Farming in an uncertain and changing climate

Mark Howden and Steven Crimp

CSIRO Climate Adaptation Flagship, GPO Box 284, Canberra, ACT, 2601

Abstract

Climate change already appears to be affecting Australia's climate, with recent changes in temperature and rainfall consistent with those projected in the future. The likelihood of further, significant changes occurring in response to sustained growth in greenhouse gas emissions increases the need for a more coherent and urgent approach to the development of effective adaptive responses. Given the sensitivity of Australia's agriculture to climatic variability and climate change, ensuring effective adaptation options are in place is of growing importance. There are many potential adaptation options available to incrementally change existing farming systems, often enhancements of existing climate risk management. These adaptations are likely to have substantial benefits under moderate climate change, but will diminish in effectiveness with growing severity of climatic change. Hence, more systemic changes in resource allocation may need considering, such as targeted diversification of production systems and livelihoods and a range of other technological and institutional responses. The high levels of uncertainty that accumulates across the information chain as we move from greenhouse emissions to regional climate change to triple-bottom-line outcomes will require an adaptive management framework for effective short-term responses underpinned by long-term scenario analyses to prepare a suite of appropriate technical options and supporting institutional arrangements. Engagement with decision-makers at all scales is needed to frame, inform and operate these activities if we are to adapt Australia's farming systems, industries and regions to meet the challenges of an uncertain future.

Key words

Climate change, adaptation, cropping systems, uncertainty

Introduction

Farming systems in Australia are sensitive to both long term climatic conditions and year to year climate variability. This is evident in the crops used, average yields and yield variability, grain quality, what areas are cropped, what soil types are preferred, the management systems and technologies used, input costs, product prices and natural resource management. Consequently if the climate changes, there are likely to be systemic changes in farming systems. This paper will outline the climate changes that are already occurring in Australia, projections of future changes that may be of significance to the future of farming systems. This paper does not address the issue of reducing net greenhouse gas emissions from the farm sector although this sector directly and indirectly makes a significant contribution to the national emissions and offers some prospect of storing carbon in soils and vegetation under some circumstances (Keating et al. 2008). Neither does it dwell substantially on the interaction of climate change with other important drivers of change such as energy prices and food demand and the opportunities and challenges that these may bring (Keating et al. 2008). Instead it focuses on the likely impacts of prospective climate changes, and how farming systems may need adapt to these: a critical set of actions that research can help inform.

Climate and atmosphere: what has changed

The atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O; IPCC 2007a) are increasing as a result of human activity. These greenhouse gases affect the radiative balance of the earth, keeping it warmer than it would otherwise be. The concentration of CO_2, the main anthropogenic greenhouse gas, is now 384ppm, about 37% above the pre-industrial concentration of 280ppm (Petit et al. 2000). Furthermore, the rate of increase of CO_2 is itself increasing, being larger during the last 10 years (1.9 ppm per year), than it has been since measurements began in 1960 (1.4 ppm per year; IPCC 2007a). There is strong evidence that these changes in atmospheric composition are affecting the climate at both global and continental levels (IPCC 2007a).

The main climate variables that are likely to be important in terms of their impact on farming systems are maximum and minimum temperatures, rainfall, solar radiation, vapour pressure deficit and wind speed. In particular there are concerns about changes in extreme temperatures, rainfall and the duration and frequency of drought conditions (Hennessy et al. 2008). We will summarise briefly here the changes in Australia's

Global Issues Paddock Action. Proceedings of the 14th Australian Agronomy Conference. September 2008, Adelaide South Australia.

climate that have been observed over the past decades and, in the next section, the anticipated changes over forthcoming decades, drawing on the recent IPCC Fourth Assessment Report (Hennessy *et al.* 2007).

Australia has been getting warmer. Since 1910, the average maximum (day-time) temperature has risen by 0.7 °C and the minimum (night-time) temperature by 1.1 °C, with much of this change occurring since 1950 (Alexander et al. 2007). There is increasing evidence of a human 'fingerprint' in recent temperature trends with increases highly likely to have been in response to continued growth in atmospheric greenhouse gas concentrations arising from human activity (e.g. Karoly and Braganza 2005). Additionally, droughts have become more severe since about 1973 because temperatures are higher for a given rainfall level (Nicholls 2004).

As well as changes in average temperatures, there have been changes in temperature extremes. From 1957 to 2004, averaged across Australia there has been an increase in hot days (35 °C or more) of 0.10 days/year, an increase in hot nights (20 °C or more) of 0.18 nights/year, a decrease in cold days (15 °C or less) of 0.14 days/year and a decrease in cold nights (5 °C or less) of 0.15 nights/year (Alexander et al. 2007). The areal extent and frequency of exceptionally hot years (defined as the hottest 5% of the past 100 years) has been increasing rapidly such that over the past 40 years (1968-2007) exceptionally hot years are occurring over 10-12% of the area in each Australian farming region. This is about twice the expected long-term average (Hennessy et al. 2008).

Rainfall has also changed. Since 1950 summer monsoon rainfall has increased in the north-western region of Australia while southern and eastern Australia have become drier (Smith 2004). Increased rainfall in the northwest during the period 1910 to 2006 may be in response to changes in cyclone activity in response to warming in the Pacific and Indian oceans (Nicholls 2006). Rainfall decreases in the southwest are likely due to a combination of increased atmospheric greenhouse gas concentrations altering synoptic pressure patterns, natural climate variability and land use change (IOCI 2002). There have been limited studies to date attributing the causes of decreased rainfall in the east although these studies cite similar drivers of change (e.g. Cai and Cowan 2008). The reductions in rainfall and increases in temperature in south-eastern and south-western Australia have resulted in significant reductions in river flows. For example, the inflow into the Murray Catchment in the last two years is the lowest on record, half the previous minimum (MDBC 2008).

Extreme rainfall events have also changed in some regions with heavy rainfall increasing in north-western and central Australia and over the western tablelands of New South Wales (NSW), but decreasing in the southeast, southwest and central east-coast (Hennessy et al. 2007).

Climate: what further changes may occur

Projections of climate changes are made using a suite of Global Circulation Models (GCMs). These model energy and mass transfers, biogeochemistry and atmospheric chemistry and other processes in the oceans, land and atmosphere. The GCMs are in turn driven by a range of scenarios of human development, technology and environmental governance (IPCC 2007a). There is substantial variance between these GCMs in their capacity to represent past climate and in their response to future emissions scenarios. There are also differences between different climate variables and scales: with more reliable projections of temperature than rainfall and at global scales than regional or local scales (Giorgi 2005). Changes in average climate will be superimposed on large daily, seasonal and yearly variability, leading to significant changes in extreme events. The climatic anomalies of an individual year will be determined by a combination of natural variability and climate change (Hennessy et al. 2008). Consequently attribution of any particular event to climate change is not possible. Furthermore, the emissions scenarios have markedly different characteristics in terms of emissions and their timing with the range of CO_2 concentrations in 2100 ranging from about 550ppm to 1000ppm. Even this range may be an underestimation of the possible future concentrations as emissions over the past decade have been at or above the highest rate considered in current scenarios – and consequently CO_2 concentrations, global temperature increase and sea level rise have also been at or above the highest scenario rates (Rahmstorf et al. 2007). Importantly, the uncertainties of the emissions and of the GCMs combine to give large projected ranges (or uncertainty) in future temperature and other climate variables (Fig. 1) and these interact with other uncertainties when analysing future farming systems impacts including uncertainty as to the impacts of such changes and the effectiveness of adaptations to those impacts. Up to the year 2030, the largest component of the global climate uncertainty is due to differences between the results of the climate models rather than the different emission scenarios. Beyond 2040 the emission scenarios become more important in terms of the total uncertainty (Hennessy et al. 2008).

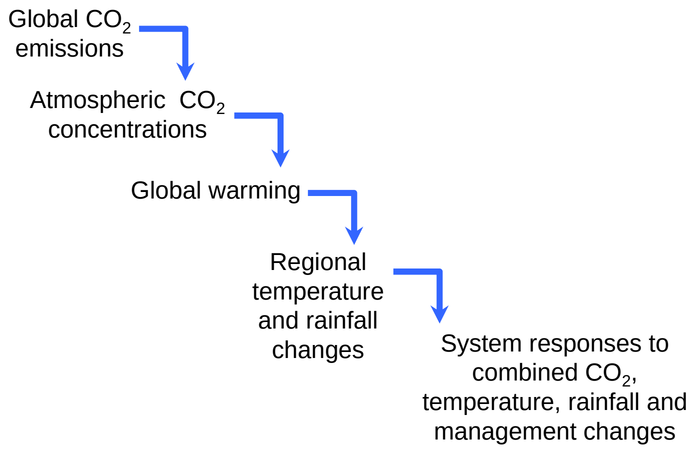

Figure 1. The ‘cascade of uncertainty’ associated with projections of how farming systems may change. Each step has significant uncertainties which combine to provide an overall uncertainty.

The climate projections derived from the GCMs and emissions scenarios suggests that average Australian temperatures will increase by 0.1 to 1.3°C by the year 2020, relative to 1990, 0.3 to 3.4°C by 2050 and 0.4 to 6.7°C by 2080. This translates to 1 to 32 more days/year over 35°C by 2020 and 3 to 84 more by 2050, with 1 to 16 fewer days/year below 0°C by 2020 and 2 to 32 fewer by 2050. By 2030, the mean area of Australia experiencing exceptionally hot years is likely to increase to 60-80%, with a low scenario of 40-60% and a high scenario of 80-95% (Hennessy et al. 2008). This compares with the historical expectation of 5%.

The climate projections show a tendency for decreased annual rainfall over most of southern, eastern Australia (Table 1) and south-west Australia (Table 2) , with a tendency for increases in Tasmania and the ‘Top End’ of the Northern Territory (Hennessy et al. 2007). The projected rainfall changes in the main farming zones vary substantially between seasons with decreases particularly likely in winter and spring and with a low likelihood of increases in rainfall in these seasons. Whilst some of the rainfall decreases do not seem large (e.g. 10%), in a location like Birchip in Victoria, such reductions would result in a doubling of the frequency of ‘exceptional’ droughts, a halving of the frequency of high rainfall years and the rainfall historically experienced in half of all years would be experienced in only 38% of years. However, it is important to note the large range of possible rainfall changes that may occur in the future, including both potential increases and declines (Table 1).

Table 1. Ranges in projected changes in rainfall across the crop growing regions of eastern Australia for 2030. Changes are expressed as proportional change (%) in the 10th, 50th (median) and 90th percentiles. For example, the 10th percentile values are the percent reductions in rainfall that are exceeded in all but 10% of the scenarios of change. The rainfall changes below reflect both the uncertainty due to the emissions scenarios as well as uncertainty from variation in projected climate changes from global climate models (CSIRO 2007).

	10th percentile	50th percentile	90th percentile
Winter	-10 to -20	-2 to -10	+2 to +5
Spring	-10 to -20	-5 to-10	+2 to +5
Summer	-5 to -20	-2 to +2	+5 to +20
Autumn	-10 to -20	-5 to +2	+5 to +10
Annual	-5 to -20	-2 to -5	+2 to +5

Table 2. Ranges in projected changes in rainfall (%) across the crop growing regions of south-western Western Australia. Changes are expressed as with Table 1.

	10th percentile	50th percentile	90th percentile
Winter	-10 to -20	-5 to -10	+2 to +2
Spring	-20 to -40	-5 to-20	-5 to +5
Summer	-5 to -20	-5 to -2	+5 to +10
Autumn	-10 to -20	-5 to -2	+5 to +10
Annual	-10 to -20	-2 to -10	-2 to +5

Increases in extreme daily rainfall seem likely. For example, the intensity of the 1-in-20 year daily-rainfall event is likely to increase by up to 10% in parts of South Australia by the year 2030, 5 to 70% by the year 2050 in Victoria, up to 25% in northern Queensland by 2050 and up to 30% by the year 2040 in south-east Queensland (Hennessy et al. 2007).

The dams and groundwater resources which supply the water used in irrigated agriculture in Australia are likely to be substantially affected by climate change. For example, annual water availability in the Murray-Darling Basin could change significantly by 2030 with possible substantial decreases (26 to 45% reductions depending on catchment) to increases (up to 19% in one catchment; Table 3). The median scenarios however, all indicate reductions. There is a tendency for more negative scenarios with the transition from the more northern catchments to the southern. In the case of the southern catchments like the Goulburn Broken, there has already been a 15% reduction in rainfall and a 45% reduction in water availability over the past decade (CSIRO 2008). There may also be reductions in water quality via increases in salt concentrations (Beare and Heaney 2002).

The frequency of severe tropical cyclones (Categories 3, 4 and 5) on the east Australian coast is projected to increase by 22% for the mid-range greenhouse gas emission scenarios from 2000-2050, with a 200 km southward shift in the cyclone genesis region, leading to greater exposure in southeast Queensland and northeast NSW (Abbs et al. 2007).

Table 3. Catchments in the Murray-Darling Basin and the prospective changes in water availability under 'dry', median and 'wet' scenarios for 2030 (see CSIRO 2008 for definitions)

	Climate change (dry)	Climate change (median)	Climate change (wet)
Condamine-Ballonne	-26	-8	+19
Lachlan	-30	-11	+6
Goulburn-Broken	-45	-14	-3
Murray	-41	-14	+7

Potential evaporation (or evaporative demand) is likely to increase with climate change (CSIRO 2007 and see below) and this combined with anticipated reductions in rainfall suggest significant increasing drought risk over most of Australia (Hennessy et al. 2008). For mid-range scenarios, what are considered 'exceptional' droughts on the basis of historical climate (the driest 5% of years) will occur more frequently in the SW, SWWA, Victorian and Tasmanian regions for 2030, with little detectable change in the other regions. Under the high emissions scenario in all regions such droughts would occur about twice as often (at least four times as often in SWWA) and over double the areas (quadruple the area in SWWA; Hennessy et al. 2008).The effects of climate change on drought frequency are likely to be modulated by phases of the El Niño system and the Indian Ocean Dipole in the future as they have been in the past (IPCC 2007a) making attribution of any individual drought to climate change difficult.

Potential evaporation is a key factor for both dryland and irrigated agriculture as it strongly influences yields in many situations. There has been some debate as to how potential evaporation may change in the future and the methods appropriate to evaluating this (Gifford et al. 2005). To examine this issue we explore changes in potential evaporation as calculated using the well-established Penman-Monteith equation (Allen 1998) for three sites across the cropping zones Emerald (Qld), Birchip (Vic.) and Kellerberrin (WA). This is applied to either daily GCM (CSIRO Mk3.5) output for each site or to historical climate where the minimum and maximum temperature are increased by the same amount as the changes in the GCM runs following the method of Reyenga et al. (2000). The increase in potential evaporation was calculated to be consistently higher (30 to 50%) using the GCM output (Table 4). Inspection of the results showed that this difference was driven by not just a change in the mean temperature in the GCM output but a change in the temperature distribution (increased variance) with the increasing frequency of very hot days disproportionately increasing potential evaporation. This effect has also been found in assessments of urban water demand under climate change (Howden and Crimp 2008).

Impacts of climate and atmospheric change

The section above outlines the likely changes in atmospheric and climatic conditions that may occur over the next decades. It also identifies the large range of uncertainty inherent in these and consequently in the implications for Australian farming systems. One approach to such situations is to deal with hierarchies of uncertainty. In this case, increases in atmospheric CO_2 levels are the most certain, followed by temperature increases and then rainfall change (IPCC 2007a). The impacts of these are outlined below. This is followed by their possible interactions with a focus on wheat systems, which is the most important crop and also the most studied in terms of climate change issues. We follow this with some comment on two additional impact areas: pests and diseases and degradation

Table 4. Increases (%) in mean annual potential evaporation (Penman-Monteith; Allen 1998) for Emerald (Qld), Birchip (Vic.) and Kellerberrin (WA) for 2030 and 2050 calculated from GCM output (CSIRO Mk 3.5) or from perturbing the historical climate records by the same mean change in maximum and minimum temperatures as found in the GCM output.

	2030		2050	
	GCM output	Modified historical	GCM output	Modified historical
Emerald	7.8	5.2	9.5	7.2
Birchip	8.6	5.7	10.3	7.3
Kellerberrin	7.9	6.0	9.4	7.4

CO_2 increase

Carbon dioxide has long been known to affect 1) photosynthetic rates through impacts on the efficiency of rubisco and 2) water use through changes in stomatal conductance leading to enhanced growth in most circumstances (e.g. Morison and Gifford 1984). Expression of these CO_2 responses is dependent on other variables such as temperature, soil moisture and soil nutrient availability, especially nitrogen. In a pioneering study, Gifford (1979) assessed the impact of increased (250ppm above ambient) CO_2 on wheat growth and yield under a range of levels of water stress. High relative impacts of CO_2 were found in the stressed treatments. For example, under well-watered conditions (about 380mm transpiration over the crop cycle) higher CO_2 increased yield by about 35% compared with the ambient CO_2 treatment. Under successively drier conditions (230mm and 160mm transpiration) whilst absolute yields decreased, the relative response to elevated CO_2 increased to about 50 and 80% whilst under extremely arid conditions (100-120mm transpiration) grain growth occurred under high CO_2 whereas none occurred with ambient levels. Consequently he suggested that there may be a strong impact of increases in atmospheric CO_2 on national yields as much of the Australian crop is grown under water-limited conditions. Further Australian glasshouse experimental work on wheat and other crops (e.g. Samarakoon and Gifford 1995) and simulation models (e.g. Wang et al. 1992, Crimp et al., 2008b) suggest a doubling of current CO_2 levels will increase national wheat yield from 5 to 43% for wet to dry conditions respectively. These relative increases are consistent with results from the Arizona FACE wheat experiment with 550ppm CO_2 increasing yields by 8% and 20% in the wet and dry treatments respectively (Kimball et al. 1995). They are also consistent with a recent review of CO_2 effects (Tubiello et al. 2007) which estimated that wheat yields would increase by a mean of 21% at CO_2 concentration of 550ppm and by 30% at 700ppm when compared with a baseline of 370ppm (noting that many of these results were from well-watered experiments where lower relative CO_2 increases are expected). That review also assessed that the key cropping system models simulated yield increases to CO_2 that are consistent with these experimental results.

Elevated CO_2 tends to reduce grain protein content (e.g. Rogers et al. 1996) requiring increased attention to nutrient management through either fertiliser application or legume rotations (Howden et al. 2003b).

Temperature increase

In contrast to CO_2, which has little direct impact on developmental rates of wheat (Slafer and Rawson 1997), temperature increases will significantly affect these rates and hence yield. For varieties adapted to existing temperature regimes, higher temperatures will result in reduced yields, if all else remains equal, due to the reduced time for accumulation of solar radiation. For example, McKeon et al. (1988) suggested that a 2°C increase in temperature in Queensland would reduce wheat yields by 6% whilst Wang et al. (1992) suggested that a 3°C increase in temperature could reduce mean yields in Wagga Wagga and Mildura by up to 50% and in Horsham by 25 to 60% depending on cultivar. However, adaptation is likely to take place by selecting alternative varieties from the substantial existing pool. Varieties with greater thermal time requirements could be chosen that attempt to offset the increased temperatures (e.g. Howden 2002).

Increased temperature will tend to increase evapotranspiration and vapour pressure deficit, resulting in more rapid depletion of soil moisture in spring when the grain is filling and ripening. This will tend to reduce grain number, reduce harvest index, and in conditions of high soil nitrogen may result in 'haying off' and subsequent major reductions in effective yield (Stone and Nicholas 1995; van Herwaarden et al. 1998). For these reasons, Gifford et al. (1996) suggested that most Australian wheats would largely be self-adapting to global warming as a result of their low photoperiod sensitivity and weak vernalisation requirement allowing ripening earlier in more favourable conditions. This hypothesis was tested by Howden et al. (1999) who simulated wheat yields for varieties with three different thermal time requirements across ten sites in the Australian wheat belt. They found that for the current planting window, in most sites, cultivars similar to those used currently in each region had the greatest simulated yield for temperature increases up to 3.5°C. At greater temperature increases, longer-season cultivars started to yield more. In many cases, the differences between the yields of the standard variety and the longer season variety were small, supporting the suggestion of Wang et al. (1992) that a greater range of varieties may be used under conditions of temperature and CO_2 increase. Horsham was the only site which showed a significant advantage with adoption of long season varieties under small warming trends. In contrast, for the sites in South Australia and southern Western Australia, adoption of more rapidly maturing cultivars may provide an advantage if using the current planting window. This is related to the low water holding capacity of the light textured soils in these locations making the crop vulnerable to rapid drying out during grainfill. Very-early maturing cultivars have been used in the hot, dry margins of the Western Australian wheat belt to counter this effect (Regan et al. 1997). However, Howden et al. (1999) found that if the planting window was adjusted to take advantage of possible changes in frost occurrence with warmer conditions, in all sites there was advantage in adoption of longer season varieties even with small warming trends. Thus, adoption of varieties needs careful evaluation on a site-by-site basis, taking into account changes in both temperature and management.

Rainfall change

Rainfall is a key determinant of yields at both farm and national levels (e.g. French and Schultz 1984, Stephens and Lyons 1998a), with much of the variability in national crop production arising from variability in rainfall. This sensitivity to rainfall is expected to continue under global change, however, different climate change scenarios may have differential impacts.

In southern Australia, a Mediterranean climate prevails with most of the rain falling in the cooler six months. Consequently, wheat can be grown on light-textured soils with relatively low water holding capacity as well as in finer textured soils which store water from the previous winter fallow (French 1978). Recent climate change scenarios (e.g. CSIRO 2007) suggest considerable reductions in winter rainfall across this zone which is likely to translate into yield reductions, all else being equal. The sensitivity of yield to rainfall changes was assessed by Howden (2002) who found that in most sites there was high sensitivity to reductions in mean rainfall but slightly lower sensitivity to increases. This is consistent with observations of yield across years and regions with yields in high rainfall years being impacted variously by diseases, pests, waterlogging and nutrient leaching (e.g. Stephens and Lyons 1998a). Reductions in rainfall are also likely to favour light-textured soils rather than heavy soils with high clay content in these situations (van Ittersum et al. 2003) as small rainfall events contribute to soil water in the available range rather than below the lower limit.

In the more northerly cropping regions in Australia, wheat cropping is restricted to heavier-textured soils with high water holding capacity. Yield is highly sensitive to the amount of water stored in the soil over the summer rainfall period as well as to rainfall over the winter months (e.g. Meinke and Hochman 2000). As with southern Australia, yields are likely to be highly sensitive to reductions in mean rainfall but less so to increases (Howden et al. 1999). However, prospective increased rainfall intensity (CSIRO 2007) could increase already problematic rates of soil erosion leading to longer-term yield decline (Littleboy et al. 1992). McKeon et al. (1988) identified increased soil erosion rates from cropped lands as one of the key negative potential impacts of climate change in northern Australia.

The El Niño-Southern Oscillation system is a key source of variability in rainfall and wheat yield in Australia (Rimmington and Nicholls 1993). El Niño events are associated with reduced rainfall across much of Australia and are known to adversely affect crop production across eastern Australia (e.g. Hammer et al. 1996). La Niña events tend to have higher rainfall and hence higher yields but they may also result in greater incidence of waterlogging, crop spoilage and pest and disease problems. There is a developing view that climate change may result in the mean state of the Pacific becoming more El Niño-like with consequent impacts on eastern Australian rainfall (IPCC 2007a) but further improvement in ocean-atmosphere modelling is needed before confidence can be increased in such projections. One possible beneficial outcome from such changes in the frequency of El Niño/La Niña events is that this may assist crop management by increasing the frequency of years in which seasonal forecasting can be used to guide crop management provided that seasonal forecast capabilities themselves adjust to climate change (e.g. Gifford et al. 1996).

CO_2 by temperature by rainfall interaction

The previous sections dealt separately with the implications of CO_2 increase, temperature increase and rainfall change, however, the expectation is for these factors to change together in some combination. There have been a limited number of studies in Australia that have dealt with these factors in combination. All have been made with simulation models and new experimentation with FACE experiments at multiple sites will provide additional information. Some of these simulation studies have used specific climate change scenarios (e.g. Reyenga et al. 1999) whilst others have developed response surfaces which allow sensitivity analysis across the range of possible climate changes (Wang et al. 1992, Howden et al. 1999, 2002, Crimp et al. 2008b). This latter approach recognizes that climate change scenarios are undergoing continuing development and enables re-evaluation of likely impacts as scenarios change and as climate change unfolds. Generally, the positive impacts on yield of increases in CO_2 are balanced to some extent by the negative impacts of temperature increase. For example, Leuning et al. (1993) suggest that for Wagga, the reduction in length of the growing season from a 2°C increase in temperature effectively offsets the beneficial impacts of a doubling of CO_2 concentration. Similarly, Reyenga et al. (1999) found that for the Burnett region in south-east Queensland, the yield increases of 25-37% with doubling of CO_2 were reduced to 10 to 23% with a concurrent 2.8°C temperature increase. There remained sensitivity to rainfall changes with the 'wet' scenario (+12% rainfall in winter) largely offsetting the negative impacts of warming whilst the 'dry' scenario (summer rainfall –24% and winter rainfall by –12%) reducing yields to around current levels. There was considerable variation in response to variety and fertilizer regime in accord with experimental evidence. Howden (2002) found major variation in interactions between the climate variables with some sites in cool climes showing positive yield responses with small increases in temperatures but declines thereafter (e.g. Minippa, Wongan Hills and Katanning), others with relatively consistent yield declines with increasing temperature (e.g. Moree, Emerald, Dalby, Geraldton) and others with temperature response dependent on rainfall changes (Dubbo, Wagga, Horsham). In a similar study in a NSW site, Crimp et al. (2008b) found that temperature increases had negative impacts on growth of approximately 2% per degree of warming when no adaptation was included but a more complex response when simple agronomic adaptations were simulated (Fig 2). The maximum yield response (42%) was achieved at the +20% rainfall with no change in temperature while the lowest (-51%) occurred in the –30% rainfall and 4°C temperature scenario. Based on the CSIRO 2007 median climate change for 2050 (i.e. 550 ppm, 2 to 2.5° and -2 to -5% rainfall change), wheat yields at this site may change between 7% to 11%.

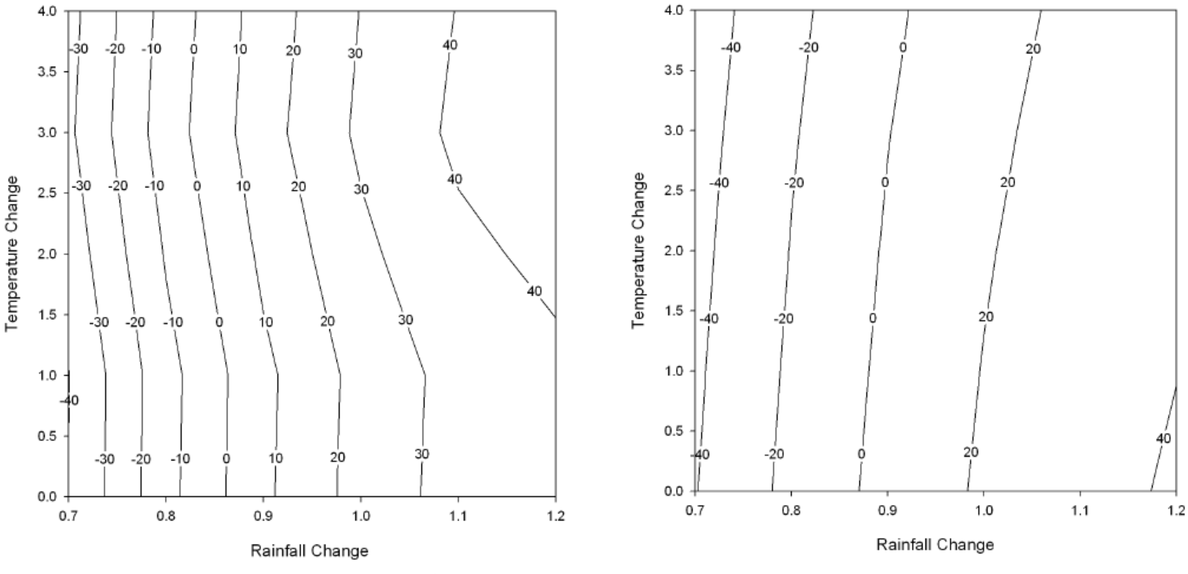

Figure 2. – Yield response (% change from baseline) of wheat at Coolamon, NSW to 650 ppm CO_2 and a range of climate change scenarios with (a) current planting window b) modified planting window; cultivar choice varied in both cases.

Pests, diseases and weeds
The potential effects of climate change on diseases of Australian wheat crops has been reviewed by Chakraborty et al. (1998). The development of stripe rust (*Puccinia striiformis*) is highly sensitive to temperature increasing with warmer temperatures up to 16° then declining with further warming. The amount of stripe rust and yield losses is dependent on temperature during grain filling such that a temperature rise may increase the amount of stripe rust but not necessarily mean additional yield losses. Current climate change scenarios suggest the changes in impact of this rust will vary regionally, with management and with cultivar. There is likely to be an ongoing need to manage this disease regardless of climate change scenario. Take-all (*Gaeumannomyces graminis*) is a fungal disease which can cause major crop losses when there are extended periods of high soil moisture. Its severity may be reduced if there is an increase in rainfall variability and drier winters as suggested by recent climate change scenarios for southern Australia (CSIRO 2007). Septoria blotch (*Septoria tritici*) incidence is affected by sowing time and rainfall at heading. The current scenarios of reduced rainfall over southern Australia (less severe infection) but increased temperature (more severe infection) result in an uncertain outcome. Viral diseases such as Barley Yellow Dwarf which rely on transfer by aphids may increase with warmer winter temperatures with potential additional risks via the positive effects of CO_2 concentration on aphid populations (e.g. Newman et al. 2003). Climate change may also affect the balance between soil-based pathogens like *Fusarium graminearum* and their antagonists such as *Trichoderma* but again, outcomes are uncertain.

Some experiments indicate that climate change and increases in atmospheric CO_2 may increase insect damage. This can occur as a result of compensatory feeding when elevated CO_2 reduces leaf nitrogen concentrations (i.e. the insect has to eat more to maintain nitrogen intake; Lincoln *et al.* 1986). In other cases, increased CO_2 results in increased concentrations of plant defensive compounds such as condensed tannins and this plus lowered nitrogen concentrations with elevated CO_2 can reduce insect herbivore weight gains, increase mortality and lower fecundity (e.g. Gao *et al.* 2008). The situation with Australian crops is currently uncertain.

There are concerns that a range of weed species (especially summer-growing C_4 weeds) will increase their competitive advantage under elevated CO_2 and higher temperatures (e.g. IPCC 2007b). This may become even more problematic with 1) emerging evidence that the widely-used herbicide glyphosate could become less effective under elevated CO_2 (Ziska et al. 1999) and 2) that the number of days suitable for spraying operations could reduce significantly (Fig 3: Howden *et al.* 2007a).

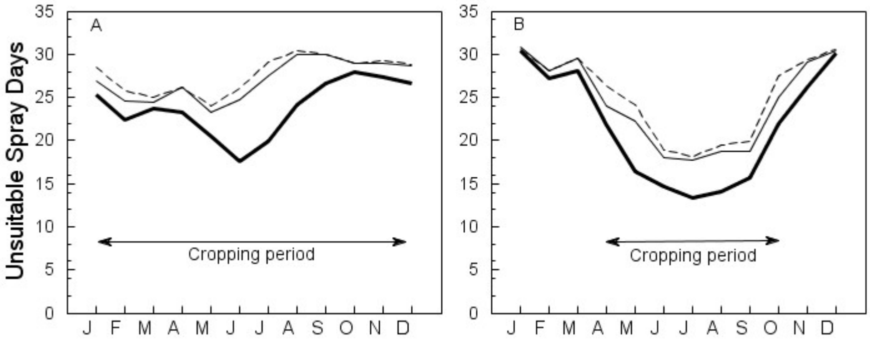

Figure 3. Frequency of days per month unsuitable for spraying due to either unfavourable Delta T or wind conditions for a) Emerald, Queensland and b) Kellerberrin, Western Australia for the historical baseline (solid bold line), 2030 (solid thin line) and for 2070 (dotted line) for the A2 emissions scenario (Howden et al. 2007).

Degradation processes
Soil degradation processes such as erosion and salinisation are strongly linked to climate. The projected increases in rainfall intensity (e.g. CSIRO 2007) are likely to increase the rate of soil erosion (McKeon et al. 1988, 2004). This may be exacerbated if the projected reductions in mean rainfall and increases in dry spell length eventuate as these are likely to reduce ground cover, increasing erosion risk. Dryland salinisation risk may be increased by increasing CO_2 levels due slightly reduced water use but if rainfall declines significantly, this effect is likely to be over-ridden and the risk may be decreased (van Ittersum et al. 2003) although there are likely to be significant lags in the response. The interaction of climate change and salinity

risk is a research area that needs addressing. Warming will also serve to enhance loss of soil carbon, possibly making some soils more susceptible to degradation.

Adaptation

The anticipated changes in atmospheric and climatic factors outlined in this paper and the potential substantial impacts will engender substantial adaptation responses from individual farmers, from industry and from government. Adaptation here refers to the actions of adjusting practices, processes and capital in response to the actuality or threat of climate change, as well as responses in the decision environment, such as changes in social and institutional structures or altered technical options that can affect the potential or capacity for these actions to be realized (Howden et al. 2007b). There is a general view that farmers and farming systems in Australia are highly adaptive, developing management, technologies and other responses to a range of challenges and opportunities. Often, these have been in the face of fairly well-defined, single factors such as changes in relative price of inputs or outputs, market access or change in consumer preference. In contrast, as indicated in the previous sections of this paper, climate change is, in many respects, highly uncertain in both the nature and degree of the change and has multiple, related dimensions. These are not only through potential climate changes (and hence productivity) at local, regional and global scales, but also through the emerging carbon economy and associated input prices and potential new products such as carbon storage and additionally through its impacts on global food security (Keating et al. 2008). How do Australian farmers, farming systems, cropping industries and governments adapt in the face of such uncertainty?

The following is a suggested approach to start dealing with this uncertainty, building adaptive capacity and changing the decision environment to promote adaptation actions (Howden et al. 2007b):

1. To change their management, enterprise managers need to be convinced that projected climate changes are real and are likely to continue. This is more likely to occur if existing trends in climate are consistent with projected changes in climate and where the underlying processes are well understood and communicated. For example, in central Queensland, this applies to the increases in minimum temperatures and reductions in frost risk, leading to rapid adoption of more flexible and productive planting regimes (Howden et al. 2003a). A corollary of this approach is that assessment of climate risk and opportunity should no longer be based on the past 100 years of climate records but rather those of the recent past *and* projections of climate in the medium term (i.e. 2030) which will need to account for decadal variability as well (McKeon et al. 2004). This adaptation element will be facilitated by policies that maintain climate monitoring and communicate this information effectively.
2. Managers need to be confident that the projected changes will significantly impact on their enterprise and that they understand the range of consequences of different adaptation options singly and in combination. Policies that support the research, systems analysis, extension capacity, industry and regional networks that provide this information could thus be strengthened. This includes modelling capabilities such as APSIM (Keating et al. 2003) that allow scaling up knowledge, for example from gene to cell to organisms and eventually to management systems and national policy-scales. Managers and policymakers also need to understand the limitations of adaptations so that they do not underestimate potential vulnerability. For example, when summarized across many adaptation studies, there is a tendency for most of the benefits of adapting existing cropping systems to be gained under moderate warming ($<2^{o}$C) then to level off with increasing temperature changes (Howden et al. 2007b). Additionally, the yield benefits tend to be greater under scenarios of increased rainfall than those with decreased rainfall.
3. The technical and other options necessary to respond to the projected changes need to be available. In many cases these will be extensions or intensifications of existing climate risk management or production enhancement activities in response to a potential change in the climate risk profile (e.g. Table 5). Where the existing technical options are inadequate, investment in new technical or management strategies may be required such as developing improved crop germplasm that is more suited to expected atmospheric and climatic conditions. One example is in developing varieties that are more responsive to elevated atmospheric CO_2 (the most certain aspect of this set of issues) where there can be large improvements in response but where the few published studies indicate that recent varieties of wheat (Mayeux et al. 2003; Ziska et al. 2004) and oats (Ziska and Blumenthal 2007) are *less responsive* than older varieties. Another example is upgrading climate forecasts in terms of

reliability, lead-times and utility so as to allow year-by-year adaptation to a changing climate as first proposed by McKeon et al. (1993)

4. Where climate impacts may lead to major land use change, there may be demands to support transitions such as industry adjustment and enterprise relocation. This may be achieved through direct financial and material support, creating alternative livelihood options with reduced dependence on agriculture, supporting community partnerships such as Landcare, enhancing capacity to develop social capital and share information and re-training. Effective planning for and management of such transitions may result in less habitat loss, less risk of carbon loss and also lower environmental costs compared to unmanaged, ex-post transitions. For example, the existing Australia's Farming Future program (www.daff.gov.au/agriculture-food/australias-farming-future) has an element that addresses some of these points. New approaches to assessing adaptive capacity and how to improve this have been developed for national to local levels and these could help inform adjustment programs (e.g. Nelson et al. 2005).
5. New infrastructure, policies and institutions could be developed to support changes in management and land and water use arrangements. Options include addressing climate change in terms of sustainable development and natural resource management such as the Caring for our Country program; enhancing investment in irrigation infrastructure and efficient water use technologies; encouraging appropriate transport and storage infrastructure; and establishing more efficient markets for products and inputs. Adaptation options that may be more difficult to implement will likely include those that i) deal with lag effects, ii) involve significant trade-offs involving other parties, iii) impact on social welfare issues and policies, iv) deal with climate extremes that by their nature are infrequent but which may require substantial up-front investment.
6. Importantly, farmers and policymakers in industry and government must maintain the capacity to make continuing adjustments and improvements in adaptation by "learning by doing" via targeted monitoring of adaptations to climate change and their costs, benefits and effects. A participatory approach that cycles systematically between the biophysical and the socio-economic aspects is likely to most effectively harness the substantial scientific knowledge of many agricultural systems, while retaining a focus on the values important to stakeholders: achieving relevance, credibility and legitimacy (Howden et al. 2007b). The inclusion of an adaptive loop in such frameworks is critical to develop flexible, dynamic policy and management that can accommodate climate surprises or changes in the underlying knowledge base. Participatory engagement with decision-makers can, by bringing their practical knowledge into the assessment, also identify a more comprehensive range of adaptations than are typically explored by scientists, as well as being able to assess the practicality of options and contribute to more realistic assessment of the costs and benefits involved in management or policy change (Crimp et al. 2008a).

Finally, it should be recognised that 'adaptation' is an ongoing process that is part of good risk management, whereby drivers of risk are identified and their likely impacts on systems under alternative management are assessed. In this respect, adaptation to climate change is similar to adaptation to climate variability, changes in market forces (cost/price ratios, consumer demands etc), institutional or other factors. Isolating climate change from other drivers of risk may be helpful, especially during the initial stages of assessment when awareness of the relative importance of this risk factor is still low. Operationally however, translating adaptation options into adaptation actions requires consideration of a more comprehensive risk management framework. This would allow exploration of quantified scenarios dealing with all the key sources of risk, providing more effective decision-making and learning for farmers, policymakers and researchers: an increase in the 'climate knowledge' (Howden et al. 2007b).

Conclusion

The climate and atmospheric changes that could impact on Australia over the next decades are substantial but key aspects of these are highly uncertain such as rainfall change. Positive impacts may arise from increases in CO_2, reduced frost risk and possible increases in summer rainfall in the north of Australia. However, these are likely to be outweighed by negative impacts from likely reduced rainfall particularly in southern Australia, higher temperatures and a range of possible secondary and tertiary impacts. We describe a set of adaptation responses to manage this uncertainty. These include a range of farm level management responses and several policy options focussed on information, technological and institutional changes that could better support effective adaptation. Enhancing existing climate risk management is likely to be a key part of this adaptation response but this needs to be broadened out into a more comprehensive risk management framework, implemented in a participatory way so as to move from adaptation analysis to adaptation action. Australia’s agronomists will have a key role in achieving this goal.

Table 5. A subset of the adaptation options available to adapt farming systems to climate changes (Stokes and Howden 2008).

- Altering inputs such as varieties/species to those with more appropriate thermal time and vernalization requirements and/or with increased resistance to heat shock and drought, increased responsiveness to CO_2, altering fertilizer rates to maintain grain quality consistent with the prevailing climate, altering amounts and timing of irrigation and other water management
- Wider use of technologies to ‘harvest’ water, conserve soil moisture (e.g. crop residue retention) and to use and transport water more effectively where rainfall decreases
- Water management to prevent water logging, erosion and nutrient leaching where rainfall increases
- Altering the timing or location of cropping activities
- Diversifying income through altering the integration with other farming activities such as livestock raising
- Improving the effectiveness of pest, disease and weed management practices through wider use of integrated pest and pathogen management, development and use of varieties and species resistant to pests and diseases and maintaining or improving quarantine capabilities and monitoring programs
- Developing improved climate forecasting and its use to reduce production risk

Acknowledgements

We would like to thank Drs Peter Hayman, Anthony Whitbread and Uday Nidumolu for their helpful review which significantly improved the manuscript.

References

Abbs DJ, Timbal B, Rafter AS and Walsh KJE (2007). Severe weather. In ‘Climate change in Australia: technical report 2007’. Eds KB Pearce, PN Holper, M Hopkins, WJ Bouma, PH Whetton, KJ Hennessy, SB Power pp 102-106. (CSIRO Marine and Atmospheric Research: Aspendale)

Alexander L, Hope P, Collins D, Trewin B, Lynch A and Nicholls N (2007). Trends in Australia's climate means and extremes, a global context. Australian Meteorological Magazine 56, 1–18.

Beare S and Heaney A (2002). Climate change and water resources in the Murray Darling Basin, Australia. impacts and adaptation. ‘Proceedings of the World Congress of Environmental and Resource Economists, Monterey, California. www.abarepublications.com/product.asp?prodid=12389 (verified 13 January 2008).

Cai W and Cowan T (2008). Dynamics of late autumn rainfall reduction over southeastern Australia. Geophys. Res. Letters 35, doi:10.1029/2008GL033727.

Chakraborty S, Murray GM, Magarey PA, Yonow T, O’Brien RG, Croft BJ, Barbetti MJ, Sivasithamparam K, Old KM, Dudzinski MJ, Sutherst RJ, Penrose LJ, Archer C and Emmett RW (1998). Potential impacts of climate change on plant diseases of economic significance to Australia. Australasian Plant Pathology, 27, 15-35.

Crimp S, Nidumolu U, Gaydon D, Howden S and Hayman P (2008a). Examining the value of dynamic seasonal forecasts in managing farm-level production and environmental outcomes in a variable climate. Australian Agronomy Conference Proceedings (this volume).

Crimp S, Howden M, Power B, Wang E and De Voil P (2008b). Global Climate Change impacts on Australia’s Wheat Crops. Report for the Garnaut Climate Change Review Secretariat, pp20.

CSIRO (2007) Climate Change in Australia. Technical Report 2007. Eds KB Pearce, PN Holper, M Hopkins, WJ Bouma, PH Whetton, KJ Hennessy, SB Power) pp 148. (CSIRO Marine and Atmospheric Research: Aspendale).

CSIRO (2007) Climate Change in Australia. Technical Report 2007. Eds KB Pearce, PN Holper, M Hopkins, WJ Bouma, PH Whetton, KJ Hennessy, SB Power pp 148 (CSIRO Marine and Atmospheric Research: Aspendale).

CSIRO (2008). CSIRO Murray-Darling Basin Sustainable Yields Project – a report to the Australian Government. www.csiro.au/partnerships/MDBSY.html

French RJ (1978). The effect of fallowing on the yield of wheat. I. The effect of soil water storage and nitrate supply. Australian Journal of Agricultural Research. 29:653-668.

French, R.J. and Schultz, J.E. (1984). Water use efficiency of wheat in a Mediterranean environment. I. The relation between yield, water use and climate. Australian Journal of Agricultural Research. 35: 743-764.

Gao F, Zhu SR, Sun YC, Du L, Parajulee M, Kang L and Ge F (2008). Interactive effects of elevated CO2 and cotton cultivar on tri-trophic interaction of *Gossypium hirsutum*, *Aphis gossyppii,* and *Propylaea japonica.* Environ Entomol. 37:29-37.

Gifford RM (1979). Growth and yield of CO_2-enriched wheat under water-limited conditions. Australian Journal of Plant Physiology 6: 367-378.

Gifford RM, Campbell B and Howden SM (1996). Options for adapting agriculture to climate change: Australian and New Zealand examples. In: Eds W.J. Bouma, G.I. Pearman, M.R. Manning, Greenhouse: coping with climate change. CSIRO Australia pp 399-416.

Gifford RM Farquhar GD Roderick ML and Nicholls N (2005).Workshop summary on pan evaporation: an example of the detection and attribution of climate change variables. http://www.science.org.au/natcoms/pan-evap.pdf

Giorgi F (2005). Interdecadal variability of regional climate change: implications for the development of regional climate change scenarios. Meteorol. Atmos. Phys. 89:1–15.

Hennessy K, Fitzharris B, Bates BC, Harvey N, Howden SM, Hughes L, Salinger J and Warrick R (2007). Australia and New Zealand. In 'Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change'. Eds ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson) pp 507–540. (Cambridge University Press: Cambridge, UK).

Hennessy KJ, Fawcett R, Kirono D, Mpelasoka F, Jones D, Bathols J, Whetton P, Stafford Smith M, Howden M, Mitchell C and Plummer N (2008). An assessment of the impact of climate change on the nature and frequency of exceptional climatic events. CSIRO and the Australian Bureau of Meteorology, Melbourne pp 31.www.bom.gov.au/climate/droughtec/

Howden SM (2002). Potential global change impacts on Australia's wheat cropping systems. In: Eds OC Doering, JC Randolph, J Southworth and RA Pfeifer, Effects of climate change and variability on agricultural production systems. Kluwer Academic Publications, pp 219-247.

Howden SM and Crimp SJ (2008). Drought and high temperature extremes: effects on water demand and electricity demands. pp 227-244 In Newton, P. W. (ed) Transitions: Pathways Towards Sustainable Urban Development in Australia. CSIRO Publishing, Collingwood, Australia. pp 891.

Howden SM, Crimp SJ and Sayer C (2007a). The effect of climate change and spraying opportunities: a risk assessment and options for adaptation. In Eds Donatelli M, Hatfield J, Rizzoli A Farming systems design. Proceedings of the International Symposium on methodologies for integrated assessment of farm production systems. Catania, Italy, September 2007. pp 197-198.

Howden SM, Meinke H, Power B and McKeon GM (2003a). Risk management of wheat in a non-stationary climate: frost in Central Queensland. In: Eds D.A. Post, Integrative modelling of biophysical, social and economic systems for resource management solutions. MSSANZ Inc., Canberra, Australia. Pp 17-22.

Howden SM, Reyenga PJ and Meinke H (1999). Global change impacts on Australian wheat cropping. Report to the Australian Greenhouse Office. CSIRO Wildlife and Ecology, Working Paper 99/04, Canberra. pp 121.

Howden SM, Reyenga PJ and Meinke H (2003b). Managing the quality of wheat grain under global change. In: Ed D.A. Post *Integrative modelling of biophysical, social and economic systems for resource management solutions*. MSSANZ Inc., Canberra, Australia. pp 35-41.

Howden SM, Soussana JF, Tubiello FN, Chhetri N, Dunlop M and Meinke HM (2007b). Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences*, 104: 19691-19696.

IOCI (2002). Indian Ocean Climate Initiative: Climate variability and change in south west Western Australia. (Indian Ocean Climate Initiative Panel, Department of Environment, Water and Catchment Protection, Perth). www.ioci.org.au/publications/reports.html

IPCC (2007a). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Eds S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor, HL Miller, Cambridge University Press: Cambridge.

IPCC (2007b). Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Eds ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson, Cambridge University Press: Cambridge.

Karoly DJ and Braganza K (2005). Attribution of recent temperature changes in the Australian region. Journal of Climate 18: 457–464.

Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JNG, Meinke H, Hochman Z, McLean G, Verburg K, Snow V, Dimes JP, Silburn M, Wang E, Brown S, Bristow KL Asseng S, Chapman S, McCown RL, Freebairn D and Smith CJ (2003). An overview of APSIM, a model designed for farming systems simulation. European Journal of Agronomy 18, 267-288.

Keating, B.A. and Carberry, P.S. (2008) Emerging opportunities for Australian agriculture? Proceedings of the 14th Australian Society of Agronomy Conference (this volume).

Kerr NJ, Siddique KHM and Delane RJ (1992). Early sowing with wheat cultivars of suitable maturity increases grain yields of spring wheat in a short season environment. Australian Journal of Agricultural Research 32: 717-723.

Kimball BA, Pinter PJ, Garcia RL, La Morte RL, Wall GW, Hunsaker DJ, Wechsung G, Wechsung F and Kartschall T (1995). Productivity and water use of wheat under free-air CO_2 enrichment. Global Change Biology, 1: 429-442.

Leuning R, Wang YP, de Pury D, Denmead OT, Dunin FX, Condon AG, Nonhebel S and Goudriaan J (1993). Growth and water use of wheat under present and future levels of CO_2. J. Agr. Met. 48: 807-810.

Lincoln DE, Couvet D and Sionit N. (1986). Response of an insect herbivore to host plants grown in carbon dioxide enriched atmospheres. Oecologia 69: 556-560.

Littleboy M, Freebairn DM, Hammer GL and Silburn DM (1992). Impact of soil erosion on production in cropping systems. II Simulation of production and erosion risks for a wheat cropping system. Australian Journal of Soil Research. 30: 775-788.

Mayeux H, Johnson H, Polley W and Malone S (2003). Yield of wheat across a subambient carbon dioxide gradient. Global Change Biology, 3: 269 – 278.

McKeon G, Hall W, Henry B, Stone G and Watson I (2004). Pasture degradation and recovery in Australia's rangelands: learning from history. Queensland Department of Natural Resources, Mines and Energy: Brisbane.

McKeon GM, Howden SM, Abel NOJ and King JM (1993). Climate change: adapting tropical and subtropical grasslands. In 'Proceedings of the XVII Int. Grasslands Congress' International Grasslands Congress: Palmerston North pp 1181-1190.

McKeon GM, Howden SM, Silburn DM, Carter JO, Clewett JF, Hammer GL, Johnston PW, Lloyd PL, Mott JJ, Walker B, Weston EJ and Wilcocks JR (1988). The effect of climate change on crop and pastoral production in Queensland. In: Ed GI Pearman, Greenhouse: planning for climate change. CSIRO, Melbourne, Australia. pp. 546-563.

MDBC (2008) Drought Updates. http://www.mdbc.gov.au/rmw/drought_updates

Meinke H and Hochman Z (2000). Using seasonal climate forecasts to manage dryland crops in northern Australia – experiences from the 1997/98 seasons. In: Eds GL Hammer, N Nicholls and C. Mitchell. Applications of seasonal climate forecasting in agriculture and natural ecosystems – the Australian experience. Kluwer, 2000, pp 149-165.

Morison, J.I.L. and Gifford, R.M. (1984). Plant growth and water use with limited water supply in high CO2 concentrations. II. Plant dry weight, partitioning and water use efficiency. Australian Journal of Plant Physiology, 11: 375-384.

Nelson R, Kokic P, Elliston L, King JA (2005) Structural adjustment: a vulnerability index for Australian broadacre agriculture. Australian Commodities 12 171-179.

Newman JA, Gibson DJ, Parsons AJ and Thornley JHM (2003). How predictable are aphid population responses to elevated CO_2? Journal of Animal Ecology, 72: 556 – 566.

Nicholls N (2004). The changing nature of Australian droughts. Climatic Change, 63:323-336.

Nicholls N (2006). Detecting and attributing Australian climate change: a review. Australian Meteorological Magazine 55: 199–211.

Petit JR, Jouzel J, Raynaud D, Barkov NI and Barnola JM (2000). Climate and atmospheric history of the past 420 000 years from the Vostok ice core, Antarctica. Nature, 399: 429-436.

Rahmstorf S, Cazenave A, Church JA, Hansen JE, Keeling RF, Parker DE and Somerville RCJ (2007). Recent Climate Observations Compared to Projections. Science 316: 709.

Regan KL, Siddique KHM, Tennant D and Abrecht DG (1997). Grain yield and water use efficiency of early maturing wheat in low rainfall Mediterranean environments. Australian Journal of Agricultural Research 48: 595-603.

Reyenga PJ, Howden SM, Meinke H and McKeon GM (1999). Modelling global change impacts on wheat cropping in south-east Queensland, Australia. Environmental Modelling and Software, 14: 297-306.

Rimmington, G.M. and Nicholls, N. (1993). Forecasting wheat yields in Australia with the Southern Oscillation Index, Australian Journal of Agricultural Research, 44(4): 625-632.

Rogers GS, Milham PJ, Gillings M and Conroy JP (1996). Sink strength may be the key to growth and nitrogen response in N-deficient wheat at elevated CO_2. Australian Journal of Plant Physiology, 23: 253-264.

Samarakoon AB and Gifford RM (1995). Soil water content under plants at elevated CO2 and interactions with the direct CO2 effects: a species comparison. Journal of Biogeography. 22: 1181-1190.

Slafer GA and Rawson HM (1997). CO_2 effects on phasic development, leaf number and rate of leaf appearance in wheat. Annals of Botany 79: 75-81.

Smith IN (2004). Trends in Australian rainfall – Are they unusual? Australian Meteorological Magazine 53: 163-173.

Stephens DJ and Lyons TJ (1998a). Rainfall-yield relationships across the Australian wheatbelt. Australian Journal of Agricultural Research. 49: 211-223.

Stephens DJ and Lyons TJ (1998b). Variability and trends in sowing dates across the Australian wheatbelt. Australian Journal of Agricultural Research. 49: 1111-1118.

Stokes CJ and Howden SM (2008). An overview of climate change adaptation in Australian primary industries – impacts, options and priorities. Report prepared for the National Climate Change Research Strategy for Primary Industries, Land and Water Australia, Canberra. pp 344.

Stone PJ and Nicholas ME (1995). A survey of the effects of high temperature during grain filling on yield and quality of 75 wheat cultivars. Australian Journal of Agricultural Research 46: 475-492.

Tubiello FN, Amthor J, Boote K, Donatelli M, Easterling W, Fischer G, Gifford R, Howden SM, Reilly J and Rosenzweig C (2007). Crop response to elevated CO_2 and world food supply. European Journal of Agronomy, 26: 215-233.

van Herwaarden AF, Farquhar GD, Angus JF, Richards RA and Howe GN (1998). 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser I. Biomass, grain yield and water use. Australian Journal of Agricultural Research 49: 1067-1081.

van Ittersum MK, Howden SM and Asseng S (2003). Sensitivity of productivity and deep drainage of wheat cropping systems in a Mediterranean environment to changes in CO_2, temperature and precipitation. Agriculture, Ecosystems and Environment 97, 255-273.

Wang YP, Handoko Jr and Rimmington GM (1992). Sensitivity of wheat growth to increased air temperature for different scenarios of ambient CO_2 concentration and rainfall in Victoria, Australia — a simulation study. Climate Research 2:131-149.

Wolf J (1996). Effects of nutrient supply (NPK) on spring wheat response to elevated atmospheric CO_2. Plant and Soil 185: 113-123.

Wu G, Chen F, Sun Y and Ge F (2007b). Response of successive three generations of cotton bollworm, Helicoverpa armigera (Hübner), fed on cotton bolls under elevated CO_2 Journal of Environmental Sciences 19: 1318-1325

Ziska LH, Teasdale JR and Bunce JA (1999). Future atmospheric carbon dioxide may increase tolerance to glyphosate. Weed Science, Vol. 47: 608-615.

Ziska LH and Blumenthal DM (2007). Empirical Selection of Cultivated Oat in Response to Rising Atmospheric Carbon Dioxide Crop Science 47:1547-1552.

Ziska LH, Morris CF and Goins EW (2004). Quantitative and qualitative evaluation of selected wheat varieties released since 1903 to increasing atmospheric carbon dioxide: can yield sensitivity to carbon dioxide be a factor in wheat performance? Global Change Biology 10: 1810 – 1819.