Impact of projected climates on drought occurrence in the Australian wheatbelt

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Abstract
Wheat is a staple crop, and in Australia it is primarily produced in rainfed environments. Climate change projections indicate an increase in future rainfall variability and in temperature across the Australian wheatbelt. Coupled with the continued increase in demand for this crop due to rising populations and living standards, climate change may significantly impact the Australian wheat industry. The lead times involved in adapting cultivars and management practices mean that planning for adaptation must often begin many years before implementation. Thus timely, realistic assessments of the crop-level implications of climate change are critical to the long-term planning of breeders, farmers and policy makers. Such assessments require extensive analysis of the complex interplay between local environment, genotype, and adaptive management practices. In this study we capture these interactions for 60 representative sites using the APSIM-Wheat crop model, and simulated the impact that 33 climate model projections had on the distribution of drought environment types across the Australian wheatbelt. Simulation results indicate that changes in future drought patterns are highly region-specific. Significant variations in projected changes were found across climate models, giving local ranges of uncertainty to consider in planning efforts. However, simulations for the majority of climate models projected increased frequencies of severe drought conditions in the Western area of the wheatbelt, and fewer severe droughts in other regions. Overall, simulations indicate that all areas of the Australian wheatbelt will continue to experience drought conditions this century, and that adaptation planning is necessary to match future wheat demand.

Key words
wheat, climate change, water deficit, environment characterisation, crop modelling, APSIM

Introduction
Due to the combination of increasing population and rising living standards, demand for staple foods such as wheat continues to increase. Most Australian wheat is produced in water-limited environments, and is exported. Recent climate projections indicate that Australia will experience increased temperature and rainfall variability this century (Zheng et al. 2012; Reisinger et al. 2014), which may have substantial implications for the local wheat industry. As it takes 5-15 years to produce new cultivars, timely assessments of the plausible impacts of climate change are of vital importance (Chapman et al. 2012).

Both the degree and timing of environmental stressors influence crop development (e.g. Fischer 2011). Thus, assessing the impact of abiotic stressors on wheat requires careful consideration of the complex interactions between the local environment, crop genotype, and management practices (Chenu 2015). In this study, we used the APSIM-Wheat model (Holzworth et al. 2014) to capture these interactions at 60 representative sites across the Australian wheatbelt. Seasonal patterns in the water-stress index output by the model were classified to identify key seasonal patterns of water-stress, termed ‘drought environment types’ (Chenu et al. 2013). For each site, a set of future climate scenarios were generated using the projections of 33 climate models from the Coupled Model Intercomparison Phase 5 Project (CMIP5; Taylor et al. 2012). The wheat model was run for each site’s current and future climate scenarios, and every simulated season was classified into one of four drought environment types. The main aims were to (1) assess likely changes in occurrence of drought across the wheatbelt, and (2) identify the range of potential changes projected by this large ensemble of climate models.

Materials and Methods
Characterizing current drought environment types
Crop simulations were performed using the Agricultural Production Systems Simulator (APSIM Version 7.6) for the wheat variety ‘Hartog’ (*Triticum aestivium* L.). For each of the 60 representative sites, two sets of

simulations were performed using historical weather observations from 1955 to 2013, obtained from SILO (Jeffrey et al. 2001). The first set was performed to identify five representative sowing dates and five initial soil water levels for each site, according to local conditions and management practices (see Chenu et al. 2013 for details). These sowing dates and initial soil water values were selected to each represent 20% of the sowing opportunities and soil water conditions, respectively. The resulting 5x5 initial conditions for each site were used in the second set of simulations, to characterize the drought patterns experienced by current wheat crops across the wheatbelt.

For each model run, a daily water-stress index was computed to reflect crop 'water supply/demand ratio', i.e. the ratio of potential soil water available to the crop to the amount that the crop could use for potential transpiration. This index ranged from 0 (no water available to the crop) to 1 (no water stress). Water-stress patterns for each environment (i.e. each unique site, year, sowing date and initial soil water combination) were defined as the water-stress indices averaged every 100°Cd, from 100°Cd after emergence to 450°Cd after flowering.

The 'clara' clustering function (Maechler et al. 2015) was used to group these water-stress patterns into four sets to define four drought 'environment types' (ET; see Figure 1).

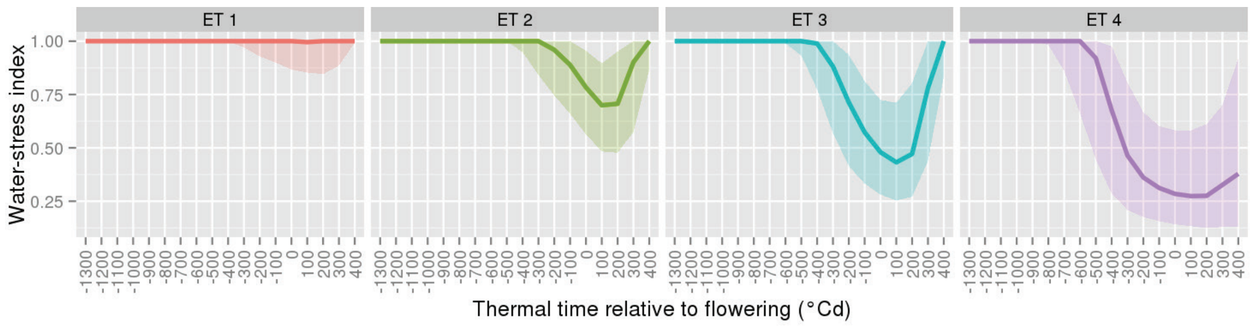

Figure 1. Water-stress patterns defining the four main environment types (ET) identified for the Australian wheatbelt. For each environment type, the median (coloured line) and variations from the 10th to the 90th percentile of the distribution (shading) are presented.

Projecting future environment types

The monthly output of 33 climate models from CMIP5 (Taylor et al. 2012) were used to generate the set of future scenarios by downscaling daily observations from SILO. We employed data from the Representative Concentration Pathway (RCP) 8.5 scenario, which assumes 'business as usual' CO_2 emissions. For each site, future climate scenarios were generated according to each climate model for three distinct time periods centred on 2030, 2050 and 2070 (baseline: 1955 to 2013). All 99 future scenarios were the result of transforming the local daily historical temperature and precipitation values by their projected future local monthly means. For each climate scenario, the water-stress patterns of each site, year, sowing date, and initial soil water combination were simulated as described above (with one set of simulations to identify initial conditions specific to each climate model, and one set of simulations to characterize drought patterns).

In total, 9.2 million crop simulations were performed (1 historical scenario + 99 future climate scenarios) x ((60 sites x 59 years) + (60 sites x 59 years x 5 planting dates x 5 initial soil water values)), which required the equivalent of over 100 days of computing time on a current processor (2.93GHz Intel Xeon X5570). In real time, these simulations were completed in approximately 2.5 days on the University of Queensland's high performance computing facility. Results were stored as compressed NetCDF files using the Python netCDF4 package[1], and the differences between future scenarios and the baseline for the frequency of occurrence of different ETs were processed and analysed using R[2].

Results and Discussion

Future projections for drought patterns varied significantly across climate models, even by 2030, primarily due to differences in projected precipitation. This is consistent with recent work showing that these climate

1 https://github.com/Unidata/netcdf4-python
2 http://www.R-project.org/

models broadly agree on future temperatures, but do not agree on future precipitation patterns in Australia (Reisinger et al. 2014).

Two key aspects of these results are (1) the range of projected environment type responses, and (2) consensus that can be found among the climate models, which indicate likely future impacts.
To assess the range of impacts, climate models were ranked according to their projected changes in occurrence of severe drought environments (ET 3 and 4; Figure 1). Figure 2 presents the range of projected changes in ET occurrence for the most optimistic (CESM1-BGC), the central (MRI-CGCM3), and the most pessimistic (GFDL-ESM2M) climate models.

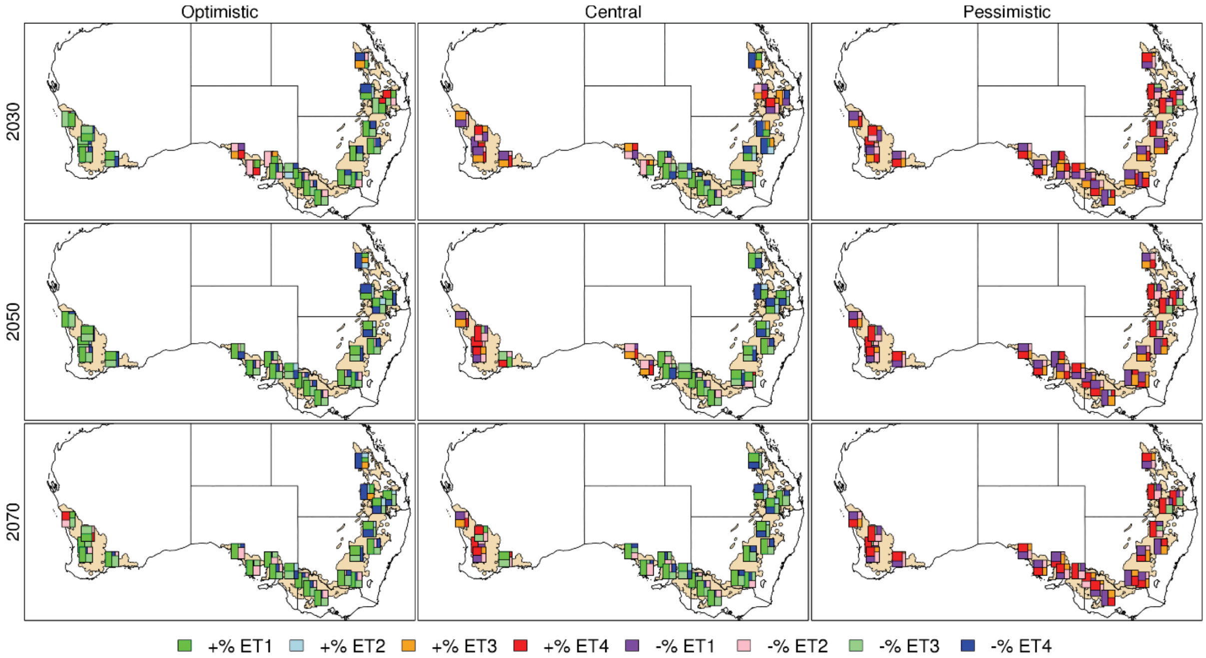

Figure 2. Regional averages for projected changes in the frequency of occurrence of environment types across the wheatbelt for three future periods (rows) and three contrasting climate models (columns). The coloured proportion of each box indicates the change in occurrence of each environment type compared to the baseline (1955 to 2013). Projections are presented for 2030, 2050 and 2070 and optimistic, central, and pessimistic climate models (see text).

Clear variations among climate models were found, even by 2030. While increased frequencies of severe drought conditions in the West of the wheatbelt were projected by both the central and pessimistic climate models, the optimistic climate model projected a decrease in these conditions. In contrast, in the East and South-East of the wheatbelt, the optimistic and central climate models indicated a decrease in severe drought conditions later this century. This reduction was primarily driven by shorter crop cycles arising from higher temperatures, and increased transpiration efficiency due to raised CO_2 concentrations. Note that the primary differences in the future drought predictions presented in Figure 2 derive more from the climate model considered than from the projection time.

When assessing the projections of all 33 climate models, occurrences of severe drought environments (ET 3 and 4) were found to decrease this century in the East, South and South-East of the wheatbelt (Figure 3). In contrast, the majority of climate models projected that the Western area of the wheatbelt will experience significant increases in drought conditions.

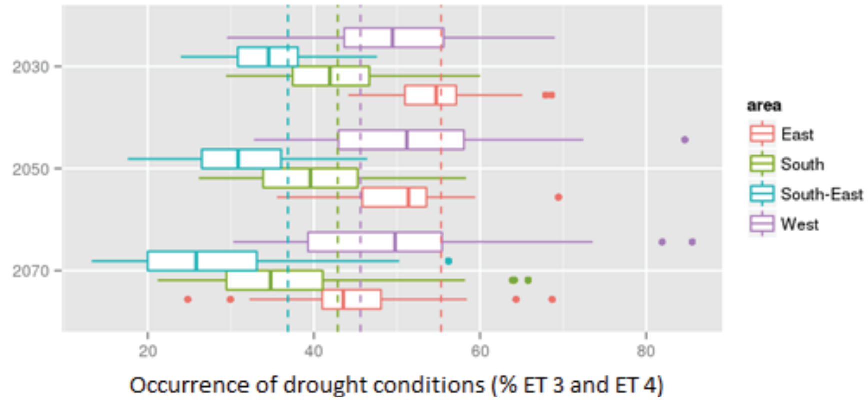

Figure 3. Projected occurrence of drought environments (ET 3 and 4) per major wheat-producing area, compared to historical occurrence (dotted lines). Boxplots summarize the distribution of percentages for each of the 33 climate models.

Conclusions

Climate model projections indicate that the West of the Australian wheatbelt is likely to experience increased drought conditions as early as 2030. Given the lead times involved for crop adaptation, and the western wheatbelt's significant contribution towards total national production, these results provide a strong case for immediate initiation of adaptation planning for this area. Other areas of the wheatbelt are projected to experience decreased frequencies of drought conditions, with rising temperatures shortening the crop cycle and CO_2 concentrations allowing more efficient water use. However, even where the frequencies of severe drought conditions are projected to decrease, their occurrences are projected to remain substantial. Overall, increased demand for wheat means that Australia must continue to improve cultivars and management practises to mitigate the drought conditions experienced across its wheatbelt.

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