Global change impacts on wheat cropping in the Burnett Region of Queensland: a simulation approach.

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Abstract Future increases in atmospheric CO_2 concentrations are likely to affect agriculture directly through the 'CO_2 fertilisation effect' and indirectly through possible climate changes. An assessment of these potential impacts on agricultural productivity is needed for both farm management and policy making purposes. I_WHEAT, a wheat module in the APSIM cropping system model, was used to investigate changes in CO_2 by modifying radiation use efficiency, transpiration efficiency, specific leaf area and critical nitrogen concentrations. The effects of several combinations of atmospheric CO_2, climate change and crop adaptation strategies on wheat production in the Burnett region were studied. The CO_2 and climate scenarios included, 1) current climate + ambient CO_2 (350 ppm), 2) current climate + 2 x CO_2, 3) temperature increase + 2 x CO_2, 4) reduced rainfall + temp. + 2 x CO_2 and 5) increased rainfall + temp. + 2 x CO_2. Mean wheat yields were increased by 32-36% under doubled CO_2. The yield response relative to ambient CO_2 was greatest in dry years. Higher temperatures under the climate change scenarios moderated the yield gains achieved with increasing CO_2 (7 - 21% increase) and actually reversed them under the reduced rainfall scenario (3 - 6% decrease). The future status of the region as a producer of prime hard wheat may be at risk due to reduced grain protein levels (12-14% decrease) under doubled CO_2 and the increased likelihood of 'heat shock' in the climate scenarios used. As the use of different crop varieties had little effect on yields under climate change, it is likely that in south east Queensland the existing crop varieties may be adequate to deal with the impacts of increasing CO_2 and climate change, particularly as the marked reduction in frost risk may allow more flexible planting/cultivar regimes. However, adaptations such as breeding of heat tolerant cultivars as well as changes in fertiliser management may be needed to counter the changes in wheat quality associated with elevated CO_2 and temperatures. Model limitations are discussed.

1. INTRODUCTION

Historical increases in atmospheric carbon dioxide concentrations (CO_2) have been well documented with mid-range projections suggesting a doubling of current concentrations to 700 ppm by the year 2100 (Houghton et al. 1996). Increasing atmospheric CO_2 can affect agricultural production both directly through the stimulation of photosynthesis, particularly in C_3 plants (eg. Cure and Acock 1986), through improved water use efficiency (eg. Gifford 1979), and indirectly as the increased concentration of CO_2 and other greenhouse gases in the atmosphere may induce climate change. Global change is the combined effect of changes in CO_2 and climate. The impacts of global change on agricultural productivity is difficult to predict, yet the assessment of these impacts is needed for both farm management and policy making purposes. The temporal and spatial scale of the issue means that simulation models when combined with experimental research are likely to be the most effective approach for assessment.

A variety of modelling approaches have been developed for such studies. These models range from complex models which represent leaf cellular processes to those which simulate crop canopies and cropping systems. There are significant issues relating to trade-offs between process description and parametisation of these approaches (Passioura 1996). This study needs to include management adaptation aspects as well as the direct impacts. Hence we use a cropping systems approach using an existing wheat model I_WHEAT (Meinke et al. 1997) linked in with the APSIM modelling framework (McCown et al. 1996). I_WHEAT replaces groups of processes with conservative, biologically meaningful, parameters which enables the model to be used across a range of environments (Meinke et al. 1997). However, I_WHEAT requires explicit modifications to include the effects of changing CO_2.

The aim of this paper is to 1) describe the modification of I_WHEAT to include the effects of elevated CO_2 concentrations and 2) present some preliminary simulations of the impact of CO_2 and climate change on cropping systems including adaptations in the Burnett region of SE Queensland. This region was selected as it is known to be sensitive to climate variability (Meinke and Hammer 1995) and hence is also likely to be sensitive to climate change.

2 MODEL DESCRIPTION

A full description of I_WHEAT and model testing is given in Meinke et al. (1997). Briefly, leaf area and tiller formation in I_WHEAT are calculated from thermal time and phyllochron interval. Dry matter accumulation is calculated either from the amount of intercepted radiation and radiation use efficiency (RUE) or from the amount of water transpired and transpiration efficiency (TE), depending whether radiation or water is the most limiting resource. Yield is simulated using a linear increase in harvest index (HI) with thermal time. The increase in HI ceases when nitrogen and water limitations occur. Nitrogen limitation first reduces leaf area development and then affects radiation use efficiency as it becomes more severe. The degree of limitation is a function of the specific leaf nitrogen (SLN) which is derived in part from specific leaf area (SLA). Critical nitrogen concentrations (CNC), which vary with phenological stage, determine the nitrogen allocation within the plant. Water or nitrogen limitations result in reduced leaf expansion, accelerated leaf senescence or tiller death.

Sensitive feedbacks between light interception and dry matter accumulation are avoided by having environmental effects acting directly on leaf area development, rather than via biomass production. This makes the model more stable across environments without losing the interactions between the different external influences (Meinke et al. 1997).

3 MODIFICATIONS TO THE I_WHEAT MODEL

The key parameters modified in the model are RUE (g/MJ intercepted radiation), TE (g/m^2/mm water transpired), SLA (cm^2/g leaf dry weight) and CNC (the concentration of nitrogen in the shoots at 90% of maximum shoot yield) (Table 1).

Modifications to parameters were determined through a regression analysis of published experimental data similar to that described in Cure and Acock (1986) except using percent changes rather than relative responses. Modifications to RUE and TE were derived from Gifford and Morison (1993).

The primary effect of elevated CO$_2$ is to increase net photosynthesis (eg Cure and Acock 1986). One measure of photosynthetic activity is RUE which represents the net biomass accumulation per unit intercepted radiation integrated over the duration of the growth period. We have used a 24% increase in RUE with doubled CO$_2$ based on the results of Gifford and Morison (1993), one of the few studies to measure RUE change under elevated CO$_2$.

The other direct effect of elevated CO$_2$ is a reduction in stomatal conductance, which reduces transpiration. Coupled with increased CO$_2$ assimilation, these changes increase TE. We used a 33% increase in TE for doubled CO$_2$ based on the results of Gifford and Morison (1993). This is a slightly conservative estimate of the impact of doubled CO$_2$ as other studies have shown increases ranging from 27-80% (eg. Gifford 1979).

Elevated CO$_2$ has also been observed to result in the accumulation of non-structural carbohydrates with resulting decreases in SLA (eg. Rogers et al. 1996). Based on the review of experimental literature we have reduced SLA in the model by 12% with a doubling of CO$_2$ to 700 ppm, however there was significant variability in experimental results.

Elevated CO$_2$ reduces leaf N and CNC (Hocking and Meyer 1991; Rogers et al. 1996). Based on the regression analysis CNC is reduced in the model by 15% with a doubling of CO$_2$ to 700 ppm.

Table 1: Modifications to I_WHEAT parameters under elevated CO$_2$ scenarios (700 ppm).

Parameter	% change with CO$_2$
RUE	+24
TE	+33
SLA	-12
CNC	-15

3.1 Validation

I_WHEAT has been tested against experimental data in a range of environments (eg. Gatton and Toowoomba, Qld; Wagga Wagga, NSW; Lincoln, NZ) (Meinke et al. 1997) providing some confidence in the suitability of this model for evaluations of climate change. Testing against regional yield responses was achieved by comparing simulations against wheat yields (Australian Bureau of Statistics) for the Gayndah Shire, Qld (1978 to 1996). These indicated a reasonable correlation ($y=1.18x$, $R^2=0.46$) between observed data and modelled wheat yields (Figure 1). However, the model tends to overpredict yields in wet years in the middle of the record. An inspection of the data shows that this is likely due to major expansion (up to 10-fold) from the 'core' cropping areas in the mid-1980's to the early 1990's resulting in cropping in more marginal situations in the landscape resulting in lower average yields than those simulated. In addition, these wet years are more prone to pests, weeds and diseases which are currently not modelled. Other potentially important factors not modelled are frost damage and the planting of sorghum during summer which reduces the soil moisture available for the following wheat crop. Furthermore, the rainfall at Gayndah is unlikely to have been fully representative of that falling across the Shire.

The modifications of I_WHEAT to simulate elevated CO$_2$ have yet to be validated. However, comparisons with Free Air CO$_2$ experiments (FACE) (Kartschall et al. 1995) show similar responses. For example dryland simulations using the modified I_WHEAT model suggest increases in biomass at anthesis of 18% compared with the FACE results of 21% and yield increases of 22% compared with the FACE results of 28%. Simulations of irrigated wheat crops suggest yield increases of 3% compared with the FACE results of 2.5%. Thus the model is underpredicting the yield and biomass production under elevated CO$_2$ with dryland simulations and hence will require further development.

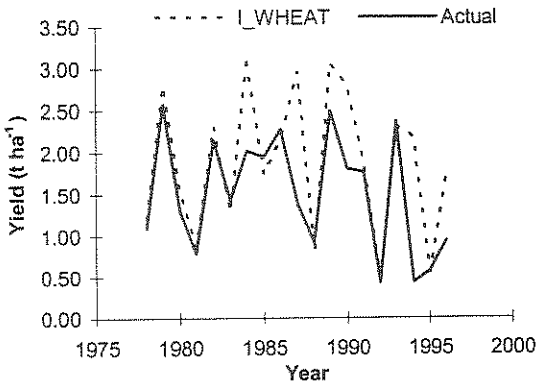

Figure 1: Actual and predicted wheat yields for the Gayndah Shire (1978-1996) in the Burnett region, Qld.

The above comparisons provide some basis for using the modified I_WHEAT model for the global change scenarios in the following exploratory study.

4 EXPLORATORY STUDY

The impact of CO_2 and climate change were modelled for wheat production in the Gayndah Shire of the Burnett region of south east Queensland. The Shire and surrounding region is dominated by a mixed cropping and grazing system, and has generally been considered a core cropping area. However recent droughts have apparently led to a re-evaluation of cropping viability by farmers judging by 10-fold reductions in planted area largely as a result of unfavourable series of years. As the region is sensitive to climate variability (Meinke and Hammer 1995) it is also likely to be sensitive to climate change.

The Gayndah Shire is centrally located in the Burnett. The mean annual rainfall of the township of Gayndah (Lat 25.67S, Long 151.75E) is 770 mm with about 70% falling in summer. Mean maximum temperature is 28°C and mean minimum of 14.2°C. Increases in minimum temperature are occurring (McKeon and Howden 1993). On average 11 frosts are experienced a year. There is considerable variation in soil types in the Burnett region with soils derived from volcanic, granitic and metamorphosed sedimentary substrates. Most cropping occurs on medium depth basaltic or alluvial soils of moderate fertility.

4.1 Simulation Scenarios

Interactions of elevated CO_2 and climate change on wheat cropping were investigated using five scenarios: 1) current climate + ambient CO_2 (350ppm), 2) current climate + doubled CO_2 (700ppm), 3) temperature increase + CO_2, 4) reduced rainfall + temp + 700ppm CO_2 and 5) increased rainfall + temp +700ppm CO_2.

Climate changes were from the CSIRO 1996 scenarios (http:www.dar.csiro.au/pub/programs/climod/cm4.htm). These scenarios were used to modify the climate record for Gayndah for the 1957-1996 period assuming mid-range emissions projections and mid-range climate sensitivities for doubling of CO_2 in about 2100. In the increased temperature scenarios 2.76°C was added to both maximum and minimum temperatures. The two extreme rainfall scenarios were constructed to represent the range of variation suggested as well as an unchanged rainfall scenario for the CO_2 + temperature increase scenarios. The 'dry' climate change scenario (Dry CC) was constructed by reducing summer (ie Oct. to Apr.) rainfall by 24% and winter rainfall by 12%. A 'wet' climate change scenario (Wet CC) was similarly constructed with no change to summer and +12% for winter. Rain days were randomly reallocated based on the results of a stochastic weather generator with GCM input (Bates et al. 1996) which suggested no change in the number of summer rain days but a 39% reduction in winter rain day frequency. Daily rainfall totals in winter were adjusted to maintain the total season rainfall.

4.2 Planting Rules and Variety Strategies

APSIM allows the use of flexible planting rules. In these simulations, sowing can occur within the given planting window (30 April until 20 July) four days after there has been 25 mm of rain (accumulated over two days) if the fraction of water stored in the soil is greater than 0.3. 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. The crop is sown at a density of 100 plants m^{-2} at a depth of 50 mm. Two fertiliser rates were simulated ± 90 kg N ha^{-1} of fertiliser (NO_3-N). A summer fallow is simulated with the water balance carried through the entire run. The nitrogen levels are however, re-initialised each year as nitrogen rundown or buildup are not simulated in this evaluation of climate and CO_2.

The higher temperatures associated with climate change will increase the rate of phenological development, which may affect the yield of standard crop varieties raising the suggestion of the use of slower maturing varieties (Gifford et al. 1996). In these simulations three different varietal strategies are used (standard, slow and quick maturing) to investigate potential adaptation options. In addition, an autonomous cultivar/management strategy is included whereby within the planting window the thermal time from emergence to the end of the juvenile phase and the phyllochron interval were modified based on the sowing date (Table 2). Other phenological characteristics are held constant.

Table 2: Varietal changes to thermal time from emergence to end of juvenile phase and phyllochron interval based on sowing date.

	Thermal time	Phyllochron Int
Standard	-3.0 x day + 1060	-0.6 x day + 195
Slow	-3.3 x day + 1206	-0.7 x day + 221
Quick	-2.7 x day + 954	-0.6 x day + 176

4.3 Frost Risk and Incidence of Heat Shock

If frosts occur during floral development, grain yields can be significantly reduced (eg Gifford et al. 1996). The risk of frost was analysed under current and changed climate scenarios by creating probability distributions of the last day of frost in each year for light, moderate and heavy frosts. Light frosts were considered to occur below 2.2°C screen minimum temperature, while moderate frosts occurred below 1°C and heavy frost below 0°C.

Wheat plants exposed to very high temperatures during grain filling produce grain with reduced bread-making qualities (Stone et al. 1996). The frequency of days with temperatures over 32°C during the grain filling period was compared for the current and changed climate scenarios.

5 RESULTS

5.1 Yield

Modelled yield is highly variable from year to year (Figure 2) and is largely driven by rainfall variability. High levels of CO_2 increased the variability due to higher yields in the wetter years.

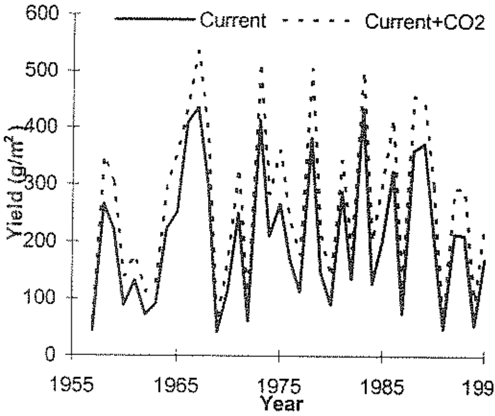

Figure 2: Simulated wheat yields under current climate for ambient and doubled CO_2 at Gayndah, Qld for the standard crop varieties.

The yield of all crop varieties was increased under the elevated CO_2 scenario, with average yields increasing by 32 to 36% (Table 3). These yield gains were largely removed by increased temperature with yield increasing by only 7 to 21% compared with current yields.

Table 3: Mean wheat yields (g m^{-2}) of the standard, slow and quick varieties for all five scenarios as described in text

	Standard	Slow	Quick
Current	206	192	209
Current+CO_2	272	261	277
Temp + CO_2	233	233	224
Dry CC	200	194	196
Wet CC	256	254	249

Increased rainfall in the 'wet' scenario increased these yields by 19 to 32% whilst the 'dry' scenario reduced yields by 3 to 6% compared with current conditions. The use of different varieties had only a minor influence on yields under the high temperature regimes.The yield response to elevated CO_2 was dependent on season type with yields increasing by around 50% in dry years and 20% in wetter years (Figure 3).

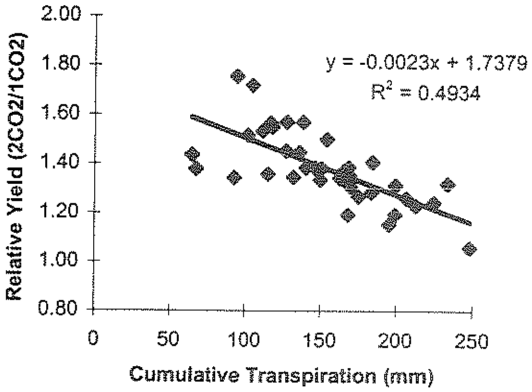

Figure 3: Relative wheat yields under doubled and ambient CO_2 compared with cumulative transpiration over crop growth.

5.2 Grain quality and frost risk

The nitrogen content of grain in all varieties was reduced both with (10-11%) and without (12-14%) fertiliser under elevated CO_2 (Figure 4). However, application of fertilisers under elevated CO_2 did bring nitrogen concentrations back up to a level equivalent with the unfertilised current climate scenario. Increased temperatures moderated the reduction (2-8% decrease) in the N content of grain slightly but was still lower than the current climate levels for the equivalent fertiliser treatment.

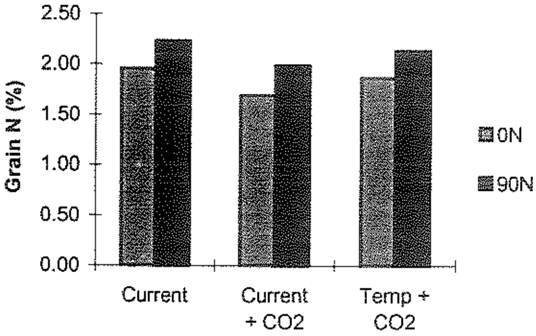

Figure 4: Average nitrogen content (%) of grain under current climate, doubled CO_2 and doubled CO_2 with climate change for standard crop varieties.

The potential risk of heat shock to wheat during grain filling was significantly increased under climate change with the frequency of threshold temperatures above 32°C increasing from 8.5% under current climate to 15.9% with climate change.

The chance of a frost in any given year was significantly reduced and the dates of last frost were brought forward under climate change (Table 4). For farmers in the Burnett region a generally accepted frost risk is 10%; this risk can be determined by a comparison of the 9th decile last day of frost and the 1st decile anthesis date. First decile anthesis for the standard varieties was reached on day 238 under current climate but this was brought forward to day 223 under the higher temperature climate change regime. Similar changes were evident in the slow (day 249 to day 233) and quick varieties (day 228 to day 213).

Table 4: Chance of a frost (COF) (% years with frost) and the 9th decile last day of frost (LDF) for light, moderate or heavy frosts under current and changed climate.

	Light	Moderate	Heavy
Current Climate			
COF (%)	95	85	74
LDF	239	234	216
Climate Change			
COF (%)	44	18	3
LDF	214	194	200*

*Frost only occurs in one year in the record

5.4 Cumulative Transpiration

Cumulative transpiration was similar under ambient and enhanced CO_2 conditions (Figure 5), although there was a slight but significant increase with doubled CO_2 under dry conditions.

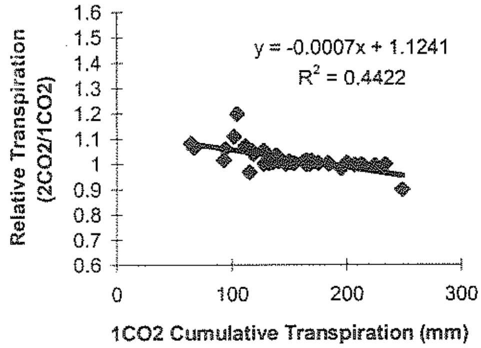

Figure 5: Relative transpiration under doubled and ambient CO_2 compared with cumulative transpiration under ambient CO_2

7. DISCUSSION

These simulations indicate large changes in wheat yields under some possible future CO_2 and climate scenarios. Simulated mean wheat yields were significantly higher (32-36%) under doubled CO_2. These increases are comparable with those found in controlled experiments (35% ± 14) (Cure and Acock 1986) but are slightly lower than the results inferred from FACE experiments at 550 ppm (Kartschall et al 1995). The absolute response of wheat yields to elevated CO_2 was greatest during wet years, resulting in increased variability of yields. However, and perhaps more importantly in relation to both buffering enterprise income and ensuring food security, the response to increased CO_2 was greatest in dry years with around a 50% yield increase compared with a 20% increase in wetter years. A similar relationship was found by Gifford (1979). The increased response in dry years is due in part to the greater water use efficiency under elevated CO_2. However, as has been found in many experiments (eg Gifford 1979), cumulative transpiration in most years did not differ significantly between the two CO_2 scenarios because increased leaf area development largely counteracted the increased efficiency. In dry years, this additional leaf area development may reduce soil evaporation slightly thus increasing transpiration over the ambient CO_2 treatment.

Higher temperatures under climate change scenarios strongly moderated the yield gains achieved with elevated CO_2 as also found by Wang et al. (1992). These reductions in yield are likely to be associated with both higher vapour pressure deficits and reduced accumulated intercepted radiation due to the faster maturity under elevated temperatures. There remained a significant sensitivity to rainfall scenarios under enhanced CO_2 with wet scenario yields increasing by 19 to 32% compared with current yields but with yields dropping by 3 to 6% under the dry scenario.

The risk of moderate to heavy frost is already reasonably low in the Burnett region and this risk is almost removed under the climate change scenarios thus increasing possible options for planting window/variety combinations to avoid the water stress that appears to be a major limit to successful cropping.

In these simulations, using slow maturing varieties was not a significant adaptation option for the warmer climate. Whilst the response of the slow variety was greatest to both increased CO_2 and temperatures, yields never exceeded those of the standard crop variety. It is likely that even with the earlier maturity dates under climate changes, water limitations at the end of the season are still restricting production in most years. Adaptations to the slower maturing wheat varieties as suggested by Gifford et al. (1996) may be more critical in cropping areas further south where frost risk is much greater. However, these are preliminary results and further evaluations of planting dates and varietal effects are required.

The impact of agricultural pests, diseases and weeds is a significant factor in determining wheat yields that is currently not modelled here. Changes in CO_2 concentrations and climate may effect the distribution and pest-plant interaction of pest and diseases and the competitive balances between weeds and crops (Sutherst 1995). However, it is not possible to predict how these changes will affect yields at this time.

This study raises concerns as to the future status of northern Australia as a major producer of prime hard wheat. The high protein levels currently achieved were significantly reduced (12-14%) with elevated CO_2 as also found in experimental data (Gifford et al. 1996, Rogers et al. 1996). The simulations suggest that increased temperatures could moderate this reduction and that fertiliser application could be used to maintain grain N at current levels. However, increased temperatures under the scenarios used almost doubled the frequency of 'heat shock' days (temp >32°C) during grain filling. These conditions change the protein composition and reduces grain quality (Stone et al. 1996).

Adaptations may thus be needed, to counter the changes in wheat quality associated with elevated CO_2 and temperatures. For example, breeding of heat tolerant cultivars, changing planting windows as well as changes in fertiliser management.

7.1 Model Limitations

The model was found to over-predict historical yields in the Burnett region, particularly in wet years. Improved simulations of the regional response could potentially be achieved by the allocation of different land classes to cover the expansion into marginal cropping areas in more favourable years, more effectively simulating regional rainfall by spatial modelling, adopting a cropping systems approach with both wheat and sorghum production and simulating pest, weeds and disease impacts.

The modified I_WHEAT model also appears to slightly under-predict the yield response to CO_2. Further development with experimental datasets and testing of representations of CO_2 effects with FACE data is needed.

The simulations represent a 'step increase' in CO_2 concentrations rather than a more realistic 'transient' increase which would result in progressive changes to factors such as the soil carbon/nitrogen dynamics. Furthermore, soil parameters are currently re-initialised each year to values representative of existing conditions. Further studies need to address these issues.

Finally, the current climate data set on which the scenarios are based incorporates existing trends in elements such as minimum temperature (eg McKeon and Howden 1993, Nicholls 1997). The implications of these trends needs to be further explored.

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