Lack of Terminal Water or Heat Stress facilitates Later Optimal Flowering Periods for Barley in Australia

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Abstract
Allowing crop flowering to occur within a window that minimises the long-term likelihood of exposure to abiotic stress is a promising but poorly explored pathway for improving yields. Here, our hypothesis was that environments with lower late season (terminal) water or heat stress would have later optimal flowering periods (OFPs) and higher yields, because lower abiotic stress exposure near the end of the growing season would be conducive to greater biomass and grain production. To test this hypothesis, we conducted a genotype (G) × environment (E) × management (M) analysis for barley crops in both short and long season cropping environments. We simulated multiple sowing times of the parameterised genotypes across the Australian cropping zone. The G×E×M showed earlier OFPs (late August to late September) in Western Australia where terminal water and heat stress were higher, and later OFPs (late-October to early-November) in environments that had generally lower late terminal water and heat stress (e.g. Tasmania). Our results show that terminal stresses, such as those associated with severe heat waves and water deficit, have greater deleterious impact on yield potential than frost risk. This is because heat and water deficit tend to truncate the growing season, while OFPs which avoid the risk of frost facilitate longer growing seasons and thus higher yield potential.

Keywords
Breeding, deterministic modelling, anthesis, biomass accumulation, barley, extreme climatic events

Introduction
Major abiotic stresses experienced by rainfed crops in Australia include frost events in winter and early spring, and water stress and heat stress during later spring and summer. For cereals, including barley, the critical period for yield for yield determination occurs slightly prior to anthesis. Any stress at this time can cause severe yield loss. Climate change has been recognised as a key threat to crop and pasture production (Arisnabarreta et al., 2008; Harrison et al. 2011; Phelan et al. 2015; Harrison et al. 2016) and in the grain cropping regions of Australia will result in higher risk of severe heat waves and drought. Such events together with increases in the frequencies of extremes necessitates greater insight into how growing season duration and flowering time can be optimised across multiple environments. Matching growing season with prevailing environmental conditions by aiming for a flowering window that avoids long-term risk of exposure to abiotic stresses facilitates higher harvest indices through increased stem biomass and assimilate reserves that are able to be transferred to developing grain kernels after anthesis (Harrison et al. 2011). Here we modelled such trade-offs using the Agricultural Production Systems SIMulator (Keating et al. 2003; Holzworth et al., 2014). The objectives of this study were to (1) parameterise and validate APSIM-Barley phenology sub-routine for specific cultivars with different development patterns and (2) identify the relationship between optimal flowering period (as dictated by prevailing abiotic stresses) and grain yield for barley.

Methods
APSIM-barley was parametrised and validated using data from field experiments conducted with and without vernalisation and photoperiod. OFPs were calculated using the approach described by Liu et al. (2019). Frost, heat and water-limited yield (FHY) in APSIM were calculated as the product of water-limited potential yield, cumulative frost stress and cumulative heat stress, respectively. The OFP for eight barley genotypes (details shown in Liu et al., 2019) were determined from flowering dates corresponding to a yield ≥ 95% of the maximum 29-year averaged (1990-2019) FHY at 10 locations. For illustrative purposes, here we choose two sites with contrasting climates (Gibson in

Western Australia and Campbell Town in Tasmania) that were representative of rainfed barley growing regions in Australia (Table 1).

Table 1. Climate conditions during the barley growing season at Gibson in Western Australia and Campbell Town in Tasmania. Data were averaged for the 29-year simulation period 1990-2019.

Site	Tmax (°C)	Tmin (°C)	solar radiation (MJ m^{-2})	Rainfall (mm)
Gibson	19.0	9.1	1621	271
Campbell Town	14.0	3.3	2514	414

Results

In general, OFPs occur when the combined long-term risk of all abiotic stresses is minimal (Figure 1). The extent and frequency of abiotic stresses varied significantly across environments, such that crops grown at Gibson (moderate dry winter and warm summer) had higher stress associated with water deficit during the growing season, while the predominant stress at Campbell Town were associated with frost. Water and heat stress increased significantly when flowering occurred later than September at Gibson. Delaying sowing at Campbell Town resulted in lower frost risk, and when combined with minimal risk of heat and water stress, resulted in a higher yield. In contrast, crops at Gibson were exposed to higher early season water stress, resulting in an earlier OFP and lower grain yields.

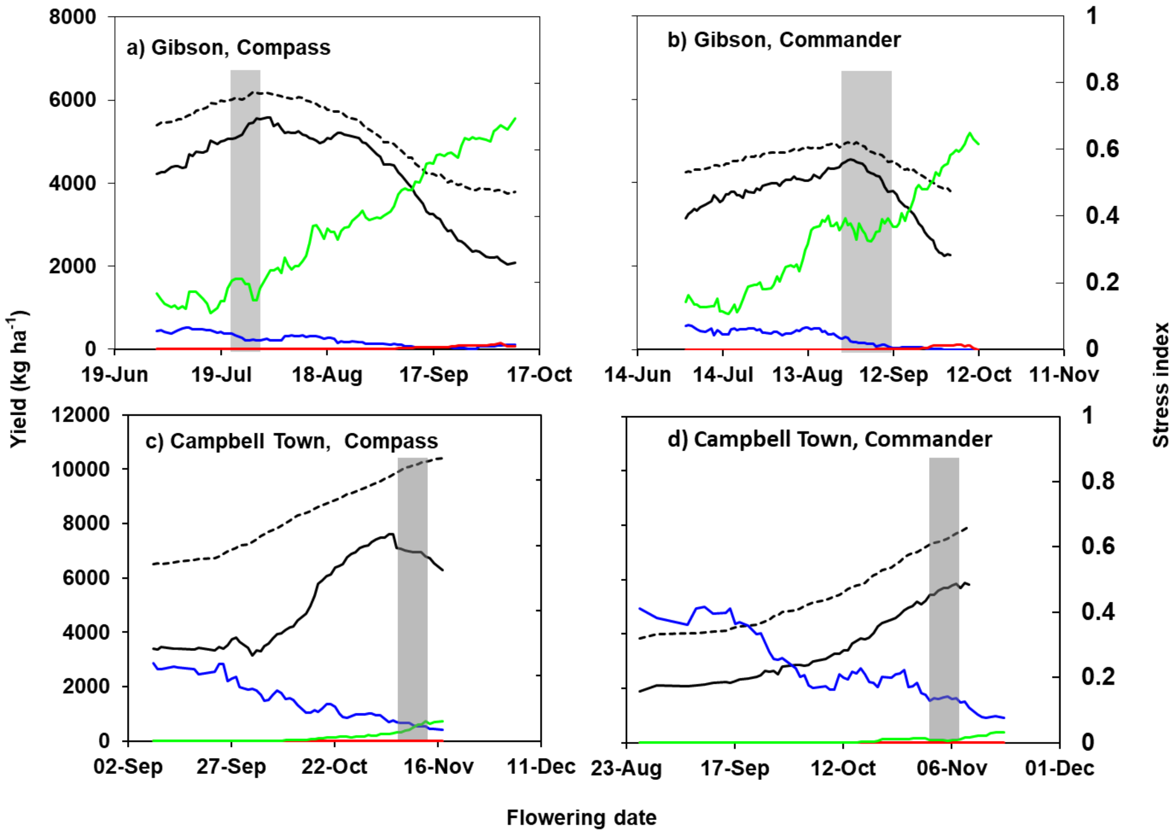

Figure 1. Illustration of the relationship between flowering date and long-term average simulated water-limited potential yield (not limited by frost and heat; dotted black) and FHY (limited by frost, heat and water stress; soil line) for a medium to fast developing barley genotype (Compass) and medium developing barley genotype (Commander) in two contrasting climatic zones. Frost (blue line) and heat (red line) stress indices reduce potential yield. Water stress (green line) represents average simulated crop

water deficit between flowering and maturity. The optimal start of flowering (grey shaded zone) is the flowering duration at which yield is ≥95% of the long-term average peak yield.

Crops grown at Gibson generally had short growing seasons, while barley cultivated at Campbell Town would have longer growing season (Figure 2). Durations from sowing to the start of the optimal flowering date were positively correlated with grain yield; this positive relationship was consistent regardless of sowing date at Campbell Town. In Gibson, longer growing periods did not necessarily result in higher grain yield because the combined terminal stresses (drought and heat) was more pronounced during flowering periods, limiting biomass accumulation and yield potential.

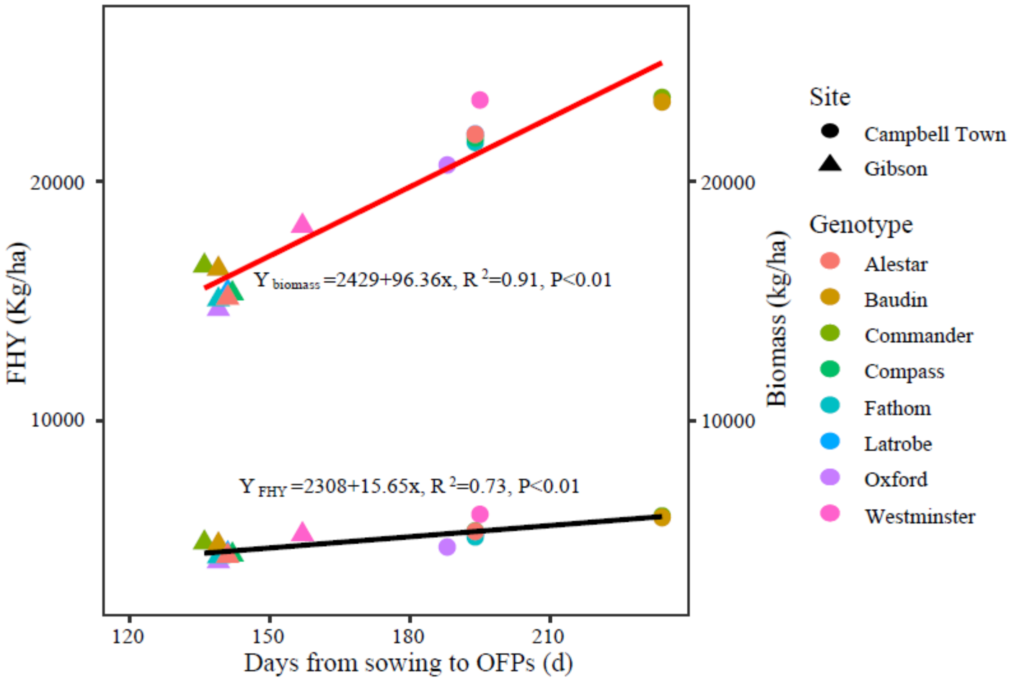

Figure 2. Relationships between the duration from sowing to optimal flowering with simulated grain yield and simulated maturity biomass. Data shown are average yields for the 29-year period 1990-2019 from eight genotypes across two sites (n=16).

Conclusion

Here we found that environments with lower terminal abiotic stress were conducive to later OFPs, greater biomass accumulation and higher yield. Better quantification of long-term OFP across environments and for a range of phenologies would be expected to help breeders develop genotypes with appropriate phenological characteristics to maximise yield potential, and grain growers to select genotype and sowing date combinations that decrease the long-term risk of stress and maximise yield. While the extent to which the interplay between growing season duration and OFP can be manipulated by sowing time and genotypic duration deserves further investigation, the results shown here contribute towards understanding of how key abiotic stresses dictate yield across a genotype by environment by management landscape.

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