increased atmospheric [CO_2] tends to increase growth and yield of wheat crops and that the relative size of this effect is bigger with droughted crops than those given unlimited water supply (24). These twin effects were recently adequately reproduced by crop simulation models based on mathematical descriptions of phenological development and physiological processes (25).

Similar crop models have been used together with outputs from global circulation models to assess the impact of climate change on wheat production in Australia (26,27). Future yields will depend on both the anticipated positive effect of increased atmospheric [CO_2] (about 24% yield increase for a doubling of [CO_2]) and the generally negative effects of climate change. The relative benefits of higher [CO_2] are likely to be greater in Australia than elsewhere because wheat is often grown under conditions of limited water supply (cf. Maricopa experiment). Table 2 shows the output from models incorporating a doubling of atmospheric [CO_2] to 700 ppm. The yield response ranges from +15 to +25% as mean temperature increases from 0-4 ?C. However, this response decreases to a range of +4 to -8% if rainfall simultaneously decreases by 20%.

Table 2. The percentage change in average annual total Australian wheat yield for a doubling of atmospheric [CO_2] and a range of changes in temperature and rainfall (from 26).

Management	Rainfall	Temperature increase (?C)				
		0	1	2	3	4
Current	Current	24	26	23	19	14
	-20%	2	4	0	-4	-8
	+20%	32	36	34	30	26
Optimal	Current	24	29	29	26	20
Planting	-20%	2	5	4	0	-4
Date	+20%	32	39	41	38	32

Although there has been no formal integrated assessment of the impact of climate change on the Australian wheat industry, sufficient studies exist to show that the situation is complex. Impacts on wheat appear to be negative in Western Australia and South Australia due to large reductions in rainfall but slightly positive in eastern Australia due to the beneficial effects of increased [CO_2] (28). However, the projections suggest that the positive effects induced by doubling [CO_2] will tend to plateau rapidly while the climate effects may continue for centuries leading to increasingly negative impacts (28).

Until recently most such impact assessments have been made assuming no modification to crop production practices. It is highly probable, though, that the changes of climate and [CO_2] will occur sufficiently slowly that changes to sowing date, cultivar, crop and other management practices will allow at least some adaptation of the production system. Simulation of production for cropping systems in northern and central Italy shows that the combined effects of increased [CO_2] and climate change would depress crop yields by 10-40% if current management practices were unamended largely because of the warmer air temperatures accelerating the phenology of current cultivars (29). Through a combination of early planting of spring and summer crops and the use of slower-maturing winter cereal cultivars, though, the model indicates that it should be possible to maintain present yields. However, a major caveat to this conclusion was that 60-90% more irrigation water was required to maintain grain yields under conditions of climate change; this water was assumed to be available (29). In Australia, similar adaptation of the wheat production system to take advantage of earlier sowing may also partially offset the negative effects of increased temperature and of reduced rainfall (Table 2; 26).

Future research

There is now increasing confidence in the ability to predict the effects of greenhouse gases in the atmosphere on future climate at a global scale (2). With this has come an associated improving ability to predict the impact of future climate and atmospheric composition on the yield of Australia's principal crops such as wheat. Further research (e.g. 30) has begun to investigate the potential impacts on national production (as opposed to the "plot-level" productivity), and while the area of scaling-up is often limited by data scarcity, methodological progress is now being made in many parts of the world (e.g. 31).

Such predictions often assume a constant technological level, and that yield loss due to pests, diseases and weeds is unchanged. However, one of the key areas insufficiently researched in relation to GEC concerns losses due to such biotic factors. Plant pathogens, in particular, are very responsive to climate, and their distributions and abundances are therefore expected to alter significantly under GEC; distributions and abundances of insect and other pests and weeds are likely to be similarly affected (32). The generation of specific predictions requires the linkage of crop growth models and insect or pathogen population models, or crop-weed competition models, run under a range of GEC scenarios. The fact that the relationship between the host and "pest" will likely change *in addition* to direct changes in the crop physiology and in the distribution and dynamics of the "pest" itself is of particular concern. Considerably strengthened research is needed to be able to estimate how crop losses will change under different environmental and management conditions; and hence how best to adapt cropping systems to reduce their vulnerability to such losses.

It is also clear that closing nutrient cycles to sustain intensive systems remains a considerable challenge for the future (18). In addition to reducing greenhouse gas production and other forms of pollution, improving the efficiency with which inputs are used will increase profitability and conserve natural resources. The real challenge is therefore to develop more productive, yet more environmentally-benign production methods. Essentially this means improving the efficiency with which nutrients (particularly nitrogen), water and other inputs are used.

While there is still much progress to be made in agronomic science to predict better the potential impacts of GEC on productivity and production, a review by the International Food Policy Research Institute (11) identified a range of "emerging issues" for world food production. Key biophysical factors such as fresh water supplies, soil fertility and fertilizer use and climate variability and climate change feature prominently, but so too do other factors such as trade liberalization and market reform, and the greater applications of emerging technologies. The inclusion of socioeconomic factors in the discussion is crucial, especially in analyses at spatial levels at farm and regional scales. Important though food production is, from a societal standpoint the critical issue is food provision, a concept which also encompasses the notions of food availability and access. New, interdisciplinary research agendas are now emerging (e.g. 33) to address this broader GEC consideration.

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