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Opportunities to reduce heat damage in rain-fed wheat crops based on plant breeding and agronomic management

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ABSTRACT

High temperatures can substantially reduce the yield of rain-fed wheat at any stage of crop development. They can result in poor establishment, poor floral fertility, inopportune flowering time, or inadequate grain filling. They can inflict damage through sudden heat shock, such as leaf scorching or pollen sterility, or by chronic effects of sustained above-optimal or average temperatures.

There are good immediate prospects to protect the crop's canopy from heat damage during reproductive phases by breeding for the specific morphological traits of erect and glaucous flag leaves, combined with the ability of the leaves to roll in hot and dry conditions. These traits are present in current cultivars, but their frequencies are low and their combination is rare. There is a good opportunity to increase their frequency and to pyramid them in the next generation of cultivars to help cope with rising temperatures.

The interactions between heat and drought can greatly reduce yield. There are synergistic interactions between breeding and agronomic management (G*M) that can substantially increase yield in hot and dry conditions. Early sowing is beneficial and can be facilitated by water in the subsoil, but it requires new cultivars with appropriate developmental patterns and long coleoptiles that enable deep sowing. Suitable management can defer the use of this water for use during grain filling, when its availability may help mitigate potential heat damage.

There is good evidence that in recent decades farmers have experienced increases in both seasonal average temperatures and extreme heat events. This trend is likely to continue. Synergistic breeding and agronomic possibilities have good prospects to substantially reduce heat damage within the trade-offs involved in farming systems. Further, recent advances in the understanding of the meteorological patterns and underlying climate drivers of heat events are leading to forecasts of the likelihood of heat events at a multi week and seasonal timescale. These forecasts, as they improve, have the potential to refine the Genetic * Environment * Management (G*E*M) choices for wheat farmers.

1. Introduction

Major heat damage in wheat crops is common globally (Teixeira et al., 2013; Zampieri et al., 2017) including Australia (Lobell et al., 2015; Sadras and Dreccer, 2015; Hochman et al., 2017; Dreccer et al., 2018). There is high confidence that temperatures will continue to rise with increased heat events (Meehl and Tebaldi, 2004; Perkins, 2015). The 2010 heatwave in Russia killed 55,000 people, and estimated crop damage was 25% (Barriopedro et al., 2011). The subsequent banning of wheat exports from Russia led to fears of food shortages and a spike in global wheat prices. In Australia, Hochman et al. (2017) found a 27% decline in simulated water-limited potential wheat yield from 1990 to 2015. They attributed 83% of the decline to reduced rainfall and 17% to increased temperature, though the latter may be an underestimate, for "heat shocks" (brief periods with Tmax > 34 °C) could not be included in the simulations.

We acknowledge that wheat is predominantly a temperate crop, and that the negative impacts of warming on cropping are generally greater in tropical regions compared to mid and high latitudes where, in some cases, there may be advantages to the early stages of warming (Fischer et al., 2005; Schlenker et al., 2006). However, by including heat shock in their analysis, Teixeira et al. (2013) found vulnerabilities from warming for cropping in continental areas of eastern China, the northern United States, south-western Russian Federation and southern

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Canada. Importantly, these regions do not have the option of irrigation to mitigate the impact of heat stress in crops (Siebert et al., 2017). Furthermore, many rain-fed wheat areas such as southern Europe, USA and Australia are prone to drought and adjacent to an arid region which serves as a source of hot and dry air. The effect of heatwaves are longer and more intense when preceded by a drought (Mueller and Seneviratne, 2012; Quesada et al., 2012). This is primarily due to the reduced latent heat flux leaving the sensible heat to dominate.

Due to the widespread impacts of heat events, there has been substantial research on the weather systems and underlying climate drivers. Recent examples relevant to rain-fed wheat growing regions include USA (Peterson et al., 2013; Teng et al., 2013), Europe (Della-Marta et al., 2007; Quesada et al., 2012), China (You et al., 2016), Ukraine (Shevchenko et al., 2014), Russia (Dole et al., 2011), India (Rohini et al., 2016) and Australia (Tryhorn and Risbey, 2006). A common finding is that the frequency and intensity of heat events are increasing and that understanding and prediction of the events is much better at shorter timescales of weather (1 to 7 days) than seasonal climate (3 to 6 months). Where heat waves are linked to a larger scale climate driver, there is potential for better prediction (Baldi et al., 2006). Seasonal and multi-week prediction of the frequency and intensity of heat events is an emerging area of climate science (Hudson et al., 2016; White et al., 2017). This prediction is currently far from perfect but it is of increasing interest to health and emergency services, fire, water and energy authorities, crop traders and potentially to wheat farmers.

High temperatures can reduce yield of wheat crops at every stage of development, either by chronic or by acute effects:

- at sowing they can increase evaporation from the seed-bed and reduce the maximum length of coleoptiles thereby resulting in poor establishment
- during the vegetative stage they can accelerate development such that crops flower too early when radiation is sub-optimal, and the risk of frost damage increased
- during spike development chronic high temperatures can hasten development relative to growth, which reduces grain number
- prior to and during flowering they can kill pollen and developing embryos, resulting in sterile florets and reduced grain number
- after flowering they can scorch leaves and accelerate senescence (e.g. haying-off (van Herwaarden et al., 1998a)), especially when solar radiation is intense, reducing photosynthetic area both before and after anthesis, thereby leading to reduced grain number, small grains and lower yield
- at all stages of development they increase evaporative demand, thereby decreasing transpiration efficiency (kg biomass per mm of water supply)

Further, the impact is worsened by drought, which reduces the possibility of evaporative cooling of the canopy. This and other influential interactions are well explored by Sadras and Dreccer (2015). Grain quality may also be affected by high temperatures but this is not well documented in field grown crops. A good guide to the effect of high temperatures on grain quality was provided by Peterson et al. (1998) who demonstrated that baking quality improves with temperature stress, but when temperatures exceed 32 °C for 100 h during grain filling then baking quality declines.

Minimising heat damage is not, however, a goal that can be considered in isolation. Rather, the broader goal is to minimise the combined risk of drought, frost and heat damage. For example, French and Schultz (1984) used wheat yield from 61 field locations in South Australia between 1964 and 1975 to identify a “stress date”. This was the first date in the growing season that the 7 day average maximum temperatures reached 23 °C or the 7 day accumulated class-A pan evaporation exceeded 40 mm. They found that maximum yields were obtained when anthesis was completed after the frost period but before the onset of the stress date. Flohr et al. (2017) used the simulation model APSIM (Keating et al., 2003; Holzworth et al., 2014) to determine that in the south eastern Australian wheat belt, stress induced by frost, heat and drought were frequently concurrent and that yields were maximised when damage from all three were minimised, rather than avoided. As well as this, there is the difficult goal of managing the seasonal water supply so that it is balanced between enabling enough vegetative growth to produce an adequate number of grains per m^2, and enough reproductive growth to enable the crop to set and fill those grains (Fischer, 1979; Passioura, 2002a).

The question arises of how best to deal with the diverse impacts outlined in the bulleted list above? Empirical breeding is helping, albeit slowly, and there is some promise in empirical phenotyping using simulated heatwaves with pots in controlled environments (Telfer et al., 2013). However, faster progress may be made by targeting specific genetic traits to deal with at least some of the issues. The fastest progress may be made by adapting agronomic management and novel genotypes to each other (G*M) as proposed for water-use efficiency by Kirkegaard and Hunt (2010), but in this case within the context of what we know about current weather patterns and their potential to induce heat damage.

Major intrinsic physiological improvements in heat tolerance in dryland wheat crops are feasible, but they will come about only through a much deeper understanding of the processes involved. Research in this area is in the category of “high risk, high return”, with a lead time of many decades. Likewise, the incorporation of heat tolerance from landraces and wild relatives or through GM, if possible, would require many decades of breeding to be successful.

By contrast, our aim in this paper is to explore the best current possibilities to reduce the impact of heat damage on wheat yield in Australia, as described below. It is likely that these possibilities will also apply to many other major rainfed regions in the world where temperatures during flowering and grain filling are similar (Asseng et al., 2011). Thus, rather than the several decades that would almost certainly be required to make major physiological improvements in heat tolerance or to adapt heat-tolerant wild relatives into productive cultivars, we propose that the opportunities described below could, if embraced, produce useful results within a decade.

2. Heat events in the Australian grains belt

Although much of the Australian grains belt is warmer than optimal for wheat production, tropical and subtropical regions such as Mexico, Sudan, Bangladesh, and peninsular India are much hotter. The International Heat Stress Genotype Experiment conducted by the International Maize and Wheat Improvement Center (CIMMYT) defines hot and very hot sites as those with mean temperatures of the coolest month of the growing season of 17.5 °C and 22.5 °C respectively (Badaruddin et al., 1999). Emerald, in central Queensland, is close to the northern boundary of the Australian grains belt and has a Mean July Temperature (MJT) of 16.1 °C, Walgett in NW New South Wales (NSW), Minnipa in the northern edge of South Australia (SA) grains belt and Merredin in the NE of the Western Australia (WA) grains belt all have MJT below 11.5 °C. An obvious difference between Australia and the very hot regions is that the latter are mostly irrigated (Fischer et al., 2014).

More concerning than the mean spring temperature are short lived heat shocks. These events are about 10 °C or more above the average daytime temperature. The weather patterns that lead to these events are well understood. For example, Fig. 1 shows a stylised synoptic chart based on 12 October 2004. Roseworthy (50 km north of Adelaide, SA) recorded a maximum temperature of 39 °C and much of the South Australian and Victorian Mallee recorded maximum temperatures above 40 °C. The hot north-westerly winds are due to the anticlockwise movement of air around the high pressure system to the east of the region. These winds are strengthened by the clockwise movement from