Assessing dangerous climate change impacts on Australia's wheat industry

[1]**Howden, S.M.** and [2]**S. Crimp**

[1]**CSIRO Sustainable Ecosystems,** [2]**Qld Natural Resources and Mines, E-Mail:** Mark.howden@csiro.au

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EXTENDED ABSTRACT

Atmospheric carbon dioxide (CO_2) concentrations and global and regional climates are already changing as a result of human activities. More change seems likely. Historical climate variations, particularly in rainfall, have had significant impacts on the Australian cropping industries and consequently we would anticipate additional impacts from future climate change. However, the magnitude of these changes is highly uncertain at regional levels especially for rainfall. To deal with this uncertainty a systematic assessment approach is described here that separates the effects of changed temperatures, rainfall and CO_2 concentration on regional and national wheat yields, including the effects of management adaptations in response to the above changes. This allows addressing questions such as 'Are there beneficial effects of moderate warming?' 'If so, at what point does further warming become negative?' and 'What is the benefit of management adaptation to climate changes?' Furthermore, the approach allows recombination of the components in a risk assessment approach to investigate questions such as 'What level of CO_2 increase is required to offset deleterious changes in rainfall and temperature ?' or 'What is the probability of reductions in the value of the wheat industry ?'

A key aspect of the international debate on climate change is in regard to what constitutes 'dangerous' climate change. Some preliminary assessments suggest that a global temperature increase of more than 2°C will have increasingly deleterious net effects. This study provides some additional support (albeit limited) to this emerging view. In southerly sites and also at a national level, small increases in temperature (up to 1°C) are simulated to slightly increase regional yields. Adaptations can extend the beneficial effects of higher temperatures out to 3°C but only in scenarios where rainfall increases. In drier scenarios, temperature increases above 1°C are deleterious. In more northerly sites in contrast, any increase in temperature reduces regional yields.

Management adaptations (changed varieties, changed planting windows) can significantly offset the negative impacts of climate changes. These adaptations were most effective with small temperature increases (1 to 2°C), raising yields by 6 to 12%. At higher temperatures, further benefit was limited, particularly under scenarios with reduced rainfall. The greatest benefit from adaptations arose from positive management responses in higher rainfall scenarios where benefits of up to 16% were simulated. The beneficial effects of elevated CO_2 concentrations on yield can also substantially offset small climate changes. An increase in CO_2 concentration to about 650ppm is calculated as needed to offset either a 20% reduction in rainfall alone **or** a temperature increase of 4°C. Smaller increases in CO_2 are required to maintain yields when adaptation is practiced.

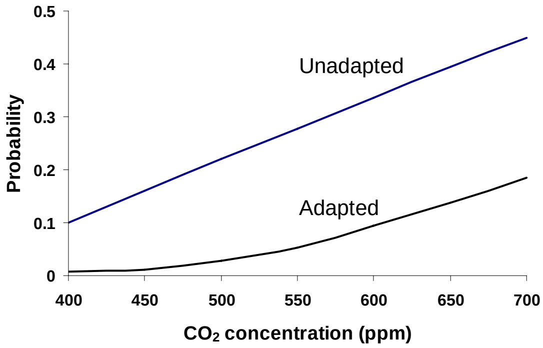

Figure 1. Probability of national value of wheat production being reduced (compared with historical average) either with or without adaptation practiced. Wheat production is affected by regionally-varying rainfall and temperatures as well as CO_2 concentration.

In a preliminary attempt to address the issue of 'dangerous' climate change, we calculate the probability (risk) of the value of the national wheat crop dropping below the historical average in response to scenarios of global CO_2 increase and associated climate change. The likelihood increases with CO_2 level and climate changes, increasing to about 45% with changes feasible within 60 years (Fig 1). The adaptations assessed in this study more than halve that risk.

1. INTRODUCTION

Wheat is the major crop in Australia in terms of value ($4.2 billion), volume (22Mt) and area (11Mha). Yields are generally low due to low rainfall, high vapour pressure deficit and low physical and chemical soil fertility. Interannual climate variations can halve or add 60% to average yields. Thus the Australian wheat industry is highly sensitive to climatic influences. Increases in levels of atmospheric CO_2 and other greenhouse gases are considered likely to significantly change global climate, increasing temperature and changing regional rainfall patterns, with consequent impacts on the wheat industry. However, there is considerable uncertainty in scenarios of CO_2 increase and related climate change - and wheat responds to both factors, with raised CO_2 levels enhancing crop growth through increased photosynthetic rates and water use efficiencies, but reducing grain protein content (e.g. Howden et al. 1999). Atmospheric CO_2 levels may rise from current levels (374ppm) to between 520ppm to 720ppm by the year 2070. In the same time frames, temperatures across Australia may increase by a range of 1ºC to almost 7ºC by the year 2070. Large changes in rainfall are possible with changes of up to $\pm$60% by 2070 – noting that there is marked variation between regions and seasons and a tendency toward lower rainfall across most of the Australian wheat belt. Such changes in climate and CO_2 levels would have potentially 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).

Earlier site-based analyses of the impact of combined changes in atmospheric CO_2 concentration and regional climate change (e.g. Howden et al. 1999) did not account for the large range of above uncertainty in CO_2 and climate changes nor scale this up to the national level. This study undertakes sensitivity analyses of the separate and interactive effects of changes in rainfall, temperature, CO_2 concentration and management practices prior to integration of these into a Monte Carlo risk assessment of the likelihood of reduction in the value of Australian wheat crops.

2. METHOD

The paper focuses on ten sites in the major Australian wheat growing districts as a pathway to scaling up results for the whole of the industry. The sites were Geraldton, Wongan Hills, Kattanning, Minnippa, Horsham, Wagga Wagga, Dubbo, Moree, Dalby and Emerald. Response surfaces of mean wheat yields to CO_2, rainfall and temperature were developed for each site using I-Wheat (Meinke et al. 1998) which is a module of the APSIM systems modelling framework (Keating et al 2003). The approach used to model CO_2 response (Reyenga et al. 1999) has been validated (Asseng et al. 2004). I-Wheat was run for a factorial combination of CO_2 increase, temperature and rainfall change using modified daily 100-year climate records (Reyenga et al. 1999) to provide response surfaces (or a summary model) of the general form:

$$\text{Yield change (\% from historical mean)} = aCO2 + bT + cR + \varepsilon \qquad \text{Eq'n 1}$$

Where T (ºC) and R (% change) are temperature and rainfall change respectively from the 100-year average, CO_2 is in parts per million and ε is the residual error. Most regressions had non-linear terms and interaction terms in the above equation. A separate response surface was developed for simulations which included management adaptations of change in variety and change in planting window optimised for each site and for different combinations of climate changes (Howden et al. 1999). Change in grain nitrogen (%) was calculated as a function of yield change using similar regression techniques. These response surfaces were sampled using Monte Carlo methods using a proprietary package (@RISK). Sensitivity analyses on the input variables (i.e. CO_2, temperature, rainfall) for this sampling was undertaken for two sites with contrasting climate conditions (Emerald, Central Qld and Horsham, Central Vic.). For each site, yield change was calculated for each combination of rainfall and temperature change keeping CO_2 constant at 350ppm. A similar sensitivity analysis was performed for national aggregated yield with temperature and rainfall changed uniformly across the ten sites. The benefit of adapting to climate change was calculated as the difference between the adapted and unadapted response surfaces. For the national yield response surfaces, at each combination of rainfall and temperature change, the CO_2 concentration needed to maintain yields at their mean historical levels was calculated.

A full risk analysis was performed using scenarios of global CO_2 concentration as the driving variable rather than the global temperature change used in other studies. This was because CO_2 concentration is the causal agent and temperature increase is a response variable as is rainfall change. Carbon dioxide concentrations from 400ppm to 700ppm were related to global temperature changes drawn from the Intergovernmental Panel on Climate

Change scenarios (IPCC 2000). For each CO_2 level, temperature changes were sampled between the maximum and minimum temperature changes using a uniform distribution (Howden and Jones 2001). The global temperature changes were then used to calculate monthly temperature and rainfall changes across the ten sites using probability distributions derived from the results of nine Global Climate Models (Howden and Jones 2001). Correlation matrices were calculated between all sites for both precipitation and temperature changes as adjacent sites are likely to have similar climate changes within a sampling whilst sites distant from each other others may be largely independent (Howden and Jones 2001). Thus, for each CO_2 concentration a Monte Carlo sampling can be made that estimates site yield as a function of CO_2 concentration, temperature change, rainfall change and adaptation. Changes in site yield (t/ha) are scaled to regional productivity (tons) using the average regional Australian Bureau of Statistics (ABS) production statistics for the past decade and the change in yield under a given global change scenario. These regional values are then aggregated to give national production. Crop value (\$/ton) is calculated as a function of grain N concentration (%N) based on several years' data (Howden et al. 1999):

$$\text{Value (\$/ton)} = -66.395x^3 + 435.6x^2 - 851.36x + 656.81$$

Where x is calculated percent nitrogen (N%) in the grain. For simplicity, the same equation is used for all States although minor differences occur. Regional crop value is then re-calculated using the yield changes and crop value and then aggregated to national values. We do not incorporate changes in cropping areas for the global change scenarios as a response of change in yield potential and risk as there may be buffering responses via landuse changes (e.g. Reyenga et al. 1999). These require further analysis. The frequency of occurrences where the national value of wheat production was below the historical average was assessed for each CO_2 level for when there was either no adaptation to climate change or adaptation.

3. RESULTS

3.1 Yield responses to temperature and rainfall

Yield at Emerald was simulated to decrease with all temperature increases and regardless of whether adaptation was practiced (Fig. 2). In the absence of CO_2 increase, rainfall changes and adaptation, yield was simulated to decrease by 30% with a 4°C temperature increase. Adaptation reduced this to a 10% decline. The most significant declines were when temperature increased in conjunction with rainfall decreases. In such conditions, yield was reduced by up to 50% without adaptation and 30% with adaptation.

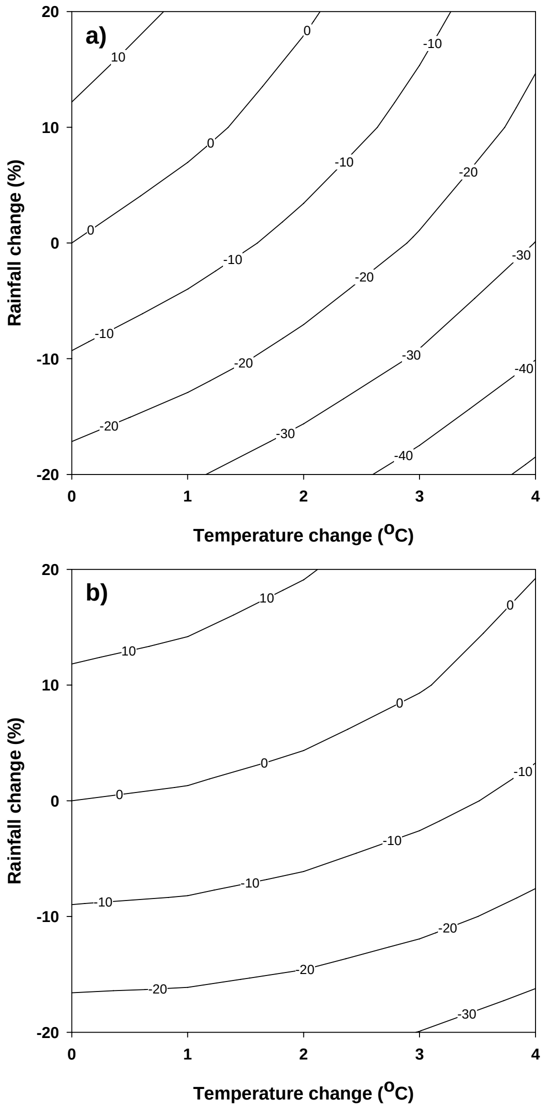

Figure 2. Wheat yield responses (% change from historical baseline indicated by contours) for Emerald, Central Qld, for temperature increases up to 4°C and rainfall changes ranging from ±20% when a) no adaptation and b) adaptation was practiced.

Yield at Horsham was simulated to increase slightly with a temperature increase of about 1°C when there was no adaptation or elevated CO_2 but declined with temperatures higher than this (Figs 3, 4). When adaptation was practiced, the higher productivity at elevated temperatures was maintained until about 3°C (with 20% rainfall increase), 2°C with small changes in rainfall and 1°C when rainfall declined by 20%. Elevated temperatures and reduced rainfall had the most deleterious effects on yield with adaptation having only marginal benefits in such circumstances.

These increases were maintained until temperatures exceeded about 1°C (when rainfall was reduced) to up to 2°C (when rainfall was increased) with declines in production at higher temperatures.

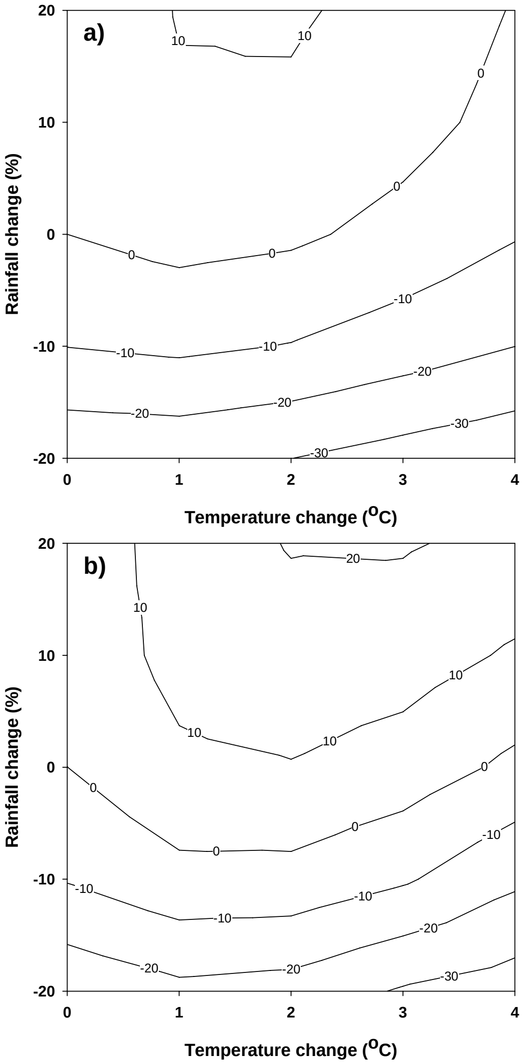

Figure 3. Wheat yield responses (% change from historical baseline) for Horsham, Central Vic, for temperature increases up to 4°C and rainfall changes ranging from ±20% when a) no adaptation and b) adaptation was practiced.

National aggregated production was similarly affected by alterations in rainfall and temperature. In the absence of adaptation and with CO_2 held at 350ppm, there was no increase in yield with elevated temperature regardless of rainfall changes (Fig 5). Maximum reductions of approximately 30% were simulated with temperature increases of 4°C and rainfall reductions of 20%. When adaptations were simulated, small increases in yield were simulated with elevated temperatures.

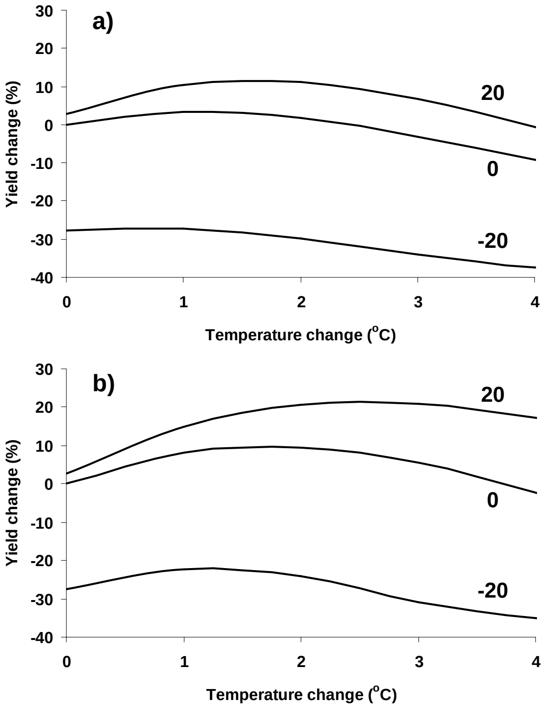

Figure 4. Wheat yield responses (% change from historical baseline) for Horsham, Central Vic, for temperature increases up to 4°C and rainfall changes of +20, 0 and -20% when a) no adaptation and b) adaptation was practiced.

Adaptations were most effective with small temperature increases (1 to 2°C), raising yields by 6 to 12% (Fig 6). At higher temperatures, further benefit was limited, particularly under scenarios with reduced rainfall. The greatest benefit from adaptations arose from positive management responses in higher rainfall scenarios where benefits of up to 16% were simulated.

Elevated CO_2 concentrations can partially reduce the negative impacts of elevated temperature and reduced rainfall (Fig 7). However, significant increases are simulated as being needed to offset possible climate changes. For example, without adaptation, an increase in CO_2 concentration to about 650ppm is needed to offset either a 20% reduction in rainfall alone or a temperature increase of 4°C (Fig 7a). Smaller increases in CO_2 are required to maintain yields when adaptation is practiced, with these being more effective at offsetting temperature increase than rainfall increase.

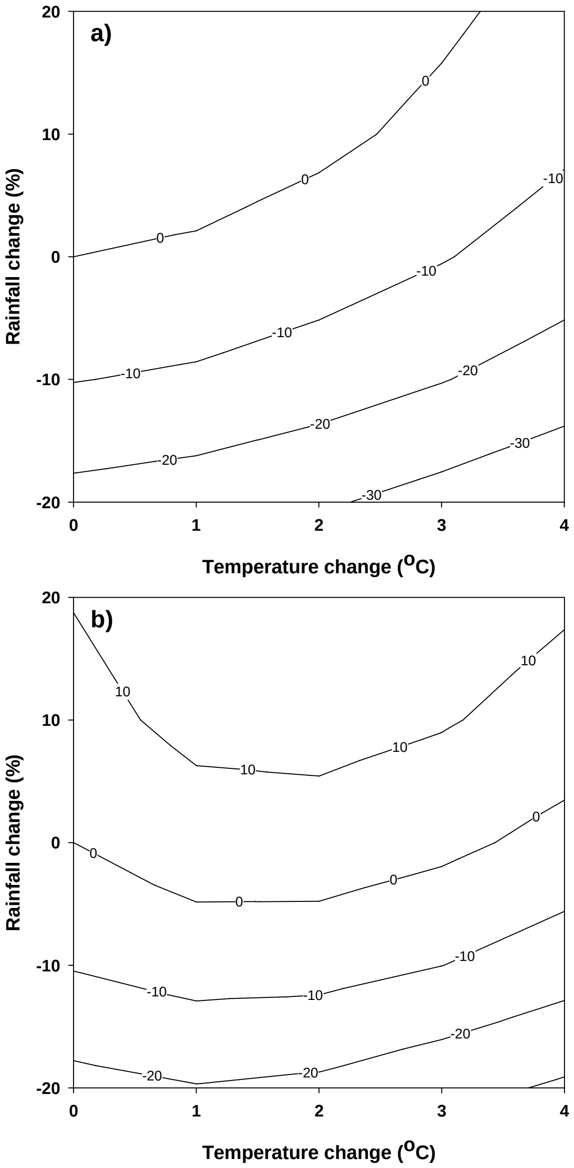

Figure 5. National aggregated wheat yield responses (% change from historical baseline indicated by contours) for temperature increases up to $4^{o}C$ and rainfall changes ranging from $\pm 20\%$ when a) no adaptation and b) adaptation was practiced. Temperature and rainfall changes are uniform across the nation. CO_2 level is held at 350ppm.

Increasing CO_2 concentrations and the resultant changes in regional temperature and rainfall will steadily increase the risk that average national value of production will decline below historical levels (Fig 1). In the absence of adaptation, the risk increases from about 17% at levels of 400ppm CO_2 to about 45% at 700ppm (concentrations anticipated in several decades). Adaptations considerably reduced the likelihood of reduced value of production limiting these to being effectively zero until levels of 450ppm. The risk of lowered production was 20% with CO_2 levels of 700ppm.

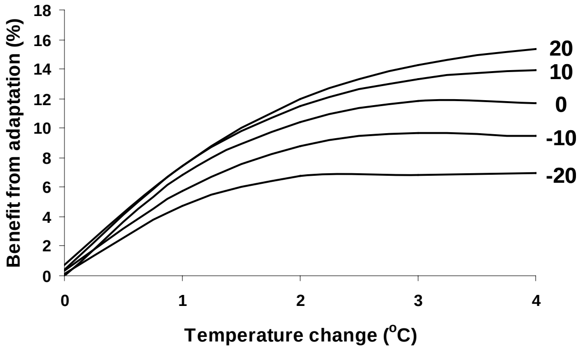

Figure 6. National aggregated yield benefit (% increase) arising from practicing adaptations for temperature increases up to $4^{o}C$ and rainfall changes of +20, +10, 0, -10 and -20%. Temperature and rainfall changes are uniform across the nation. CO_2 level is held at 350ppm.

4. DISCUSSION

There is a developing science-policy debate arising from the UN Framework Convention on Climate Change regarding what constitutes 'dangerous anthropogenic interference' with the global climate system. Some participants in this debate have tentatively identified emissions that would result in warming of $2^{o}C$ as a 'threshold' beyond which the risks increase rapidly (e.g. Hansen 2005) whilst others have expressed the risk in terms of greenhouse gas concentrations (e.g. Wigley 2004). In assessing impacts, these assessments have tended to address global-scale issues such as glacial degradation and sea-level rise, thermohaline circulation stability, coral reef bleaching and of course have included caveats regarding unequal distribution of impacts across locations, sectors and time and the uncertain impacts of mitigation and adaptation. In this study we have undertaken some preliminary assessments at a national level and for a specific industry (wheat) using a combination of sensitivity analyses and risk assessments.

At a national aggregated level, the temperature 'thresholds' beyond which yield is progressively reduced with further temperature increases are $2^{o}C$ if rainfall is increased and $1^{o}C$ if rainfall remains the same or is reduced. This assumes that adaptations are practiced. If no adaptations are practiced any warming will decrease crop yields (i.e. the temperature threshold is $0^{o}C$). Consequently, these preliminary results tend to provide general support to the view $2^{o}C$ may be a general temperature beyond which climate risks increase rapidly. However, these results also indicate that caution needs to be used in adopting single values for 'dangerous thresholds'. This is emphasized further when the results are disaggregated to consider both regional responses and adaptations. For example, in the subtropics where temperatures are already high during the winter cropping period, any temperature increase had negative effects on regional yield regardless of the rainfall scenario, CO_2 level or adaptation options. In contrast, in southern temperate Australia when no adaptations were practiced there was a general threshold of 1°C whereas adaptation options changed this threshold up to 3°C in scenarios where rainfall was increased and 2°C where rainfall was unchanged and it remained at 1°C where rainfall was reduced. Clearly it is not possible to define a single 'threshold' for problematic temperature increase.

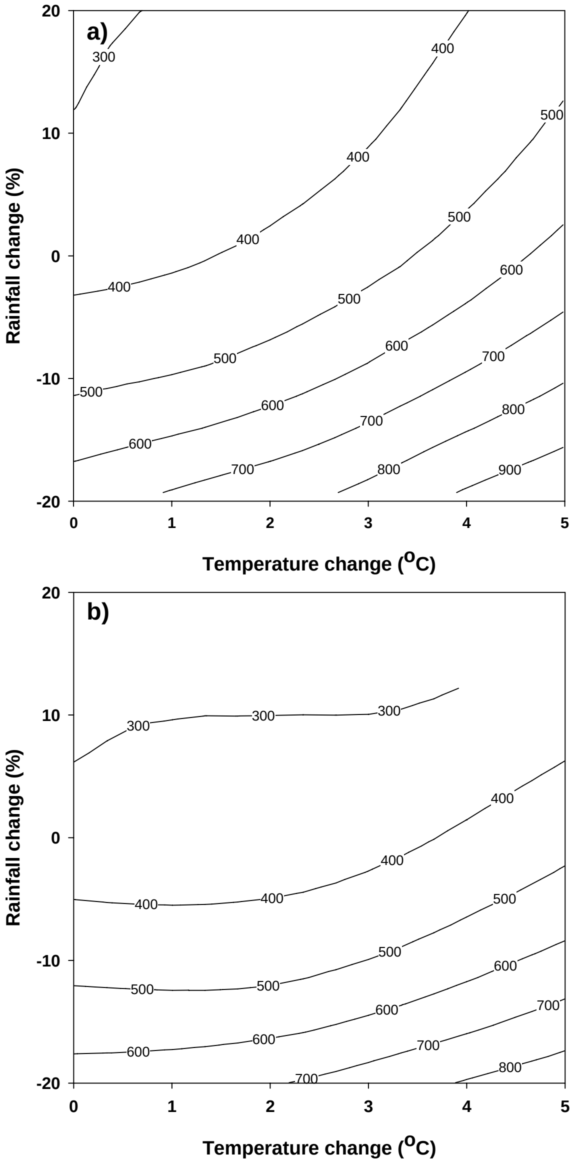

Figure 7. CO_2 concentrations needed to offset the effects of different combinations of rainfall and temperature change on yield when a) no adaptation and b) adaptation was practiced. Temperature and rainfall changes are uniform across the nation.

In an attempt to further address the issue of 'dangerous' climate change, we calculate the probability (risk) of the value of the national wheat crop dropping below the historical average in response to scenarios of global CO_2 increase and their associated, but uncertain climate changes. The probability of yield reductions increases with CO_2 level, increasing to about 45% with CO_2 concentrations and climate changes feasible within 60 years (700ppm: Fig 1). The adaptations assessed in this study more than halve that risk. The selection of an acceptable level of risk is a socio-political process rather than a scientific one. However, relationships like these could help to inform such processes. If for example, some participants in the debate considered a 10% risk was the limit of what was acceptable, then this may be exceeded with CO_2 concentrations of as little as 400ppm assuming no adaptation. If adaptation practices are widely used, then a 10% level of risk of reduced national yields may arise with CO_2 concentrations of 600ppm.

Crop management adaptations are likely to have a significant role in maintaining or increasing yields as well as influencing the potential temperature threshold beyond which yield is negatively affected. The adaptations assessed here were most effective with small temperature increases (1 to 2°C), with the adaptations raising yields by 6 to 12%. At higher temperatures, further benefit from adaptation was limited, particularly under scenarios with reduced rainfall. The greatest benefit from adaptations arose from positive management responses in higher rainfall scenarios where benefits of up to 16% were simulated. A previous study identified that these adaptations are likely to be worth \$100m to \$500M per annum to the industry (Howden and Jones 2004). Further adaptations such as opportunity cropping with summer crops or integration with livestock could also be implemented.

The potentially beneficial effects on yield from elevated CO_2 can offset only limited deleterious climate changes. We estimate that an increase in CO_2 concentration to about 650ppm is needed to offset either a 20% reduction in rainfall alone **or** a temperature increase of 5°C. A similar increase in CO_2 would approximately offset the effects of a combined 3°C warming and a 10% reduction in rainfall. Substantially smaller increases in CO_2 (50 to 100ppm lower) are required to maintain yields when adaptation is practiced.

There are several limitations to this study. The risk assessment does not deal independently with non-CO_2 forcing (e.g. Wigley 2004), thus underestimating the range of potential impacts. The results are also highly reliant on the wheat simulation model used. This has been validated for

CO_2 responses within the range of CO_2 concentrations used here (e.g. Asseng et al. 2004, Reyenga et al. 1999) although a case for further testing under a combination of high CO_2 and high water stress could be made. Similarly, the model has been tested in a wide range of environments which broadly cover those conditions simulated in the climate change scenarios but combinations of high temperature and low rainfall outside historical experience may have more deleterious effects than indicated here. However, the model does not incorporate possible changes in pest and disease incidence, changes in the frequency or severity of El Niño/La Niña events, the influence of decadal climate variation or other climate forcing factors, changes in resource status arising from climate change impacting on degradation processes (e.g. van Ittersum et al. 2003) nor other technological changes such as genetic modification of crops that may improve potential yield. Similarly, there are other improvements possible in crop management and seasonal climate forecasting that may offset some of the risks of production loss in a more challenging climate.

5. ACKNOWLEDGMENTS

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