Impacts and Adaptation to Climate Change in Western Australian Wheat Cropping Systems

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EXTENDED ABSTRACT

The environment in which crops will be grown in the future will change. Temperatures and CO_2 concentrations [CO_2] will increase. Also a decline in winter rainfall of up to 30% in 2070 is predicted for south-west Australia. Effects of climate change on cropping systems were simulated with the Agricultural Production Systems Simulator (APSIM-Nwheat) using transformed historic weather data. Fifty years of yield were simulated for three soil types at different locations on a north – south transect within the wheatbelt of south-west Australia.

Simulation results showed that there were complex interactions between different aspects of climate change on crop systems. Effects of higher temperatures, elevated [CO_2] and changed rainfall were in general not linear and differed significantly between soil types and location. Higher [CO_2] increased yield especially at drier sites while higher temperatures especially had a positive effect in the cooler and wetter southern part of the region. The main difference between soil types was that heavier clay soils were most vulnerable to reduced rainfall while sandy soils were more vulnerable to higher temperatures.

We tested which changes in crop traits would be a good adaptation to climate change for wheat systems. Earlier flowering varieties can increase production at lower rainfall and ambient temperatures. At increased temperatures a later maturing variety will promote wheat production.

On clay soils early vigor did not improve yields for historic and future climate scenarios. Also increased rooting depth did not positively affect yields on clay soils. So the options for adapting cropping systems to climate change on clay seem to be limited. This in combination with the results that yields on clay soils are reduced the most by climate change makes these soils very vulnerable to the impacts of a drying climate.

On loamy sand soils however there are plenty of opportunities to adapt cropping systems to climate change. In addition to longer season varieties and early vigor also increased rooting depth can significantly increase yields under future climate change.

1. INTRODUCTION

Different aspects of climate change, such as higher atmospheric CO_2 concentration [CO_2], increased temperature and changed rainfall all have different effects on plant production and crop yields. In combination, these effects can either increase or decrease plant production and the net effect of climate change on crop yield depends on the interactions between these different factors.

In general, higher [CO_2] increases plant production due to higher rates of photosynthesis and increased water use efficiency (Morison, 1985; Drake et al. 1997; Garcia et al. 1998). Increased temperatures can reduce plant production through heat stress and increased water demand (Herwaarden et al. 1998, Lawlor and Mitchell 2000). Especially in Mediterranean environments where crops are grown in winter, warmer temperatures can also increase plant production (Van Ittersum et al. 2003). Changed rainfall patterns due to climate change will have the most significant effect on agricultural production especially in (semi)-arid regions.

The most likely future climate scenarios for south west Australia are a reduction in winter rainfall of about 15% by 2030 and 30% by 2070 (Pittock 2003). This reduction in rainfall is a significant threat for the grains industry in Western Australia. To sustain future agricultural production in this changing climate, farming systems have to adapt and future crops will probably need a different set of traits.

With a warmer and drier climate the growing season will be shorter in the future. However at the same time there are opportunities to increase growth rates due to higher temperatures and increased CO_2 concentrations. Early vigor can potentially help reaching this high potential growth rate. Wheat varieties which are currently used in Australia have a low vigor and grow relatively slowly during the earlier part of the season (Botwright et al. 2002). Changes in temperatures and rainfall could also change the phenological requirements of future crops. For example, to avoid terminal drought earlier flowering could be an adaptation to a drying climate while a warmer climate might require later flowering because crops tend to flower too early in warmer weather (Lawlor and Mithchell 2000).

We used a simulation model to study the impacts of climate change on wheat cropping systems and to test which changes in plant traits can potentially be a good adaptation to climate change.

2. METHODS

2.1. APSIM

For our simulations, we used the Agricultural Production Systems Simulator (APSIM) configured with the Nwheat crop module, SOILN2, SOILWAT2 and RESIDUE2 soil and residue modules (Probert *et al.* 1998; www.apsim.info). This model configuration simulates carbon, water and nitrogen dynamics and their interactions within a wheat crop/soil system that is driven by daily weather information (rainfall, maximum and minimum temperature and solar radiation). It calculates the potential yield, that is, the yield not limited by pests and diseases, but limited only by temperature, solar radiation, water and N supply.

APSIM-Nwheat has been tested extensively against field measurements in various studies under a large range of growing conditions (Probert et al., 1995; 1998; Asseng et al., 1998; 2000; 2004) For the purpose of modelling implications of elevated [CO_2], the Nwheat module was extended with two functions derived from the literature, as described by Reyenga et al. (1999). Briefly, with elevated CO_2 concentrations both radiation use efficiency, and transpiration efficiency are increased. These changes in the model to simulate [CO_2] effects on crop growth have been tested against experimental data from free-air CO_2 enrichment experiments (Asseng et al., 2004).

2.2. Study sites and soils

For this study we used three sites along a North-South transect within the Western Australian Wheatbelt. The most northern and warmest site was Binnu (latitude 28.04°S, longitude 114.67°E). Kellerberrin (31.6°S, 117.7°E) was the central site and the third site was Kojonup in the south (33.8°S, 117.1°E). Average annual rainfall over the last 50 years (1954-2003) was lowest in Kellerberrin (320 mm), a little higher in Binnu (382 mm) and highest in Kojonup (562 mm) (Figure 1). For the simulations, two different soil types were used: an acid loamy sand and a clay soil. Due to the different textures, soils varied in water holding capacities and thus in plant available water (PAW). PAW was highest for clay soil, 109 mm, up to 150 cm depth which is assumed to be the maximum rooting depth. For the acid loamy sand soil, PAW was 90 mm. Full details of the soils are described in Asseng et al. (2001).

2.3. Simulation experiments

The climate scenarios we simulated covered the complete range of predicted changes for south west Australia (Pittock 2003). We modelled ambient temperatures and +2, 4, and 6°C higher temperatures. For changes in rainfall five different scenarios were used: historic rainfall, -15%, -30%, -45% and +10% rainfall. For reduced rainfall scenarios, rainfall was only reduced for the winter months (May-October) (Pittock 2003). For every scenario, we simulated 50 different years. Daily weather records for each scenario were created by modifying the historic weather data of the last 50 years (1954-2003) according to Reyenga et al. (1999). For the elevated temperature scenarios daily minimum and maximum temperatures were increased by adding 2, 4 or 6 degrees to the historic records. Rainfall was reduced or increased by changing every individual rainfall event. So, the number of rainfall events remained equal but the intensity of each event was changed. Every climate scenario was run for 3 different atmospheric [CO_2]: 350 ppm ([CO_2] at the time when the APSIM model was developed), 525 ppm and 700 ppm. All simulations were done with 50 kg N ha^{-1} yr^{-1} fertilizer.

To test which changes in plant traits would be a good adaptation to climate change we modified a range of plants traits in the ASPIM-Nwheat model to simulate the growth of these new varieties for current and future climates using the historic and modified climate data. Early vigor was simulated by increasing the specific leaf area (SLA) of seedlings (see Asseng et al. 2003 for details). Increased early root growth was simulated by reducing the root hospitability factor by 50% in the top 30 cm of the soil. Early and later flowering was simulated by increasing and reducing the tillering phase of the crop. The standard crop simulated in ASPIM-Nwheat has a tillering phase of 400 degree*days (°Cd). We modified the tillering phase in the model by both reducing and increasing it by 50 and 100 °Cd.

Data on the effect of changes on crop traits are presented for the historic climate (1954-2003) and for two future climate scenarios. For 2050, a scenario was selected with 525 ppm [CO_2], 2°C higher temperatures and 15% reduced winter rainfall. The second climate scenario (2100) was 700 ppm [CO_2], 4°C higher temperatures and 30% reduced winter rainfall.

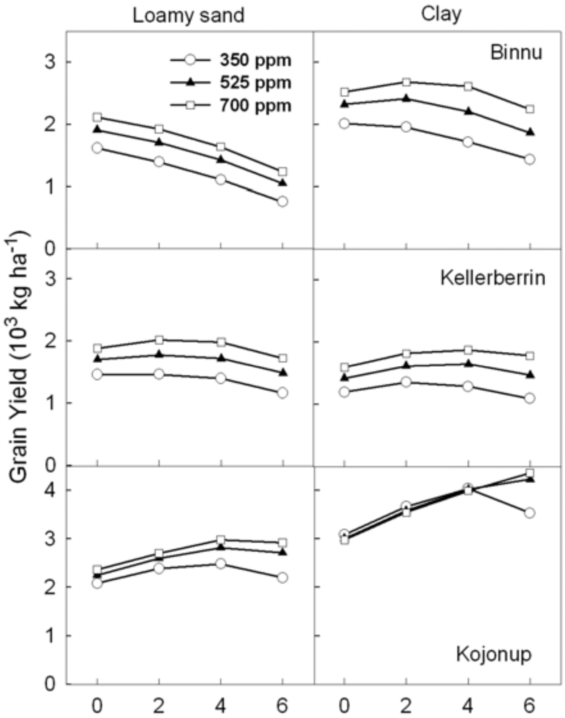

Figure 1. Effects of increased temperature on simulated wheat yields for three different atmospheric CO_2 concentrations. Each point is the average of 50 years of simulations. Every graph represents a different soil type at a different location. For all simulations a fertilizer level of 50 kg N ha^{-1} was used. Note different scale of Kojonup graphs.

3. RESULTS

Higher atmospheric CO_2 concentrations [CO_2] increased production, especially at the two drier sites, Binnu and Kellerberrin (Figure 1). However, elevated [CO_2] did not necessarily increase yield in all cases. For example, at clay soils in Kojonup higher [CO_2] had hardly any effect on yields.

Effects of increased temperatures on yields differed between locations. At Binnu, the most northern and warmest site, an increase of 2°C reduced yield on loamy sand soils and an increase of 6°C reduced the yield by more than 50%. At Kojonup, up to 4°C higher temperatures increased the potential yield up to 32%.

The impact of higher Temperatures on yield differed between soil types. For example, at Binnu, higher temperatures reduced yield much more at loamy sand soils than at clay soils. At Kojonup, higher temperatures increased production more on clay than on loamy sand soils. There was also a clear interaction between higher temperatures and elevated [CO_2]. At higher temperatures, elevated

[CO_2] increased production more than at ambient temperatures (Figure 1).

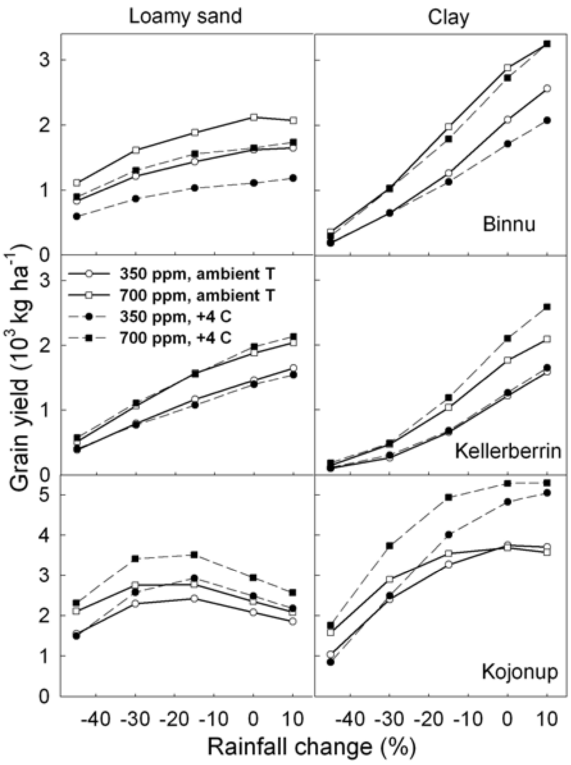

Figure 2. Effects of altered rainfall on simulated wheat yields for two different atmospheric CO_2 concentrations using either historical temperatures and + 4°C. Each point is the average of 50 years of simulations. Every graph represents a different soil type at a different location. All simulations are based on 50 kg N ha^{-1} fertilizer. Note different scale of Kojonup graphs.

Lower rainfall reduced yields on both soil types at Kellerberrin and Binnu (Figure 2). Lower rainfall reduced yields much more on clay than on loamy sand soils. In Kojonup, a reduction in rainfall of 15-30% increased yield at the loamy sand soil. On clay soils, however, reduced rainfall had a negative effect on grain yield at Kojonup.

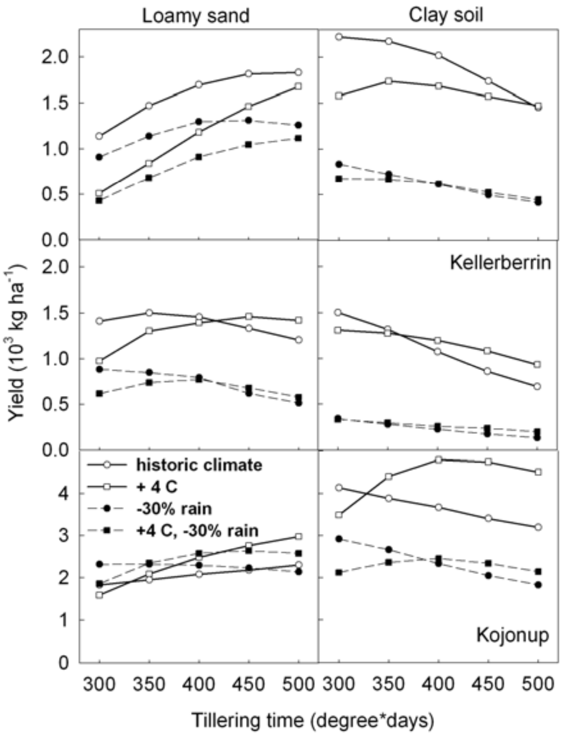

Figure 3. Effect of changed tillering time on simulated wheat yields for the historic climate, at warmer temperatures and at reduced rainfall. A longer tillering time results in a later flowering and maturing crop. Each point is the average of 50 years of simulations. Every graph represents a different soil type at a different location. Note different scale of Kojonup graphs.

There were important interactions between increased temperatures, higher [CO_2] and reduced rainfall. For example, at Kojonup, higher [CO_2] had little effect on yield at ambient temperatures and reduced rainfall. However, if temperatures were increased by 4°C, doubling [CO_2] concentrations increased yield by about 1000 kg per hectare (Figure 2).

Changes in the length of the tillering phase and consequent flowering date had large impacts on grain yield (figure 3). Both rainfall and temperature affected whether earlier or later flowering increased yield. For the historic climate a longer tillering phase increased yield at loamy sand soil while at clay soil earlier flowering increased yield. At higher temperatures the optimal tillering time was longer than for ambient temperatures. If only the rainfall was reduced the optimal tillering time was shorter than for the historic rainfall. In a dryer and warmer climate the changes depended on soil type

Whether later or earlier flowering increased or decreased crop yield for future climate scenarios depended on soil type and location (Figure 4). Later flowering increased production on loamy sand soils, especially in Binnu in the Northern (warmer) part of the region. Early flowering decreased yield at loamy sand soil, particularly for future climate scenarios. On clay soils flowering time had less effect on yield than loamy sand soils.

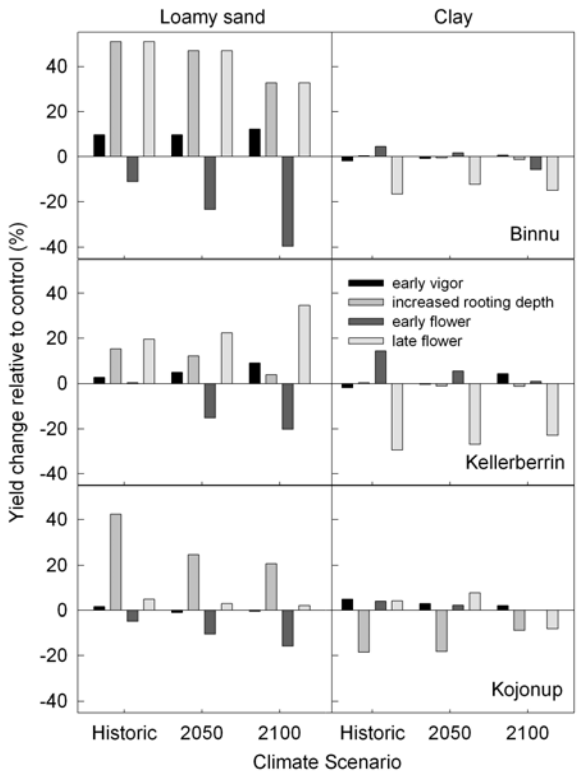

Figure 4. Difference in simulated yield between traditional varieties and varieties with different changes in traits. Yields were simulated for the historic climate (1954-2003) and two future climate scenarios: 2050: 525 ppm [CO_2], + 2°C and -15% rainfall, and 2100: 700 ppm [CO_2], + 4°C and -30% rainfall. Every graph represents a different soil type at a different location.

Early vigor increased yield at the acid loamy sand soil at the two drier locations (Binnu & Kellerberrin) (Figure 4). The relative increase in yield was quiet small but tended to be higher for future climates scenarios. On clay soil, early vigor hardly affected yields. Increased rooting depth improved yield at the loamy sand soils at all locations but the beneficial effect was larger for current than for future climate scenarios. Increased rooting depth slightly reduced yield at the clay soil in Kojonup.

4. DISCUSSION

Our results showed that there are complex interactions between different aspects of climate change on crop systems. Effects of higher temperatures, elevated [CO_2] and changed rainfall were in general not linear and differed significantly between soil type and location. The most important difference between soil types is that heavier clay soils are more vulnerable to reduced rainfall than sandy soils. Sandy soils however are more vulnerable to higher temperatures. These differences indicate that impacts of climate change will vary significantly for different farms and regions depending on the dominating soil types.

As future climate change has the potential to significantly reduce crop yield, adaptation is necessary to sustain profitability of farming systems in Western Australia (WA). Changing to longer or shorter season varieties is one option for adapting crops to climate change (Lawlor and Mitchell 2000). However different aspects of climate change require different changes in the season length of the variety. In a drying climate shorter varieties increase yield but in a warming climate longer varieties improve yield.

Also different soil types have different optimal flowering dates. Crops growing on clay soils in south west Australia are more vulnerable to terminal drought so earlier flowering tends to increase yields on these heavier soils. On loamy sand soils yield is more limited by biomass production. In this case later flowering which increases the number of growing days can increase the biomass production and eventually grain yield.

Differences in response to climate change between the two soil types partly explains why different adaptation strategies are needed. On loamy sand soils, introducing later maturing varieties is probably a good climate change adaptation strategy because crops growing on lighter soils are vulnerable to the reduced number of growing days caused by higher temperatures. On clay soils later maturing varieties do not increase yields for future climate scenarios because crops are more sensitive to reduced rainfall which increases the harmful effects of terminal drought.

Also early vigor varieties can be used to adapt wheat systems to climate change on loamy sand soils. The positive effect of early vigor tended to be larger for future than for the historic climate. The amount of fertilizer used in our simulation was relatively low and the positive effects of early vigor can be further improved by increasing N fertilizer rates (Asseng et al. 2003). So there is a potential to use early vigor varieties to improve crop production in a changing climate.

On clay soils, early vigor does not improve yields. Also increased rooting depth does not positively affect yield on clay soils. So the options for adapting cropping systems to climate change on clay seem to be limited. This in combination with the results that yields on clay soils are reduced more severely by climate change makes these soils very vulnerable to the impacts of a drying climate.

On loamy sand soils however there are plenty of opportunities to adapt cropping systems to climate change. In addition to longer season varieties and early vigor also increased rooting depth can significantly increase yields.

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6. 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

Asseng, S., Keating, B. A., Fillery, I. R. P., Gregory, P. J., Bowden, J. W., Turner, N. C., Palta, J. A., & Abrecht, D. G. (1998) Performance of the Apsim-Wheat Model in Western Australia. *Field Crops Research* 57, 163-179

Asseng S, Keulen Hvan, Stol W, & van Keulen H (2000) Performance and application of the APSIM Nwheat model in the Netherlands. *European Journal of Agronomy* 12, p37-54

Asseng, S., Turner, N. C., Botwright, T., & Condon, A. G. (2003) Evaluating the Impact of a Trait for Increased Specific Leaf Area on Wheat Yields Using a Crop Simulation Model. *Agronomy Journal* 95, 10-19

Keating, B.A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D. , Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., Mclean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., Mccown, R. L., Freebairn, D. M., & Smith, C. J. (2003) An Overview of Apsim, a Model Designed for Farming Systems Simulation. *European Journal of Agronomy* 18, 267-288

Lawlor, D.W. & Mitchell, R. A. C. (2000) Crop ecosystem responses to climatic change: wheat. *Climate change and global crop productivity* (eds Reddy, K.R. & Hodges, H.F.), 57-80. CAB International, Cambridge

Pittock, B. (2003) *Climate Change: An Australian guide to the science and potential impacts*. Australian Greenhouse Office, Canberra

Probert, M. E., Carberry, P. S., McCown, R. L., and Turpin, J. E. Simulation of legume-cereal systems using APSIM. Contributions of legumes to nitrogen nutrition and sustainable production of cereals. Proceedings of a workshop. 317-327. 1998. Collingwood, Victoria, CSIRO Publishing.

Probert, M.E., Keating, B. A., Thompson, J. P., & Parton, W. J. (1995) Modelling water, nitrogen, and crop yield for a long-term fallow management experiment. *Australian Journal of Experimental Agriculture* 35, 941-950

Reyenga, P.J., Howden, S. M., Meinke, H., & Mckeon, G. M. (1999) Modeling global change impacts on wheat cropping in South-East Queensland, Australia. *Environmental Modelling & Software* 14, 297-306

Van Herwaarden, A.F., Richards, R. A., Farquhar, G. D., & Angus, J. F. (1998) 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser. III. The influence of water deficit and heat shock. *Australian Journal of Agricultural Research* 49, 1095-1110

Van Ittersum, M.K., Howden, S. M., & 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 & Environment* 97, 255-273