Challenges and opportunities for cropping systems in a changing climate

Marco Bindi[1] and Mark Howden[2]

[1] Dept. of Agronomy and Land Management, University of Florence, P.le delle Cascine 18 – 50144, Florence, Itlay. www.unifi.it/unifi/disat/ Email marco.bindi@unifi.it
[2] CSIRO Sustainable Ecosystems, GPO Box 284, Canberra, ACT, 2601. www.csiro.au Email mark.howden@csiro.au

Abstract

Human activities are affecting the composition of the atmosphere, influencing global and regional temperatures and rainfall and through these a large range of physical and biological processes. These changes appear likely to continue over the forthcoming century. As climate and atmospheric CO_2 concentration are key factors in influencing plant production and other ecosystem processes such as decomposition, it is not surprising that changes in these will have consequences for the functioning of cropping systems. These consequences are likely to vary widely depending on the cropping system being investigated (i.e. cereals vs forage crops vs perennial horticulture), the region and the likely climate changes. For many cool-temperate systems, the prospect of global warming may bring new opportunities provided rainfall doesn't decline substantially. For warm-temperate and tropical regions, the impacts may be significant and negative with increasing water stress, increasing problems associated with high-temperature conditions and a need for either substantial change in varieties and management activities or land-use change. There are a large number of adaptation options that may be explored to minimise negative impacts of climate changes and to take advantage of positive changes. These can be categorised as operating within different time-scales (i.e. short-term or long-term) or different spatial scales (i.e. farm-level to national policy level). We outline what some of these options may be at these different scales.

Media summary

Global climate is already changing. Further change seems inevitable with far-reaching consequences for cropping activities globally. Some negative impacts of these changes can be reduced by management adaptations which can also enhance benefits from positive changes.

Key Words

climate change, greenhouse effect, adaptation, cropping systems

Introduction

Human activities such as combustion of fossil fuels and industrial and agricultural development appear to be affecting the global climate. Global mean temperatures have risen approximately 0.6^{o}C since the mid 1800s and changes in rainfall patterns, sea levels, rates of glacial retreat and biological responses have also been detected which are consistent with expectations of 'greenhouse' climate change. The 1990s were the warmest decade ever recorded instrumentally, and the last 100 years were the warmest of the millennium. The most recent report of the Intergovernmental Panel on Climate Change (2001a) concluded that there is now strong evidence for a human influence on global climate and that these trends will continue for the foreseeable future due to continued emissions of carbon dioxide (CO_2) and other greenhouse gases from fossil fuels and other sources. The most up to date predictions are for an increase in global average temperatures of 2-6^{o}C by the end of the present century. Intuitively, it is hard to conceive that such changes will not have implications for cropping systems and their management. Such high global temperatures have not been experienced before by the human species – we have no precedent for managing them. In addition to these projected temperature increases there will be increases in atmospheric carbon dioxide (CO_2), changes in average rainfall with the prospect of substantial rainfall declines in some regions but increases in others, increases in rainfall intensity, and the possibility of entering a more El-Ni?o-like climate condition**.** We outline how climate and atmospheric composition is already changing and how it may change further, how these changes may be affecting cropping system function, the adaptations that may be needed for cropping systems in the future and some key research challenges in the next five years.

What is changing, and by how much?

Atmospheric concentrations of ‘greenhouse gases’ such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have increased markedly over the past century (IPCC 2001a). It is likely that they are now higher than at any time in the past 420 000 years (Petit et al. 2000). The concentration of these atmospheric constituents affects the absorption of long wave radiation from the earth by the atmosphere, with higher concentrations of the main greenhouse gases (CO_2, CH_4 and N_2O) warming both the earth’s surface and the lower atmosphere. In the case of the minor or more transient gases (such as the tropospheric ozone-precursors), the effect is known to be warming, but the degree, duration and spatial distribution of the warming is less certain.

There have also been changes in the concentration of particulates (aerosols). For aerosols, the direct effect can either be warming (for dark, highly absorptive particles such as soot) or cooling (for reflective particles such as sulphate), and their impact depends somewhat on their location in the atmosphere. Aerosols can cause or prevent the formation of clouds, which in turn either cool or warm the earth, depending on their type and location. This is known as the ‘aerosol indirect effect’, and is highly uncertain. Thus the net effect of aerosols remains uncertain in both sign and magnitude. Nevertheless, 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. It is very likely that the global mean atmospheric temperature near the earth’s surface has risen by 0.6?C since 1850, when measurements began, and is now higher than at any time during at least the past two thousand years (Mann and Jones 2003). About three-quarters of the change observed since 1850 is attributed to human actions (IPCC 2001a). 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 (Myneni et al. 1997), widespread and rapid glacial melting and progressively earlier flowering of plants. A large number of such studies have been synthesised by the IPCC (2001b). In addition to these changes in temperature, there are trends in rainfall amounts and rainfall intensity (e.g. Angel and Huff 1997).

What may change further?

Future climate changes are highly uncertain. A selection of climate models, driven by a range of scenarios of human development, technology and environmental governance, project the global mean temperature to rise a further 2 to 6?C during the 21st Century (IPCC 2001a). 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 (IPCC 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. southern Australia and much of Africa), there may be substantial reductions in rainfall. 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 $\pm$ 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 2003). Most models suggest drying in the subtropical belts and increased rainfall in the temperate northern hemisphere. The interannual variability of rainfall is likely to increase, leading paradoxically to both more frequent droughts and more frequent floods.

How will global change affect cropping system functioning?

Biophysical processes of agroecosystems are strongly affected by environmental conditions. The projected increase in greenhouse gases will affect agroecosystems either directly (e.g. response to CO_2 and tropospheric ozone) or indirectly via effects on climate (e.g. temperature and rainfall). The exact responses depend on the sensitivity of the particular ecosystem and on the relative changes in the controlling factors.

Cereals and seed crops

Cereals, oilseed and protein crops including pulses are mostly determinate species, and the duration to maturity depends on temperature and in many cases daylength. A temperature increase will therefore shorten the length of the growing period, reducing yields, if management is not altered (Porter and Gawith 1999; Tubiello et al. 2000), and change the area of cultivation. Simple management options to counteract the warming effect are changes in sowing dates and use of longer season cultivars (Olesen et al. 2000; Tubiello et al. 2000, van Ittersum et al. 2003). This warming effect is counteracted by the CO_2 fertilisation effect, which also will lead to increased symbiotic nitrogen fixation in pulses (Serraj et al. 1998).

Root and tuber crops

Potato, as well as other root and tuber crops, is expected to show a large response to rising atmospheric CO_2 due to its large below ground sinks for carbon (Farrar 1996) and apoplastic mechanisms of phloem loading (Komor et al. 1996). On the other hand warming may shorten the growing season in some species and increase water requirements with consequences for yield. Climate change scenario studies performed for Europe using crop models show no consistent changes in mean potato yield (Wolf 2002), but an increase in yield variability is predicted for the whole of Europe, which raises the agricultural risk for this crop. However, available crop management strategies (i.e. earlier planting and the cultivation of earlier varieties) seem effective in overcoming these changes (Wolf 2002).

Root crops such as sugar beet may be expected to benefit from both the warming and the increase in CO_2 concentrations, as these crops are not determinate in their development and an extended growing season will increase the duration of growth, provided sufficient water is available.

Horticultural crops

Horticultural crops include both vegetables and ornamental crops, either field-grown or grown under protected conditions. The main effects of a climatic warming anticipated for protected crops are changes in the heating and cooling requirements of the housing. Most field-grown vegetables are high value crops, which are grown under ample water and nutrient supply. Therefore they are likely to mainly respond to changes in temperature and CO_2. Responses to these factors vary among species, largely depending on the type of yield component and the response of phenological development to temperature change. For determinate crops like onion, warming will reduce the duration of crop growth and hence yield, whereas warming stimulates growth and yield in indeterminate species like carrot (Wheeler et al. 1996; Wurr et al. 1998). For lettuce, temperature has been found to have little influence on yield, whereas yield is stimulated by increasing CO_2 (Pearson et al. 1997).

For many field-grown vegetable crops in Europe, increasing temperature will generally be beneficial, with production expanding out of the presently cultivated areas. A temperature increase will in some areas offer the possibility of a larger span of harvesting dates thus giving a continuous market supply during a longer period of the year. For cool-season vegetable crops such as cauliflower, large temperature increases may decrease production during the summer period in dry areas due to decreased crop quality (Olesen and Grevsen 1993).

Forage crop and grasslands

Forage crops include cereals for silage and some root crops. When these crops are grown as forage crops, the yield components and the quality criteria change. The effects of climate change on production and quality of wheat crop silage depends on the relative magnitudes of changes in CO_2 concentration and temperature (Sinclair and Seligman 1995). If the CO_2 effect dominates, then a yield increase but a decrease in nitrogen content will result, and vice versa if the temperature increase dominates. The potential impacts of these changes for livestock production are outlined below in 'Livestock systems'. Yields of indeterminate crops such as silage maize can be expected to show a larger increase than the yield of whole crop cereals.

Permanent grasslands occupy a large proportion of many agricultural areas. The type of grassland varies greatly from grass and shrub steppes in the drier regions to mires and tundra in colder, wetter regions. Temperate grasslands vary from intensively managed monocultures to species-rich communities with local variations depending on soil type and drainage. The different species will vary in their responses to CO_2 and climate change, resulting in alterations in the community structure of grasslands in the future. However, the management and species-richness of grasslands may increase resilience to change (Duckworth et al. 2000). Legumes, which fix nitrogen from the atmosphere, may benefit more from a CO_2 increase than non-fixing species (Schenk et al. 1995). This has experimentally been found to lead to larger nitrogen inputs to grass-clover swards (Zanetti et al. 1996).

The effects of atmospheric CO_2 increase on grasslands could be significant. Overall, the stimulatory effect of double ambient CO_2 concentrations on grassland production averages about 17% in ecosystem-based experiments (Campbell et al. 2000). Individual system responses varied widely and were higher in moisture-limited and warm-season grassland systems, particularly where nutrients were not limiting. Simulation models also suggest that intensively managed and nutrient-rich temperate grasslands will respond positively to both the increase in CO_2 concentration and to a temperature increase (provided that water supply does not become limiting) (Thornley and Cannell 1997). Simulation studies and experiments in seasonally-dry tropical grasslands suggest similar responses (e.g. Stokes et al. 2003). The positive effect of increased CO_2 on biomass production and water use efficiency can be offset by climate change (particularly rainfall reductions), depending on local climate and soil conditions (Topp and Doyle 1996a; Riedo et al. 1999) and is also affected by management decisions such as stocking rate, harvesting, fertilisation and fire management. These effects will also determine the spatial distribution of agricultural grassland (Rounsevell et al. 1996). The importance of water management including drainage may, however, also be important under changed climatic conditions in wetter areas (Armstrong and Castle 1992). A proper evaluation of these effects requires that the source and sink relations are considered, in particular as affected by phenology and defoliation (Schapendonk et al. 1998).

Permanent crops

Permanent crops are very sensitive to climate change since they need a few years to reach reproductive maturity and remain economically productive for a long time. Several studies have been conducted on high value (economic and environmental) permanent crops like grapevine and olive.

Grapevine is a woody perennial plant, which requires relatively high temperatures. A climatic warming will therefore expand the suitable areas northwards and eastwards in Europe (Kenny and Harrison 1992; Harrison et al. 2000). In the current production areas the yield variability (fruit production and quality) may be higher under global change than at present. Such an increase in yield variability would neither guarantee the quality of wine in good years nor meet the demand for wine in poor years, thus implying a higher economic risk for growers (Bindi et al. 1996; Bindi and Fibbi 2000). However, yields in grapevine may be strongly stimulated by increased CO_2 concentration without causing negative repercussions on the quality of grapes and wine (Bindi et al. 2001).

Olive is a typical Mediterranean species that is sensitive to low temperature and although resistant to water shortage produces best at higher rainfall sites or with irrigation. Thus the northern and southern limits of cultivation in Europe and north Africa are conditioned by low temperature and low rainfall, respectively. A study on the spatial distribution of the Mediterranean basin showed that the area climatically suitable for olive cultivation could be enlarged due to changes in temperature and precipitation patterns that make some areas of France, Italy, Croatia, and Greece newly suitable for olives (Bindi et al. 1992). As for other crops in Europe a spatial increase and a northward shift of the potential area of olive cultivation is expected under a climate warming.

Current agricultural policy of many European states encourages the growing of energy crops (e.g. willow and *Miscanthus*). These crops are established over a period of a few years, and subsequently harvested every year or every few years. The harvested biomass is used for fuel or as a source of fibre for industrial use. These crops are generally indeterminate and will be favoured by conditions that extend the growing season and increase the light or water use efficiencies. The effect of climatic change on willow production has been studied for the UK (Evans et al. 1995). A warming was found to be generally beneficial for production with increases in yield up to 40 % for a temperature increase of 3 ?C.

Livestock systems

Livestock are often integrated with cropping activities in many agricultural systems. Climate and CO_2 effects influence livestock systems through both availability and price of feed and through direct effects on animal health, growth, and reproduction (Fuquay 1989). The impacts of changes in feed-grain prices or the production of forage crops are generally moderated by market forces (Reilly 1994). However, effects of climate change on grasslands will have direct effects on livestock living on these pastures via both impacts on feed and via heat and cold stress.

Experiments have generally shown that elevated concentrations of CO_2 significantly decrease leaf N-content, increase non-structural carbohydrate, but cause little change in digestibility in those species studied so far (Lilley et al. 2001). It appears that the total content of protein is relatively unchanged, but it is diluted by relatively easily-digested carbon-based substances such as sugars and starches. The implications of these changes differ between production systems. In production systems with high nitrogen forage (e.g. temperate pastures) the fodder generally has more protein content than can be usefully used by stock owing to insufficient metabolisable energy in the herbage for its full utilisation. In such situations, the effects of CO_2 are likely to increase energy availability, increasing nitrogen processing in the rumen thus increasing productivity. For example, in Scotland simulation studies of dairy herds grazing on grass-clover swards suggest that milk output may increase when the concentration of CO_2 is enhanced (Topp and Doyle 1996b). In contrast, in situations that are chronically nitrogen deficient (many agricultural areas in the developing nations, Australia and parts of South America), the effect of CO_2-induced nitrogen dilution may be to exacerbate the existing feed quality problems. This effect may be compounded if there is concurrent warming as such conditions tend to significantly decrease non-structural carbohydrate concentrations and digestibility in tropical species while also slightly reducing leaf N-content (Wilson 1982).

Warming trends will also substantially increase the frequency of heat stress days, particularly in tropical climates and in the warm months in currently warm-temperate regions (e.g. Klinedienst et al. 1993), reducing productivity, decreasing reproductive rates and increasing concerns about animal welfare in intensive livestock handling activities (Howden et al. 1999). The correlation of heat-stress tolerance and lower productivity characteristics in livestock means that the search for effective adaptation options will be challenging. Warming during the cold period for cooler regions may on the other hand be beneficial due to reduced feed requirements, increased survival, and lower energy costs. Impacts will probably be minor for intensive livestock systems (e.g. confined dairy, poultry and pig systems) because climate is controlled to some degree. Climate change may, however, affect requirements for insulation and air-conditioning and thus increase or decrease housing expenses in different regions. The impact of climate change on housing depends not only on temperature, but also on radiation and wind (Cooper et al. 1998). Climate change will also affect the turnover and losses of nutrients from animal manure, both in houses, storages and in the field. An example of this is the increase in ammonia volatilisation with increasing temperature (Sommer and Olesen 2000).

How can farming systems adapt to a changing world?

The direct impacts 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. It will be the integrated impacts of these changes that we will need to adapt to – either to 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.

Short-term adjustments

Short-term 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. A large range of short-term adjustments has been reported for dealing with the effect of climate change, these include:

<u>Changes in planting dates and cultivars</u>. For spring crops, climate warming will allow earlier planting or sowing than at present. Crops planted earlier are more likely to be already matured when extreme high temperatures, such as temperature in the middle of summer, can cause injury. Earlier planting in spring increases the length of the growing season; thus earlier planting using a long season cultivar will increase yield potential, provided moisture is adequate and the risk of heat damage is low. Otherwise earlier planting combined with a short-season cultivar would give the best assurance of avoiding heat and water stresses. Deeper planting of seeds will also contribute to make seed germination more likely. This approach may also be used for winter crops (i.e. cereals). Early sowing and late-season cultivars may be used to match cold temperature requirements (vernalization) that may be not be completely fulfilled during warmer winters and to offset the reduction in the length of the growing season due to warmer climate. Alternatively, in scenarios with large increases in temperature and significant reductions in rainfall, short-season cultivars may be used to escape heat and drought risks during anthesis to grainfill (van Ittersum et al. 2003).

<u>Changes in external inputs.</u> External inputs are used to optimise the production of crops in terms of productivity and profitability. The use of fertilisers is generally adjusted to fit the removal of nutrients by the crop and any losses of nutrients that may occur during or between growing seasons. A change in yield level will therefore, all other things being equal, imply a corresponding change in fertiliser inputs. The projected increases in atmospheric CO_2 concentration will cause a larger nitrogen uptake by the crop, and thus larger fertiliser applications. This may be exacerbated by the tendency for lower grain nitrogen levels with elevated CO_2 concentration particularly in low nitrogen situations (e.g. Sinclair et al. 2000). On the other hand climatic constraints on yields may lead to less demand for fertilisers. Changes in climate may also change losses of nitrogen through leaching or gaseous losses with the direction of change depending on the specific climate changes at a location. This may also lead to changes in the demand for fertiliser.

The use of pesticides reflects the occurrence of weeds, pests and diseases. Global warming will in many areas lead to a higher incidence of these problems and thus to a potentially increased use of pesticides. The use of pesticides can, however, be limited through the adoption of integrated pest management systems, which adjust the control measures to the observed problem and also takes a range of influencing factors (including weather) into account.

Current fertiliser and pesticide practices are partly based on models and partly on empirical functions obtained in field experiments. These models and functions are updated regularly with new experimental evidence. This process will probably capture the response of changes in the environment through CO_2 and climate. It is, however, important that agricultural researchers and advisors are aware of the possible impact of global change on use of external inputs, so that older empirical data are used with proper caution.

<u>Practices to conserve moisture.</u> A range of water conserving practices is commonly used to combat drought. These may also be used for reducing climate change impacts (Easterling 1996). Such practices

include conservation tillage and irrigation management. Conservation tillage is the practice of leaving some or all the previous season's crop residues on the soil surface. This may protect the soil from wind and water erosion and retain moisture by reducing evaporation and increasing infiltration of precipitation into the soil. Conservation tillage may also decrease soil temperature. Irrigation management can be used to improve considerably the utilisation of applied water through proper timing of the amount of water distributed. For example with irrigation scheduling practices, water is only applied when needed by the crop. This tunes the proper timing and amount of water to actual field conditions allowing a reduction in water use and cost of production.

Long-term adaptations

Long-term adaptations refer to major structural changes to overcome adversity caused by climate change. These may include:

- changes in land allocation
- introduction of more resistant crop varieties
- substitution of crops
- enhancement of irrigation efficiency
- changes in farming systems

Changes of land use result from the farmer's response to the differential crop performance under climate change. Studies reported by Parry et al. (1988) for Central Europe showed an “optimal land use” in which the area cultivated with winter wheat, maize and vegetables increased under climate change, while the allocation to spring wheat, barley, potato decreased. Changes in land allocation may be used also 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). Market forces are likely to significantly influence such changes.

Crop breeding may be considered as another adaptive response to climate change by the use of both traditional and biotechnology techniques that 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 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 (Goodman et al. 1987). Species not previously used for agricultural purposes may be identified and others already identified may be introduced into farming systems.

Crop substitution may be useful also for the conservation of soil moisture. Some crops use less water and 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 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) (Kromm and White 1990) may be used to improve irrigation efficiency in agriculture. Moreover a wide array of techniques (such as inter-cropping, multi-cropping, relay cropping etc.) can be useful to improve water use efficiency.

Nutrient management will need to be adapted not only 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 standard tables of soil nitrogen mineralisation rates 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 may be necessary in some areas for farming to remain viable and competitive. In many regions of Europe farms have become specialised in either specific livestock or arable farming. This specialisation is often linked to the local soils and climate conditions. Dairy farming is thus often located under conditions that ensure an appropriate water supply to the grass and forage crops during summer, as continuity of feed supply is essential. Specialised pig or poultry production on the other hand only requires access to cereals and protein feeds, which are easier and cheaper to transport. These farms are therefore less reliant on local feed supply, but often have restrictions as to disposal of urine and manure. Specialised arable farms with production of vegetables, cereals, seed crops, fruits etc. often have only a few species on the farm, depending on soil and climate conditions. These 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.

Studies on adaptation of farming systems to climate change need to consider all the agronomic decisions made at farm level (Kaiser et al. 1993). The economic considerations are very important in this context (Antle 1996; Rounsevell et al. 1999). Results of farm level analyses on the impact and adaptation to climate change have generally shown a large reduction in adverse impacts, when adaptation is fully implemented. This will, however, result in land use changes (Parry et al. 1999).

(a) Farm level adaptations

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 (e.g. '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 early warning systems of the likelihood of very hot days and high erosion potential

Whilst a range of technological and managerial options may exist as indicated above, the adoption of these new practices will require 1) 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, 2) the motivation to change to avoid risks or to use opportunities, 3) development of new technologies and demonstration of their benefits, 4) protection against establishment failure of new practices during less favourable climate periods; and 5) alteration of transport and market infrastructure to support altered production (McKeon et al. 1993)

Adaptation strategies that incorporate the above considerations are more likely to be of value, as they will be more readily incorporated into existing on-farm management strategies.

Provided climate changes are not overly large nor rapid, many cropping enterprises in developed nations are likely to be largely self-adapting if adequate information and appropriate technologies are available, costs/price ratios and the policy environment are favourable and there is altered infrastructure suited to the new conditions. For example, there is emerging evidence that at least some farmers in some regions of Australia are making rational adaptations to the existing trends in climate (e.g. frost reductions) which maintain risk at historical levels but which enhance economic returns (Howden et al. 2003b). However, for farmers in less-developed nations, climate change is likely to provide a significant challenge, interacting with a range of other pressures on those systems. Few studies have been undertaken on such systems so far.

(b) Regional level adaptations

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 1) 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 2) 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.

Table 1. National-scale climate change issues and suggested policy activities to enhance adaptation (Howden et al. 2003a).

Issue	Action
Policy	Establish linkages to existing initiatives to enhance resilience
Managing transitions	Provide support during transitions to new systems
Communication	Develop industry-specific and region-specific information
R&D and training	Use a participatory approach to improve self-reliance and provide the knowledge base for adaptation
Model development and application	Develop systems modelling to integrate and extrapolate anticipated changes
Climate data and monitoring	Maintain data collection to link into ongoing evaluation and adaptation
Seasonal climate forecasting	Communicate to allow incremental adaptation when linked to other information
Breeding and selection	Support programs and ensure access to global gene pools
Pests, diseases and weeds	Enhance quarantine measures, sentinel monitoring and management
Water	Establish trading systems that allow for climate variability and climate change, improve distribution systems, develop water management tools

	and technologies
Landuse change and diversification	Undertakes risk assessments and support rational changes

(c) National - developing more resilient systems

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 that would enhance the capacity of agricultural systems to deal with a changing climate (Table 1).

What are the key research challenges for the next five years?

Many needs for future research emerge from the previous sections of this paper. Key research challenges for the forthcoming years include:

- To perform studies of the integrated impacts of climate change and CO_2 increase on cropping *systems* more than on single crops and on mixed farming systems more than on monoculture farms, especially in the developing nations where few such studies have yet been undertaken.
- Develop linkages between GCM’s and farming systems models to undertake these studies at a range of scales
- To conduct similar studies on the effects of climate change and CO_2 increase on specialised farming systems, which have a particular reliance on product quality
- To undertake more research on adaptation at the farm level to influence strategies for improving the sustainability of farming systems that can deal with a large array of climate changes. There is a need to assess the rates of adaptation of new management strategies relative to rates of climate change for different farming systems and different cropping regions. This will need to include exploration of a range of technological and policy adjustments (short and long term strategies) available in agriculture, in order to evaluate their efficiency in mitigating negative impacts or exploring new options offered by climate change
- To develop integrated assessments using climatic and non-climatic conditions (economic, social, technological, environmental, institutional) to identify necessary changes in agriculture in a changing climate
- To develop seasonal weather forecasts and methods for using such forecasts in farm management. These climate forecasts may provide one of the most efficient ways of adapting to climate change.
- To better understand how farmers perceive climatic related risks and how they respond, in both the short and long term, to variable climatic conditions, including the magnitude and frequency of extreme events. A key element here will be in reducing the uncertainty of the climate change forecasts
- To scope how biotechnology could be better used for coping with drought, heat and other climate related problems much more rapidly than it is possible today by means of the identification of genotypes and species not previously used for agricultural purpose or others already identified

that may be quickly developed into widely available varieties. Genetic traits from other species may also be introduced in domesticated species to overcome some of the anticipated problems. Sound research on the impact of climate change on agriculture, as well as in other sectors, requires extensive and sound data. Even when suitable data exits, the identification of changes in agriculture by integrated assessment using climatic and non-climatic conditions should be performed. These analyses will allow a detailed exploration of a range of technological and policy adjustments in agriculture for mitigating negative impacts or the exploration of new options for agriculture. Finally, these results need to be communicated effectively so as to be useful for research and decision-making by governments and the cropping industries.

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