Modelling the growth and grain yield response of wheat crops under Free Air Carbon dioxide Enrichment at Horsham and throughout Victoria, Australia

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Abstract

We validated the landscape-scale Catchment Analysis Tool (CAT) wheat model against field data including data from the Free Air Carbon dioxide Enrichment (FACE) experiment located at Horsham, Victoria, Australia. Yield was simulated with a RMSE of 0.74 t/ha. The model was applied across the whole of Victoria to inform policy on likely changes to wheat crop production at the landscape scale due to climate change. Significant changes in crop production across Victoria are predicted if the climate changes according to the Inter-governmental Panel on Climate Change A1Fi 2050 scenarios. Most critical to north-western Victoria are scenarios of reduced rainfall. For the more arid zones, sowing a faster-maturing type (cv. Silverstar) in June was predicted to result in the best outcome with some small gains and losses predicted. Sowing earlier or later than June resulted in yield losses of around 10 to 20%. In the higher-rainfall areas of southern Victoria, consistent gains in yield of around 10-20% by 2050 should occur in all cultivar types (e.g. Silverstar, Chara or Mackellar types without vernalisation requirements), but only from later sowing times (July to August). Despite the greater uncertainty in climate models compared to crop models, in the context of a moderate temperature rise of about 2 degrees, we expect that wheat crop phenological development can be re-engineered towards slower-developing spring types and that growers will need to alter sowing times to maximise grain yield under future climate scenarios across Victoria.

Key words

Climate change, FACE, simulation models

Introduction

Crop simulation models provide robust and objective methods to extrapolate likely crop response to climate change over different landscapes and time periods (Hoogenboom 2000). Previous regional analyses of climate change in Australia have been made as a series of point-source analyses using representative localities to describe the likely response of wheat to future climate scenarios (Hammer et al. 1987; Wang and Connor 1995; Asseng et al. 2004; Howden and Crimp 2005; Anwar et al. 2007; Crimp et al. 2008). In Victoria, the few locations previously modelled are not considered representative of the region (e.g. Birchip or Mildura), particularly for southern Victoria where future crop productivity and the area of production might increase under a warmer and drier climate. This paper reports progress applying a landscape-scale crop model against experimental data across the region, including elevated atmospheric CO_2 data in a Free Air Carbon dioxide Enrichment (FACE) experiment located at Horsham, Victoria, Australia from 2007 (Mollah et al. 2009). The landscape-scale crop model was selected from the suite of the Catchment Analysis Tools (CAT) (from Beverly et al. 2005). After validation, we applied the landscape-scale crop model to simulate likely effects of climate change on crop production across the whole of Victoria, to help inform future policy on adaptive strategies needed in rural Victoria. Specifically, we examined how crop phenology might need to be altered to maximize yield in various production zones in Victoria and how farmers can use this knowledge to minimize the risks of uncertain climatic change and variability.

Methods

Model description and modification

The CAT model is a daily time step model that simulates water balance for a crop including crop transpiration and deep drainage. It comprises sub-models that simulate crop phenology, above-ground

biomass and grain yield accumulation. The yield model is based on the model of O'Leary and Connor (1996) that allows pre-anthesis assimilation partitioning to grain and partitioning to grain during the grain-filling stage on a daily basis, unlike its parent the PERFECT wheat model (Littleboy et al. 1992) that was originally designed for tropical environments and does not perform well with respect to grain yield simulation in southern Australia. The model simulates a catchment water balance in a 3-dimentional mode that allows analyses of the fate of water in the root zone (0-2m), aquifers and streams. The model requires significant soil parameters such as lower and upper extractable water limits, bulk density, pH and initial soil water and mineral and organic carbon and nitrogen. A spatial database comprising these data is interpolated across the landscape with respective weather data used as input to apply the model to a 100 x 100m grid across Victoria. The CAT model was modified to account for elevated atmospheric CO_2 by the method used in the CROPSYST model (St?ckle and Nelson 2001). This involved amending both the radiation use efficiency (RUE) and transpiration efficiency (TE) with simplifying assumptions of aerodynamic resistance of crop canopy of 300 s m^{-1} and canopy resistance of 36 s/m at 350 ppm CO_2.

$$RUECC = (-1.7/(350*(1-1.7))*C02*1.7)/(-1.7/(350*(1-1.7))*CO2 + 1.7) \quad \textbf{(1)}$$

$$TECC = RUECC/\{[delta+(gamma*(36+300)/300)]/[delta +gamma*(((36*CO2)/(350*RUECC)+300)/300]\} \quad \textbf{(2)}$$

Where, RUECC is the proportional adjustment made to RUE (g/MJ) such that RUECC=1 is equivalent to present day RUE, TECC is the proportional adjustment made to TE (kg/ha/mm) such that TECC=1 is equivalent to present day TE, CO2 is the atmospheric CO_2 concentration (ppm), delta (kPa/^oC) and gamma kPa/^oC) are the psychrometric constant and slope of saturated vapour pressure-temperature curve, respectively.

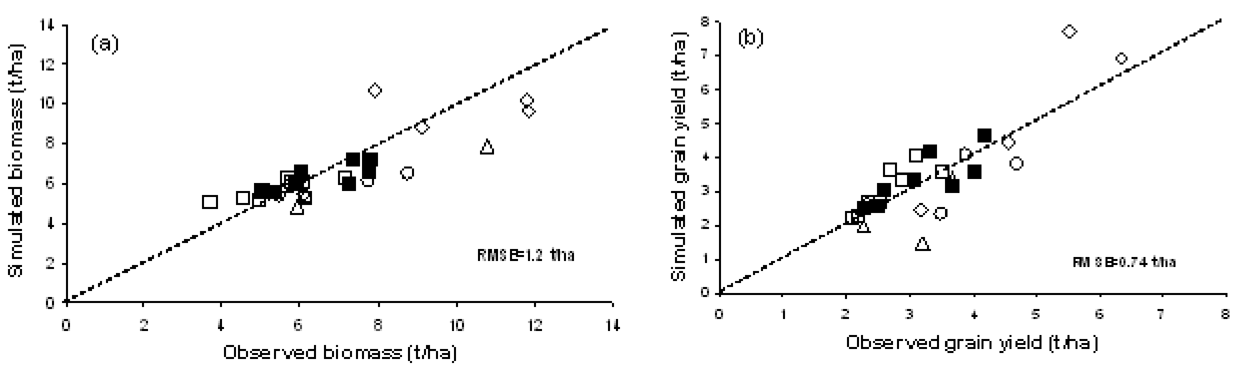


Figure 1. (a) Comparison of simulated wheat biomass at anthesis (a) and grain yield (b) from a range of crops from the Mallee (∆), Wimmera (○, □ and ■) and Western Districts (◊) of Victoria. Data from the 2007 Australian AGFACE experiment show the ambient CO2 (□) and elevated CO2 (■) environments. The 1:1 relationship is the dashed line.

Model performance

We tested the CAT-Wheat model against observed data from Victorian field experiments under the current climate at Walpeup, Horsham and Hamilton and under elevated CO_2 at Horsham (Figure 1). One year of data (2007) from the Horsham FACE experiment was available to test performance under elevated CO_2 (550 ppm, to represent the year 2050 under the A1Fi scenario). The FACE experiment comprised two atmospheric CO_2 levels (ambient 350 and elevated 550 ppm), two times of sowing (18 June and 22 August, 2007), two rates of applied nitrogen (0 and 138 kg N/ha) under two irrigation regimes (48 and 106 mm additional water applied). A rainfed treatment with zero water applied was originally proposed but local dry conditions prompted an early application of the 48 mm water to both regimes. Daily weather data was obtained from the experimental site. The root mean squared error (RMSE) for biomass and grain yield of 1.2 and 0.74 t/ha, respectively is typical for such models and considered satisfactory for subsequent applications. Two further years of FACE data will be available later to complete a more comprehensive analysis despite providing an initial satisfactory validation. Other crop models are currently being tested.

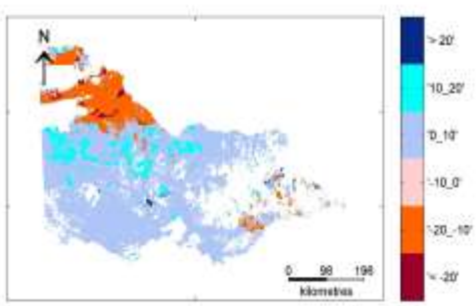
Model application

We applied the IPCC (2001; 2007) extreme climate change scenario (A1Fi) using 68 years of data representing that scenario at 2050 across the whole of the available cropping and pasture land in Victoria (Weeks et al. 2010). We simulated wheat yield with the CAT model from twelve times of sowing (one per month from January through to December) for three crop types (fast-, medium- and slow-developing crop types without vernalisation requirements) under the CCAM Mark 2 and Mark 3 downscaled climate data. Spring wheat is normally sown in autumn and winter to coincide with the winter dominant rainfall of the region. This typically results in sowing from April through to July in the northern region and from March through to September in the southern region.

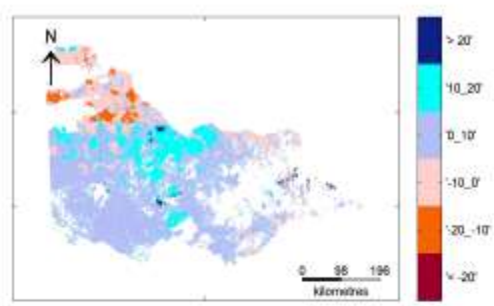
Results and Discussion

The future climate change projections based on IPCC scenarios indicate significant changes for Victoria. Expectations of warmer and drier conditions with rising atmospheric CO_2 concentrations are predicted for western Victoria. Significant differences occurred between the CCAM Mark 2 and Mark 3 climate data reflecting some uncertainty in an IPCC A1Fi climate outlook. Despite this uncertainty, clear trends are evident. For the more arid zones, sowing a faster-maturing type (e.g. cv. Silverstar) in June resulted in the best outcome with some small gains and losses predicted (data not shown). Sowing earlier or later resulted in yield losses of around 10 to 20%. In the higher-rainfall areas of southern Victoria, consistent gains in yield of around 10-20% should occur in all cultivar types (e.g. Silverstar, Chara or Mackellar), but only from later sowing times (July to August) (Figure 2).

Sowing: 1 July CCAM Mark 2



Sowing: 1 July CCAM Mark 3



Sowing: 1 August CCAM Mark 2

Sowing: 1 August CCAM Mark 3

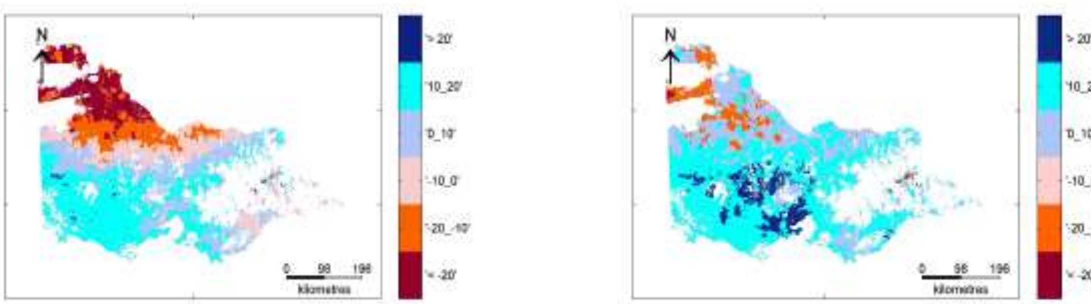


Figure 2. Effect of IPCC scenario A1Fi downscaled by two models (CCAM Mark 2 and CCAM Mark 3) on percentage change in mean wheat grain yield (?20%) from current climate, examining the impact of sowing time on a slow-developing type (e.g. cv. Mackellar, without vernalising requirements).

In southern Victoria, however, the highest yields occurred for a slow-developing type (e.g. like cv. Mackellar, but without vernalising requirements) sown in July under the present climate, with potential for greater yields if sown in August under the A1Fi scenario (CCAM Mark 2 or Mark 3) (data not shown).

Conclusions

Under the A1Fi climate change scenario reduced rainfall in north-western Victoria is the big challenge with significant yield losses (-10 to -20%) likely if crops are sown outside the June sowing window. For the high rainfall zone yield gains (+10 to +20%) are more likely in the South West. There is potential to optimise phenology for high yield by breeding for slower-developing spring types and employing later times of sowing.

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