Change in abiotic stress and atmospheric CO2 concentration significantly affected Australian wheat productivity over 1981-2018

Brian Collins and **Karine Chenu**

The University of Queensland, Queensland Alliance for Agriculture and Food Innovation (QAAFI), 13 Holberton Street, Toowoomba, QLD 4350, Email: brian.collins4@uq.edu.au, karine.chenu@uq.edu.au

Abstract

Recent climate changes have affected wheat crops in Australia. Changes in drought, heat and frost stress affecting a mid-maturing cultivar sown on May 15 were quantified using the Agricultural Production Systems sIMulator (APSIM) including a heat and frost stress module. Between 1981 and 2018, national drought-induced yield loss significantly increased, estimated to exceed 40% on average. In the simulations, the national average impact of heat-shocks on grain number and individual grain weight increased by 0.3% and 2.7% per decade, respectively. Frost damage significantly increased by 6.4% per decade while the beneficial yield impact of atmospheric CO_2 concentration increased by 1.8% per decade. Since 1981, heat-shocks and frost are estimated to have caused average yield losses of 15% and 14%, respectively. Rising atmospheric CO_2 concentration compensated for 2.4% of long-term average yield loss. Overall, without improvements in crop genetics and management, simulated yield decreased at a significant rate of 183 kg ha^{-1} per decade. Breeding for warm and dry environments appears to be a priority to enhance yield in Australia.

Keywords

Climate trend, historical trend, heat, frost, water stress, drought, wheat, Australia, crop modelling.

Introduction

The climate has changed over recent decades, and climate models project further increases in average temperatures and atmospheric CO_2 concentration ([CO_2]), more hot days, and increased variability in rainfalls for the near to mid future (IPCC 2012; Collins and Chenu 2021). In Australia, average temperature increased by 0.9ºC since 1910 (CSIRO and Bureau of Meteorology, 2015). Most of the change occurred after 1950, with the warmest years recorded in the last decade (Suppiah et al. 2001; Ababaei and Chenu, 2020). Under the Representative Concentration Pathways (RCP) 8.5, which is the pathway most consistent with the current pace of global emissions, an increase by 2.8–5.1°C is projected in Australian annual mean temperature by 2080–2099, with a possible decrease in spring and winter rainfall (CSIRO and Bureau of Meteorology, 2015). Global warming has complex effects on crops, due to changes in occurrence and intensity of abiotic stress factors, CO_2 fertilisation, and acceleration of crop development at warmer temperatures (e.g. Lobell et al. 2015). Historically, yield losses due to heat (Ababaei and Chenu, 2020), drought (e.g. Hochman et al. 2017; Fletcher et al. 2020), and even frost (Zheng et al. 2015; Crimp et al. 2016) have increased in recent decades. This paper assesses how yield impacts of heat shocks, frost, drought and CO_2 have evolved over recent decades in the Australian wheatbelt, and compares the impacts of these different environmental factors.

Methods

A modified version of APSIM-wheat (Holzworth et al. 2014) that accounts for impacts of frost and heat events (Zheng et al. 2015; Ababaei and Chenu 2020) was used to assess the changing impacts of heat, frost and drought stress, as well as atmospheric [CO_2] on Australian wheat crops. Simulations were setup at 60 locations across the Australian wheatbelt (Figure 1; Chenu et al. 2013) for the mid-maturing cultivar Janz sown on Apr 15, May 1, May 15 and June 1. Weather data were collected from the SILO patched point dataset (Jeffrey et al. 2001) for the period 1981-2018. Monthly [CO_2] data were obtained from Ziehn et al. (2016) for one set of simulations, and kept at the 1980 level in another set of simulations conducted to evaluate the impact of atmospheric [CO_2].

At each location, soil characteristics and fertilisation levels were set to represent local soils and farming practices (Chenu et al. 2013). Each year, initial soil conditions were reset on November 1 with soil nitrogen as per Chenu et al. (2013) and a 20% soil moisture. A small amount of irrigation was applied at sowing, when needed, to raise soil moisture of the soil top layer and allow germination the day after sowing. An additional set of simulations was conducted with irrigated crops. The yield impact of drought was defined as the yield difference between fully irrigated and rainfed crops. Significance of trends were assessed with the Mann-Kendall test combined with the Trend Free Pre-whitening procedure (Yue et al. 2002).

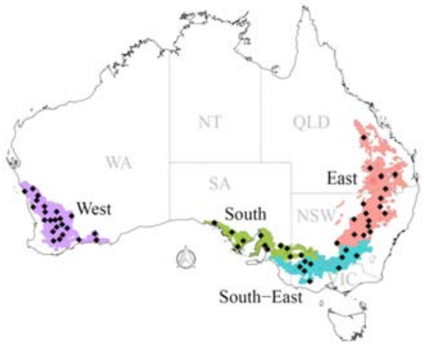

Figure 1. The Australian wheatbelt and the 60 studied sites in the East (red), South-East (blue), South (green) and West (purple).

Results and discussion

Frost has become more frequent and impactful

In the studied period (1981-2018), grain yield losses due to frost were estimated to be in excess of 14% nationally for a mid-maturing cultivar sown on May 15 (Figure 2). The impact of frost is particularly high in the East and South-East but was substantial in all regions.

Frost occurrence has significantly decreased over the last few decades in almost half of the north-eastern part of the Australian wheatbelt, while it has increased in other regions with, in addition, an extension of the frost season (Zheng et al. 2015; Crimp et al. 2016). Increased temperatures from global warming are expected to accelerate crop development, which could counter-intuitively increase the chance of frost at sensitive post-heading stages (Zheng et al. 2012). Between 1981 and 2018, frost-induced yield loss has increased by 6.4% per decade in Australia (Figure 3).

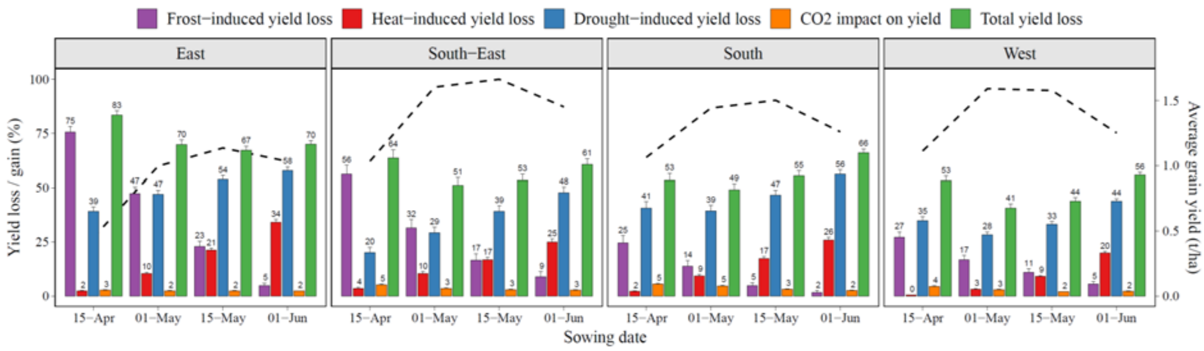

Figure 2. Regional average frost, heat, drought and total yield loss along with the positive impact of atmospheric [CO_2] for four sowing dates for the 1981-2018 period. Dashed lines correspond to average simulated grain yield. Error bars correspond to 90% confidence intervals.

Heat shock has been a major limiting factor

Heat events were associated with a 15% yield loss, nationally, for a mid-maturing cultivar sown on May 15, with larger impacts in the eastern part of the wheatbelt (Figure 2; Ababaei and Chenu 2020). From 1985 to 2017, the frequency of daytime heat shocks has significantly increased across the wheatbelt, with an extra 0.6 and 1.2 hot days (maximum temperature > 26°C) per decade occurring around anthesis and during early-mid grain filling respectively (Ababaei and Chenu 2020). By contrast, the occurrence of warm nights (minimum temperature > 17°C) has not significantly changed in most regions (Ababaei and Chenu 2020). From 1981 to 2018, heat-induced yield loss has increased by 2.8% per decade nationally (Figure 3), increasingly affecting grain size (2.7% per decade) more than grain number (0.3% per decade).

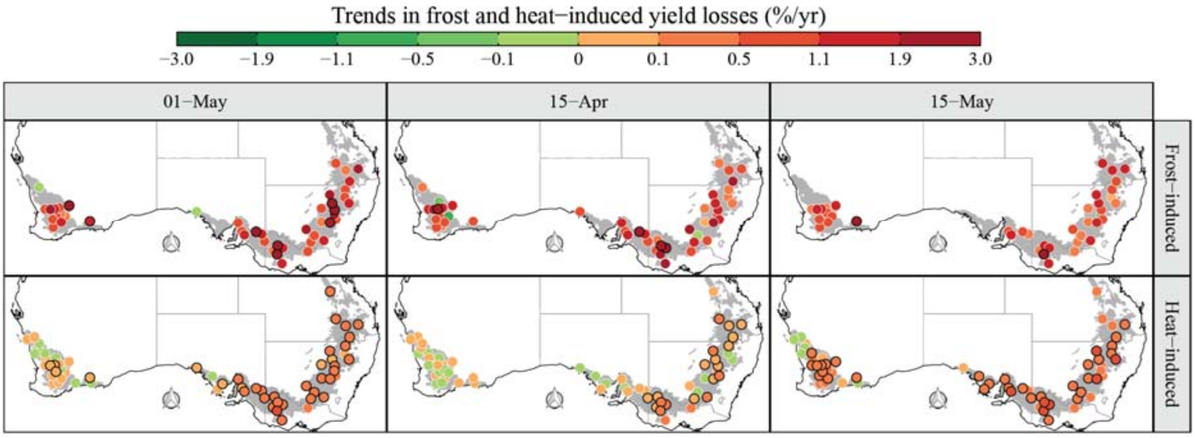

Figure 3. Linear trends in frost- and heat-induced yield loss over 1981-2018 for three sowing dates. Points circled in black represent statistically significant trends (P<0.1).

In addition, the increase in average temperature has an impact on the crop development, and resulted in shortening the crop cycle by 1.3 days per decade over 1981-2018 for a mid-maturing cultivar sown on May 15 (data not presented; Ababaei and Chenu 2020). Accelerated phenology helps reduce crop exposure to terminal heat and drought stress (Chenu et al. 2013; Lobell et al. 2015) but at the same time reduces the time for assimilation and thus potential yield (Zheng et al. 2012).

Drought has been the dominant stress factor

Drought impact, defined as the yield difference between fully irrigated and rainfed crops, has been responsible for a 42% yield loss for a mid-maturing cultivar sown on May 15 (Figure 42).

Drought-induced yield loss has increased nationally by 3.6% per decade from 1981 to 2018 (Figure 4). Low water-stress environments ET1 and ET2 (as defined in Chenu et al. 2013) have become less frequent by 1% and 2% per decade nationally for a mid-maturing cultivar sown on May 15, and by 9% and 5% per decade for a mid-maturing cultivar sown on April 15.

In the near to mid future, the frequency of severe drought environments (ET3-4, Chenu et al. 2013) is projected to further increase in the West, but decrease in the eastern part of the wheatbelt due to (i) shorter crop cycle associated to warmer temperature, and (ii) greater water use efficiency associated to increased [CO_2] level (Lobell et al. 2015; Watson et al. 2017; Collins and Chenu 2021). Nevertheless, all regions are still expected to be subjected frequent severe drought in coming decades.

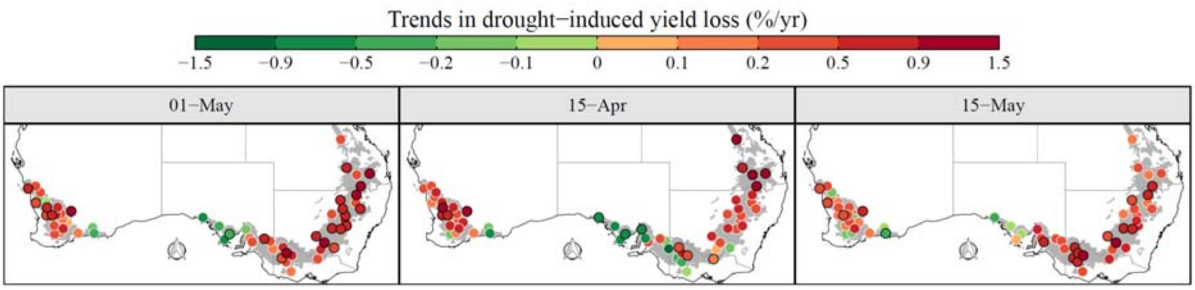

Figure 4. Linear trends in drought-induced yield loss over 1981-2018 for three sowing dates. Points circled in black represent statistically significant trends (P<0.1).

Atmospheric CO_2 concentration increasingly fertilises wheat crops

Rising atmospheric [CO_2] concentration compensated for 2.4% of national long-term yield loss on average (Figure 2). The benefit of CO_2 enrichment on wheat yield, through increased photosynthetic activity and water use efficiency, has increased by 1.8% per decade over 1981-2018 (data not presented) and is expected to further increase in the future (Lobell et al. 2013; Christy et al. 2018).

Abiotic stress are increasingly affecting grain yield

Overall, without improvements in crop genetics and management, simulated yield decreased at a statistically significant rate of 183 kg ha^{-1} per decade between 1981 and 2018.

With agronomic adaption of sowing dates and/or crop maturity, yield could increase in future decades despite the adverse effects of climatic factors such as heat events (Collins and Chenu 2021). Other strategies to increase yield and yield stability include management practices related to soil water conservation (Kirkegaard and Hunt 2010), and breeding for better adapted genotypes e.g. with higher transpiration efficiency (Chenu et al. 2018; Christy et al. 2018; Collins et al. 2021), greater stay-green (Christopher et al. 2016) or beneficial morphological traits (Hunt et al. 2018).

Conclusion

Over 1981-2018, abiotic stresses have increasingly impacted yield, resulting in an estimated national yield decreased of 183 kg ha^{-1} per decade, for a mid-maturing cultivar sown on May 15. Average simulated yield has decreased by 6.4% per decade due to frost (as increased average temperature has hasten flowering), 2.8% per decade due to heat shocks, and 3.6% per decade due to drought. On the other hand, rise in atmospheric [CO_2] has allowed a 1.8% yield benefit per decade. While climate keeps changing, agronomic and genetic adaptations are to be sought and applied to increase yield and yield stability across the wheatbelt.

References

Ababaei B, Chenu K (2020) Heat shocks increasingly impede grain filling but have little effect on grain setting across the Australian wheatbelt. Agricultural and Forest Meteorology 284:107889.

Chenu K, Deihimfard R, Chapman SC (2013) Large-scale characterization of drought pattern: a continent-wide modelling approach applied to the Australian wheatbelt spatial and temporal trends. New Phytologist 198:801-820.

Chenu K et al. (2018) Integrating modelling and phenotyping approaches to identify and screen complex traits: transpiration efficiency in cereals. Journal of Experimental Botany 69:3181-3194.

Christopher J, Christopher MJ, Borrell AK, Fletcher S, Chenu K (2016) Stay-green traits to improve wheat adaptation in well-watered and water-limited environments. Journal of Experimental Botany 67:5159-5172.

Christy B et al. (2018) Benefits of increasing transpiration efficiency in wheat under elevated CO2 for rainfed regions. Global Change Biology 24:1965-1977.

Collins B, Chapman S, Hammer G, Chenu K (2021) Limiting transpiration rate in high evaporative demand conditions to improve Australian wheat productivity. In silico Plants 3.

Collins B, Chenu K (2021) Improving productivity of Australian wheat by adapting sowing date and genotype phenology to future climate. Climate Risk Management.

Crimp SJ, Zheng B, Khimashia N, Gobbett DL, Chapman S, Howden M, Nicholls N (2016) Recent changes in southern Australian frost occurrence: implications for wheat production risk. Crop and Pasture Science 67:801-811.

CSIRO, Bureau of Meteorology (2015) Climate change in Australia: Projections for Australia's NRM regions.

Fletcher AL, Chen C, Ota N, Lawes RA, Oliver YM (2020) Has historic climate change affected the spatial distribution of water-limited wheat yield across Western Australia? Climatic Change 159:347-364.

Hochman Z, Gobbett DL, Horan H (2017) Climate trends account for stalled wheat yields in Australia since 1990. Global Change Biology 23:2071-2081.

Holzworth DP et al. (2014) APSIM – Evolution towards a new generation of agricultural systems simulation. Environmental Modelling & Software 62:327-350.

Hunt JR, Hayman PT, Richards RA, Passioura JB (2018) Opportunities to reduce heat damage in rain-fed wheat crops based on plant breeding and agronomic management. Field Crops Research 224:126-138.

IPCC (2014) Climate change 2014: Synthesis report. Contribution of working Groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, Switzerland.

Jeffrey SJ, Carter JO, Moodie KB, Beswick AR (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling and Software 16:309-330.

Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water-limited environments. Journal of Experimental Botany 61:4129-4143.

Lobell DB, Hammer GL, Chenu K, Zheng B, McLean G, Chapman SC (2015) The shifting influence of drought and heat stress for crops in northeast Australia. Global Change Biology 21:4115-4127.

Suppiah R, Collins D, Della-marta P (2001) Observed changes in Australian climate. Atmospheric Research:1-6.

Watson J, Zheng B, Chapman S, Chenu K (2017) Projected impact of future climate on water-stress patterns across the Australian wheatbelt. Journal of Experimental Botany 68:5907-5921.

Yue S, Pilon P, Phinney B, Cavadias G (2002) The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrological Processes. 16:1807-1829.

Zheng B, Chapman SC, Christopher JT, Frederiks TM, Chenu K (2015) Predicting heading date and frost impact in wheat across Australia. Paper presented at the 17th Australian Agronomy Conference, Hobart, Australia.

Zheng B, Chenu K, Dreccer MF, Chapman SC (2012) Breeding for the future: what are the potential impacts of future frost and heat events on sowing and flowering time requirements for Australian bread wheat (*Triticum aestivium*) varieties? Global Change Biology 18:2899-2914.

Ziehn T, Law RM, Rayner PJ and Roff G (2016) Designing optimal greenhouse gas monitoring networks for Australia. Geoscientific Instrumentation, Methods and Data Systems 5:1-15.