

Garnaut Climate Change Review

Global climate change impacts on Australia's wheat crops

Prepared by

Steven Crimp¹, Mark Howden¹, Brendan Power², Enli Wang¹, Peter De Voil²

¹CSIRO, ²Queensland DPIF

June 2008

Contents

1	Executive summary	2
2	Introduction	4
3	Methodology.....	6
	3.1 Climate files.....	6
	3.2 Simulation scenarios	6
	3.3 Model settings	7
	3.4 Crop varieties	8
	3.5 Modifications to planting windows.....	8
4	Results	9
	4.1 Response coefficients	9
	4.2 Individual site results.....	9
5	References	13

Important disclaimer

CSIRO advises that the information contained in this publication comprises general statements based on scientific research. The reader is advised and needs to be aware that such information may be incomplete or unable to be used in any specific situation. No reliance or actions must therefore be made on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, CSIRO (including its employees and consultants) excludes all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

1 Executive summary

- Historical increases in atmospheric carbon dioxide (CO₂) concentrations have been well documented with mid-range projections suggesting an approximate doubling of current concentrations to 700 ppm by the year 2100 (e.g. Houghton et al. 1996). Increasing atmospheric CO₂ can affect agricultural production both directly through the stimulation of photosynthesis, through improved water use efficiency and indirectly as the increased concentration of CO₂ and other greenhouse gases in the atmosphere may induce climate change. Global change is used here to refer to the combined effect of changes in CO₂ and climate.
- The impacts of global change on crop productivity are difficult to predict, yet the assessment of these impacts is needed for both farm management and policy making purposes.
- We use an existing validated crop model APSIM modified to simulate varying CO₂ to investigate the impacts of doubling CO₂ interactively with a wide range of feasible climate change scenarios on the yields for Australian wheat cropping systems.
- We include practical management adaptations to global change, as impacts studies without such adaptation are unlikely to provide a balanced analysis. Key adaptation options investigated in this report are choice of cultivars and sowing windows.
- Studies are conducted for 10 sites distributed across the existing Australian wheat belt (Figure 1).

Site yields

- General response functions were developed to express likely wheat yield changes derived from multiple simulations run for varying CO₂ concentrations (350 to 750 ppm), temperature (0 to 4°C change) and rainfall (-30% to +20% change). The impacts on wheat yields may differ considerably outside of these ranges and so care must be taken when operating these response functions. Operating the empirical models outside these ranges is not advised and CSIRO project leaders must be consulted if this was to occur.
- With this in mind, increasing CO₂ concentrations to 750 ppm alone (i.e. *without* changes in temperature and rainfall) resulted in increases in simulated yield within the current wheat belt by 18 to 36% compared with the simulated 60-year historical mean (1957 to 2006). The relative increase was least at sites where evaporative demand and hence soil moisture stress was least and tended to be greater at drier and warmer sites as found in controlled experiments. The results from the study sites were consistent with previous assessments where they have been made.

Adaptation

- Temperature increases are likely to result in a reduction in the duration of the annual frost period, thus allowing earlier planting in some sites. Modifying the planting window to take advantage of this opportunity and varying cultivars in response to temperature change, resulted in yield benefits of up to 36% for a future environment with 750 ppm, no change in rainfall and 4°C warmer, when compared with simulated yields with no change in current practices.
- Key varietal adaptations in response to changing conditions are a switch from fast-maturing to slower maturing varieties particularly with increased temperature and rainfall and under the modified planting windows.

National yields

- In previous analyses (Howden et al 2001, Howden and Jones, 2003, Howden and Crimp 2005) site yields were aggregated across the continent based on currently cropped areas. This approach has not been undertaken for this study, but will be required as part of the larger review.
- A major limitation of the scaling approach is that it assumes a static area of production based on historical boundaries. The production area is likely to expand and contract in a number of local

areas in response to change climate conditions. The simple aggregation approach will not account for these changes.

- There are likely to be opposing influences arising from potential increases in pest and disease incidence with global change (e.g. Sutherst 1995) and the substantial losses in productivity expected through continuing land degradation processes such as dryland salinity, soil structural decline and acidification. These drivers of change have also not been considered.
- There are a number of limitations to this study in addition to those above. Chief among these is the representation of climate change used. We do not incorporate explicitly changes in the frequency or intensity of El Niño events—a growing concern. Nor do we include such factors as changes in rain days or rainfall intensity which are likely to impact on cropping in various ways.

Grain quality

- A range of studies indicate that grain protein contents are likely to fall in response to combined climate and CO₂ changes (i.e. protein losses of 4 to 14% Howden et al., 2001), which will significantly downgrade prices received unless fertiliser application or pasture rotations are incorporated to reduce the effect. To maintain protein contents at current levels, fertiliser application rates need to increase by 40 to 220 kg/ha depending on the scenario. These adaptations will have their own impacts on soil acidification processes and water quality in some regions and on farm economics. Furthermore, such adaptation could be a significant source of greenhouse gas emissions as production, packaging and distribution of nitrogenous fertiliser generates about 5.5 kg CO₂ per kg N and as both fertilisation and legume rotations increase emissions of nitrous oxide.
- Increases in heat shock also may reduce grain quality by affecting dough-making qualities.

2 Introduction

Wheat is the major crop in Australia in terms of value (\$4.2 billion), volume (22 Mt) and area (11 Mha). Yields are generally low due to low rainfall, high vapour pressure deficit and low physical and chemical soil fertility and can vary by as much as 60% in response to climate variability (Howden and Crimp 2005). Thus the Australian wheat industry is highly sensitive to climatic influences. Increases in levels of atmospheric CO₂ and other greenhouse gases are likely to significantly change global climate, increasing temperature and changing regional rainfall patterns, with consequent impacts on the wheat industry (Howden and Crimp 2005).

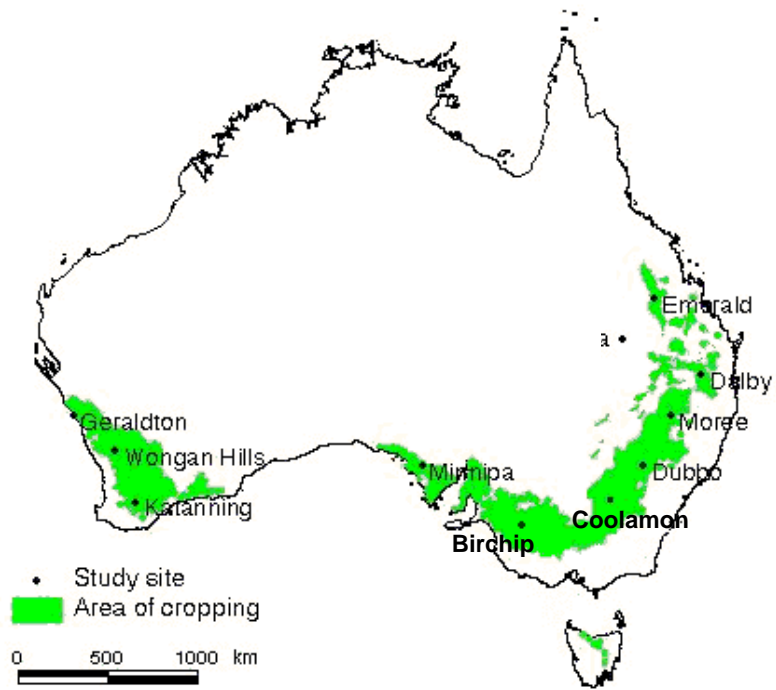
Atmospheric CO₂ levels may rise from current levels (378 ppm) to between 520 ppm to 750 ppm by the year 2100. At the same time, temperatures across Australia may increase by a range of 1°C to almost 6°C. Large changes in rainfall are possible with changes of up to 60% by 2100—noting that there is marked variation between regions and seasons and a tendency toward lower rainfall across most of the Australian wheat belt (Howden and Crimp 2005). Such changes would have significant impacts on wheat yields in Australia as well as areas suitable for cropping, changes in salinity and erosion risk (e.g. Reyenga et al. 1999, van Ittersum et al. 2003).

As part of the Ross Garnaut Review this study has examined the likely impacts to Australia's wheat industry. This has been achieved by establishing a sensitivity analysis to examine simulated yield responses to a range of temperature, rainfall and CO₂ changes using the APSIM cropping systems modelling framework (McCown et al. 1996). The sensitivity of yield in response to a wide range of feasible climate change scenarios and CO₂ concentrations (described later) was expressed empirically in terms of response surfaces for each location.

In this study we wanted to include possible management adaptations to global change, as impacts studies without such adaptation are unlikely to provide a balanced analysis. Key management decisions which are amenable to adaptation include choice of cultivar, window for sowing, fertiliser application rate, soil surface and fallow management and crop/pasture rotation strategies. A cropping systems approach such as that in APSIM is ideally suited to addressing these adaptations. In this study we have considered the impacts of changing sowing windows and cultivars as a way of offsetting likely impacts.

We have chosen sites distributed across the existing wheat belt to sample regional differences (Figure 1).

Figure 1 Area of cropping in Australia and location of the ten study sites



3 Methodology

3.1 Climate files

APSIM is a daily timestep model which uses daily climate as input data. There are a range of methods of constructing daily climate records for climate change scenarios, however in this study we have chosen an approach that simply scales existing daily rainfall and temperature records for the period 1957 to 2006 (Table 1). The change in temperature was added to both maximum and minimum temperatures. No changes were made to the frequency of rain days, but raindays were proportionally adjusted.

Table 1 Location of meteorological stations and climate records used for long-term wheat simulation

Location	State	Latitude	Longitude	Start Date	End Date
Emerald	Qld	23.57	148.18	1957	2006
Dalby	Qld	27.17	151.27	1957	2006
Moree	NSW	29.47	149.85	1957	2006
Dubbo	NSW	32.22	148.57	1957	2006
Coolamon*	NSW	34.82	147.20	1957	2006
Birchip*	VIC	35.68	142.67	1957	2006
Minnipa	SA	32.83	135.15	1957	2006
Katanning	WA	33.65	117.90	1957	2006
Wongan Hills	WA	30.90	116.72	1957	2006
Geraldton	WA	28.80	114.70	1957	2006

* The climate record for these sites were generated by using interpolated daily climate surfaces (Carter et al. 1996) due to there being no nearby long-term climate station.

This approach is a pragmatic solution to the problem of generating climate records rather than an ideal solution. The approach implicitly assumes that there is no change in either the frequency or intensity of El Niño/La Niña events with climate change whereas there is growing concern that El Niño frequencies will increase, thus changing the proportion of good and bad years in the record and the net impact on wheat may be different from the average change in rainfall. The temperature changes are equally weighted between maximum (daytime) and minimum (nighttime) temperatures whereas to date the majority of warming experienced is via increase in minimum temperatures. Lastly, particularly with greater changes to the daily values, the autocorrelation between factors such as radiation, precipitation, maximum temperature and minimum temperature will change and the climate record will become less representative. Nevertheless, the approach we have adopted is likely to maintain the gross linkages between these factors within the climate scenario envelopes described below.

3.2 Simulation scenarios

Whilst some convergence in future projections of climate changes has occurred there are still significant levels of uncertainty regarding the extent of these changes. Our approach is thus not to restrict ourselves to analysing a small subset of the possible Global Climate Model (GCM) results but to develop for each location a surface of all possible combinations of temperature and rainfall change within a certain envelope of change. The envelope we have used limits temperature change to an increase of up to 4°C above current temperatures (0, 1, 2, 3, and 4°C) and +20% to –30% change in rainfall (–30, –20, –10, 0, 10, and 20%), for a series of different CO₂ concentrations, including 350, 450, 550, 650 and 750 ppm (Table 2).

Table 2 The possible temperature and rainfall combinations for a given CO₂ concentration

Rainfall scenario (%)	Temperature change (°C)				
	0	1	2	3	4
-30	Scenario	Scenario	Scenario	Scenario	Scenario
-20	Scenario	Scenario	Scenario	Scenario	Scenario
-10	Scenario	Scenario	Scenario	Scenario	Scenario
0	Scenario	Scenario	Scenario	Scenario	Scenario
10	Scenario	Scenario	Scenario	Scenario	Scenario
20	Scenario	Scenario	Scenario	Scenario	Scenario

Response surfaces of mean wheat yields to CO₂, rainfall and temperature were developed for each site. The approach used to model CO₂ response (Reyenga et al. 1999) has been validated for a number of independent studies (Asseng et al. 2004). The general form of the response surface was assumed to be quadratic in order to capture the shape of the observed yield responses. The quadratic response surface can be expressed as follows:

$$\% \text{ Yield change} = (a\text{CO}_2 + b(\text{CO}_2)^2 + c(\text{CO}_2)^3 + d(\text{CO}_2)^4 + e(T) + f(T)^2 + g(T)^3 + h(R) + i(R)^2 + j) \times 100$$

Where T and R are temperature (°C) and rainfall (proportional change from baseline - 0.7 = 30% less rainfall and 1.2 = 20% more rainfall) change respectively from the baseline period, CO₂ is expressed in parts per million and j is a constant.

Two separate response surfaces were developed. One that considered no change in current sowing practise (i.e. fixed planting window) and one which included management adaptations of change in planting window (Howden et al. 2001).

The key benefit of using this approach is that as climate scenarios change, new estimates of the likely impact can be made through locating the scenario on the surface without the need to re-run the analyses.

3.3 Model settings

To conduct the simulations described above we required information on regional management practices, varieties, growing conditions and soil types. This information was collated for each of the ten sites from expert knowledge of practices in each region and from information available from the literature.

The model was run with a continuous wheat monoculture. The soil water balance was maintained between crops, however, soil N and organic matter were reset at sowing. This is necessary so that starting conditions reflect the 'average' district conditions. Resetting soil N and organic matter also avoided problems such as fertility run-down in a continuous wheat monoculture, which would make interpretation difficult.

In the simulations, sowing can occur within a given planting window after certain rainfall and soil moisture criteria are met. If there has been no sowing opportunity at the end of the planting window then a crop is automatically sown and is arbitrarily given 25 mm of water to ensure crop establishment. The seeds were sown at a density of 100 plants m⁻² at a depth of 50 mm with 80 kg N ha⁻¹ of fertiliser (NO₃-N). This level of nitrogen fertiliser is likely to be more than is current practice in many regions but was adopted so that the results represent good management in the varying environments. The impacts of important factors such as frost damage, pests, weeds and diseases are not modelled. Hence, the yields presented here may, in some instances, be higher than those actually achieved in these regions.

3.4 Crop varieties

Three varietal strategies (standard, slow and quick) are used to investigate potential strategic cultivar adaptation options to broadscale climate change. Varieties classified as 'standard', 'slow' and 'quick' were independently selected for each site based on expert knowledge of regional management. An additional adaptation was also considered to change the planting window to adjust to changes in temperature and moisture stress (see below).

3.5 Modifications to planting windows

At most of the study sites, the planting window is currently determined by (1) the risk of frosts during and after anthesis (flowering) and (2) drought stress during grain filling. Under the higher temperatures of the climate change scenarios the chance of frost can be significantly reduced thereby allowing farmers to plant earlier in the season.

Planting windows were modified at each of the ten sites to respond to either increasing temperature or water stress. The methodology employed to vary planting windows at a site by site basis are based on approaches outlined in Howden et al., 2001.

4 Results

4.1 Response coefficients

The tables below contains the coefficients required to examine the percentage change in wheat yields for a given CO₂ concentration, temperature (difference in °C) and rainfall change (proportional change i.e. 0.7 = 30% less rainfall and 1.2 = 20% more rainfall) assuming no change in current management practice (Table 3) and adapting current management practices (Table 4).

Table 3 Coefficients to determine yield responses assuming no change in current management

Location	Coefficients									
	a	b	c	d	e	f	g	h	i	j
Dalby	3.29E-03	-3.62E-06	1.72E-09	-2.98E-13	-8.14E-02	8.34E-03	-4.63E-04	3.85E+00	-1.23E+00	-3.33E+00
Emerald	3.19E-03	-3.55E-06	1.71E-09	-3.00E-13	-3.17E-02	1.95E-03	-9.96E-05	5.00E+00	-1.89E+00	-3.82E+00
Coolamon	2.80E-03	-3.23E-06	1.61E-09	-2.94E-13	-2.19E-02	6.19E-04	-3.39E-04	6.07E+00	-2.33E+00	-4.36E+00
Dubbo	3.37E-03	-3.96E-06	2.02E-09	-3.77E-13	-5.76E-03	1.09E-03	-9.77E-04	5.93E+00	-2.45E+00	-4.28E+00
Geraldton	3.01E-03	-3.57E-06	1.84E-09	-3.46E-13	1.53E-02	-1.26E-02	2.12E-03	3.73E+00	-1.75E+00	-2.69E+00
Katanning	2.90E-03	-3.51E-06	1.84E-09	-3.52E-13	2.00E-02	1.19E-03	-1.31E-03	4.75E+00	-2.39E+00	-3.04E+00
Minnipa	4.01E-03	-4.52E-06	2.20E-09	-3.93E-13	-3.32E-02	-5.33E-03	-2.75E-04	3.54E+00	-5.55E-01	-3.89E+00
Wongan Hill	5.15E-03	-6.18E-06	3.21E-09	-6.10E-13	-1.13E-02	-2.61E-02	2.61E-03	4.68E+00	-2.05E+00	-3.83E+00
Moree	3.67E-03	-4.06E-06	1.93E-09	-3.36E-13	-2.75E-02	5.40E-03	-1.08E-03	3.85E+00	-1.03E+00	-3.65E+00
Birchip	4.15E-03	-4.57E-06	2.17E-09	-3.75E-13	-8.14E-03	-7.96E-03	5.92E-05	2.30E+00	3.91E-01	-3.64E+00

Table 4 Coefficients to determine yield responses assuming adaptation of current management through modification of current planting windows in response to temperature change

Location	Coefficients									
	a	b	c	d	e	f	g	h	i	j
Dalby	3.56E-03	-3.89E-06	1.83E-09	-3.13E-13	-1.02E-01	3.42E-02	-5.12E-03	3.84E+00	-1.19E+00	-3.43E+00
Emerald	3.21E-03	-3.58E-06	1.72E-09	-3.01E-13	-3.62E-02	1.10E-02	-1.82E-03	4.79E+00	-1.75E+00	-3.77E+00
Coolamon	2.62E-03	-3.04E-06	1.53E-09	-2.82E-13	-4.69E-02	5.08E-02	-8.76E-03	6.85E+00	-2.78E+00	-4.61E+00
Dubbo	3.41E-03	-4.04E-06	2.07E-09	-3.89E-13	1.83E-02	2.47E-03	-1.89E-03	5.87E+00	-2.45E+00	-4.23E+00
Geraldton	3.85E-03	-4.66E-06	2.43E-09	-4.66E-13	-4.16E-02	-9.15E-03	2.52E-03	2.37E+00	-1.20E+00	-1.99E+00
Katanning	2.62E-03	-3.28E-06	1.77E-09	-3.48E-13	1.51E-01	-5.72E-02	6.58E-03	2.81E+00	-1.43E+00	-1.97E+00
Minnipa	4.25E-03	-4.84E-06	2.38E-09	-4.29E-13	-4.14E-02	-6.68E-03	3.21E-03	2.21E+00	6.13E-02	-3.27E+00
Wongan Hill	4.15E-03	-4.92E-06	2.52E-09	-4.74E-13	8.52E-02	-3.58E-02	3.53E-03	4.60E+00	-1.66E+00	-3.84E+00
Moree	4.14E-03	-4.65E-06	2.26E-09	-4.01E-13	1.23E-01	-5.92E-02	6.55E-03	4.51E+00	-1.30E+00	-4.15E+00
Birchip	4.72E-03	-5.28E-06	2.55E-09	-4.51E-13	9.69E-02	-3.84E-02	3.33E-03	4.97E+00	-8.98E-01	-5.14E+00

4.2 Individual site results

The responses described below highlight how wheat yields may change as a result of varying rainfall, temperature and CO₂. The examples below represent possible yield responses at 650 ppm for a range of temperature and rainfall changes. In all three examples both adaptation (changing planting windows) and non-adaptation (fixed planting window) cases are shown.

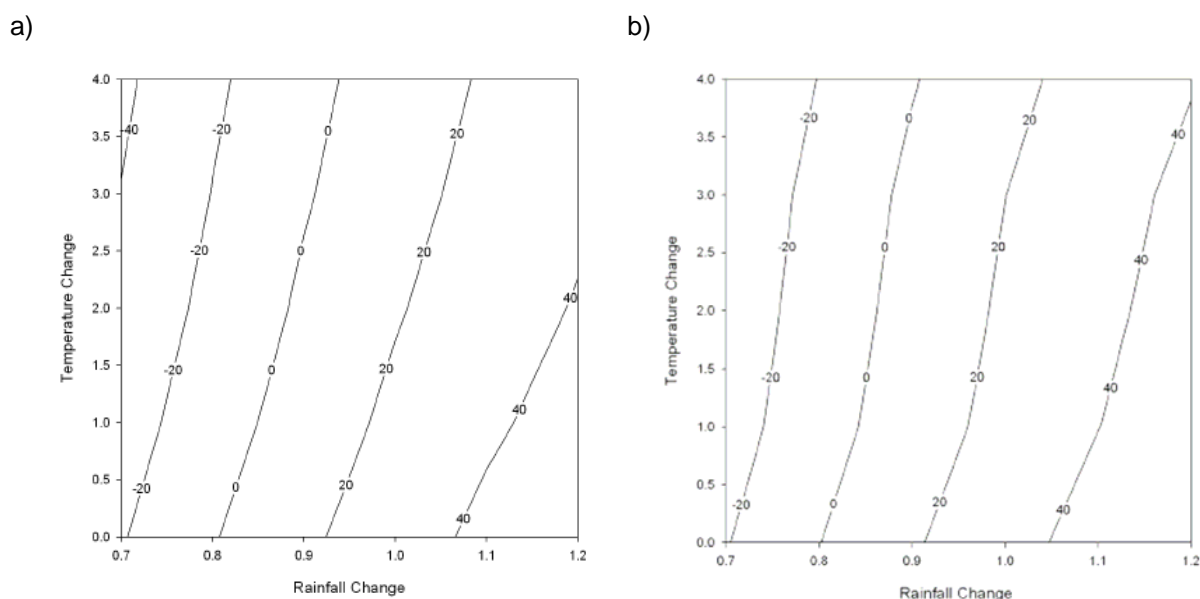
Yield changes at Dalby

An increase in CO₂ of up to 650 ppm alone (i.e. 0°C and 0% rainfall change scenario) resulted in a 34% increase in potential yields (Figure 2a). The yield response increases with increased rainfall but no change temperature (Figure 2a). Temperature increases had a negative effect on yields of

approximately 8% per degree of warming with no change in management. The maximum yield response (54%) was achieved at the +20% rainfall and no change in temperature scenario while the lowest (-44%) occurred in the -30% rainfall and 4°C temperature scenario. Based on the CSIRO 2007 best estimate of climate change by 2050 (i.e. 550 ppm, 2 to 2.5°C and -5 to -10% rainfall change), wheat yields may change between -5% to 6% depending on the combination of temperature and rainfall change (Figure 2a).

Modifying the planting window resulted in higher yields under all global change scenarios with the maximum yield response (58%) achieved at the +20% rainfall and no temperature change scenario while the lowest (-39%) occurred in the -30% rainfall and 4°C temperature scenario (Figure 2b). Based on the CSIRO 2007 best estimate of climate change by 2050 there is likely to be between -1% and 9% yield response with the modified window (Figure 2b).

Figure 2 Dalby—yield response (% change from baseline) to 650 ppm CO₂ and a range of climate change scenarios with (a) current planting window b) modified planting window; cultivar choice varied in both cases

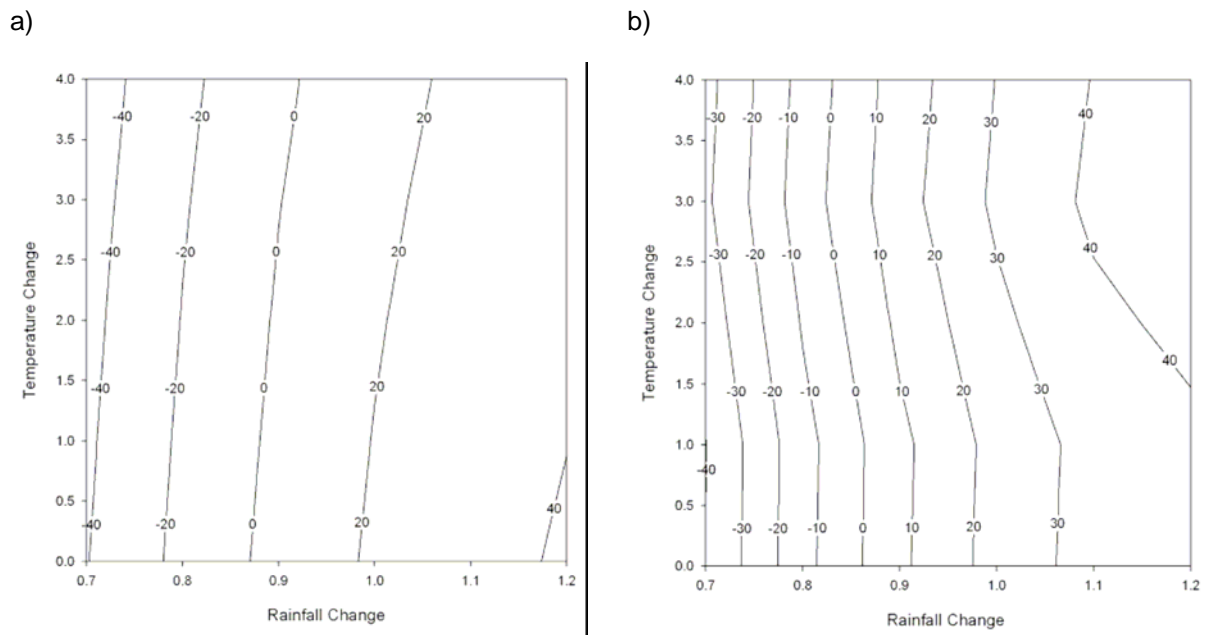


Yield changes at Coolamon

An increase in CO₂ of up to 650 ppm alone (i.e. 0°C and 0% rainfall change scenario) resulted in a 23% increase in potential yields (Figure 3a). Using the current planting window, the yield response increased with increasing rainfall (Figure 3a). Temperature increases had negative impacts on growth of approximately 2% per degree of warming. The maximum yield response (42%) was achieved at the +20% rainfall and no change in temperature while the lowest (-51%) occurred in the -30% rainfall and 4°C temperature scenario. Based on the CSIRO 2007 best estimate of climate change by 2050 (i.e. 550 ppm, 2 to 2.5°C and -2 to -5% rainfall change), wheat yields may change between 7% to 11% depending on the combination of temperature and rainfall change (Figure 3a).

Modifying the planting window resulted in higher yields under all global change scenarios with the maximum yield response (46%) achieved at the +20% rainfall and 3°C temperature scenario (Figure 3b). Based on the CSIRO 2007 best estimate of climate change by 2050 there is likely to be between 19 and 21% yield response with the modified window (Figure 3b).

Figure 3 Coolamon—yield response (% change from baseline) to 650 ppm CO₂ and a range of climate change scenarios with (a) current planting window b) modified planting window; cultivar choice varied in both cases



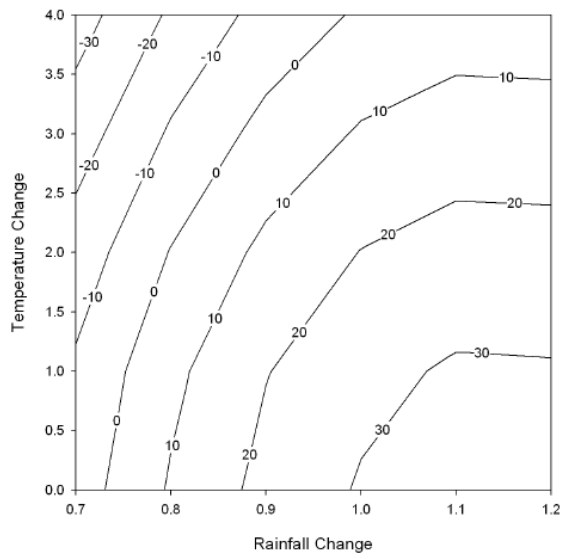
Yield changes at Wongan Hill

Sandy soils predominate in this region, so unlike other response surfaces, yields can decline with higher rainfall. This is due to rainfall draining through the profile and leaching soil nitrogen. Under higher rainfall conditions more nitrogen is leached thus resulting in nitrogen limitations and hence lower yields. In the simulations where the planting window remained fixed increases in CO₂ of up to 650 ppm alone (i.e. 0°C and 0% rainfall change scenario) resulted in a 30% increase in potential yields (Figure 4a). The yield response declined in response to increasing temperature (Figure 4a). The maximum yield response (35%) was achieved at the +10% rainfall and no change in temperature. Further increases in rainfall resulted in yield reductions. The lowest yield response (-34%) occurred in the -30% rainfall and 4°C temperature scenario.

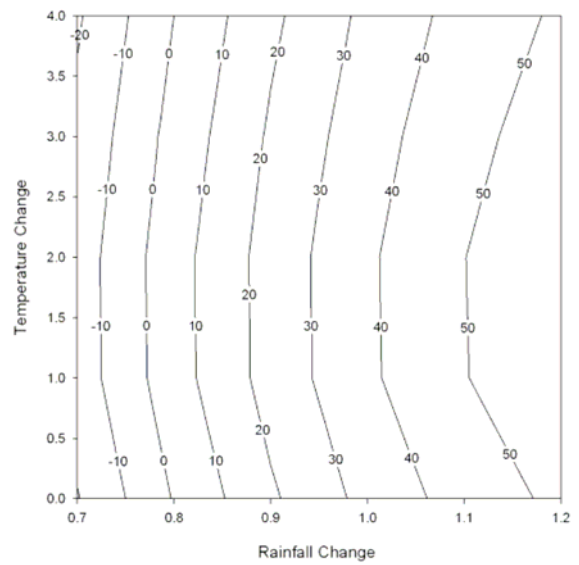
Modifying the planting window resulted in higher yields under all global change scenarios with the maximum yield response (57%) achieved at +20% rainfall and 2°C temperature change while the lowest (-21%) occurred in the -30% rainfall and 4°C temperature scenario (Figure 4b).

Figure 4 Wongan Hill—yield response (% change from baseline) to 650 ppm CO₂ and a range of climate change scenarios with (a) current planting window b) modified planting window; cultivar choice varied in both cases

a)



b)



5 References

- Asseng, S., Jamieson, P.D., Kimball, B., Pinter, P., Sayre, K., Bowden, J.W. Howden, S.M. (2004). Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO₂, *Field Crops Research*, **85**: 85–102.
- Carter, J., Flood, N., Danaher, T., Hugman, P., Young, R. and others (1996). Development of data rasters for model inputs. Development of a National Drought Alert Strategic Information System, Vol. 3. Final Report to LWRRDC.
- Hammer, G.L., Woodruff, D.R. and Robinson, J.B. (1987). Effects of climatic variability and possible climatic change on reliability of wheat cropping—A modelling approach. *Agricultural and Forest Meteorology*, **41**:123–143.
- Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell K. (eds) (1996). *Climate Change 1995. The Science of Climate Change*, IPCC 1996.
- Howden, S.M., McKeon, G.M., Walker, L., Carter, J.O., Conroy, J.P., Day, K.A., Hall, W.B., Ash, A.J. and Ghannoum, O. (1999). Global change impacts on native pastures in south-east Queensland, Australia. *Environmental Modelling and Software*, **14**:307–316.
- Howden, S.M., Reyenga P.J. 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*.
- Howden, M. and Jones, R.N. (2004). Risk assessment of climate change impacts on Australia's wheat industry. In: *New directions for a diverse planet: Proceedings of the 4th International Crop Science Congress*, Brisbane, Australia, 26 Sep – 1 Oct 2004.
- Howden SM and Crimp S. (2005). Assessing dangerous climate change impacts on Australia's wheat industry In: Zerger A, Argent RM (eds). MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand. December 2005. Pp. 170–176. ISBN: 0-9758400-2-9.
- van Ittersum M.K., Howden, S.M. and Asseng, S. (2003). Sensitivity of productivity and deep drainage of wheat cropping systems in a Mediterranean environment to changes in CO₂, temperature and precipitation, *Agriculture, Ecosystems and Environment*, **97**: 255–273.
- McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., Freebairn, D.M. (1996). APSIM: a novel software system for model development, model testing, and simulation in agricultural research. *Agricultural Systems*, **50**: 255–271.
- Sutherst, R.W. (ed) (1995). Impacts of Climate Change on Pests, Diseases and Weeds in Australia. Report of an International Workshop, Brisbane 9–12 October 1995, DEST, RIRDC.