Heat waves and wheat growth under a future climate

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Abstract

Heat wave conditions (heat shock) that coincide with anthesis of dryland crops have the potential to significantly limit crop production in southern Australia and are expected to become more common due to anthropogenic climate change. In addition, atmospheric CO_2 is increasing and it is not known whether this will enhance or ameliorate the effects of heat shocks on crops. Heat wave conditions in early November 2009, which coincided with grain-set, had a devastating effect on yield throughout south-eastern Australia. Yield loss was reported to be as high as 70% in some lentil crops. Similarly in parts of southern Australia cereal yields were estimated to be reduced by up to 50% due to heat wave conditions that occurred in October 2004. At the Australian Grains Free Air CO_2 Enrichment (AGFACE) facility in Horsham, wheat (*cv.* Yitpi) grown under daytime ambient (365 ppm) and elevated (550 ppm) CO_2 conditions and contrasting water supply (rain-fed and supplemented irrigation) was tested against the effects of a single heat wave either before or after anthesis using purpose built chambers that imposed short-term heat stress. Heat stress (37°C for 3 days) imposed six days after anthesis caused a 12% reduction in grain number (20099 to 17768 grains/m^2) and a 13% reduction in grain yield (8.33 to 7.25 t/ha). In contrast, no yield penalty occurred for wheat exposed to heat six days prior to anthesis, although this is likely due to target temperatures (36 to 38°C) not being reached during this phase. Kernel size was not affected by heat stress conditions. The impact of heat stress was not affected by atmospheric CO_2 concentration or water supply. Validation data under future climate conditions are needed for crop simulation models, to account for the effect of short-term heat stress on grain-set, thus enabling robust assessment of crop production under expected future climates.

Key words

climate change, heat stress, simulation models

Introduction

Heat waves in southern Australia have the potential to significantly reduce grain production of rain-fed cropping systems. It is anticipated that under future climatic conditions there will be higher atmospheric CO_2 concentrations and reduced growing season rainfall combined with an increase in the frequency of heat waves. Wheat is considered to be most sensitive to sudden heat stress (31 to 32ºC) if it occurs during the reproductive period of flowering under controlled conditions (Wardlaw and Wrigley 1994; Wollenweber *et al.* 2003) and in the field (Alexander *et al.* 2010). The timing of maximum sensitivity in pulses is likely to be similar, although there is limited published literature (Materne and Siddique 2009). For lentil crops, a heat wave in November 2009 (temperatures exceeding 35ºC over 6 days) was estimated to have reduced yields by 70% (Brand, pers. comm.). This equated to financial losses of around $1000/ha ($50M for the Victorian Agricultural Industry). Previous studies of the effect of heat stress on wheat growth have estimated that yields were reduced by 18-35% for 35ºC heat stress imposed over a single day (Alexander *et al.* 2010; Talukder *et al.* 2010). There are no studies, however, assessing the impact of heat waves on wheat production under free-air CO_2 enrichment (FACE) conditions and varying water supply. Future crop adaptation to heat waves ideally requires: a) improved understanding of crop mechanisms for modelling/ agronomic management; and b) assessment of genetic solutions, for developing avoidance and tolerance strategies respectively. This paper reports on the performance of heat chambers within an elevated CO_2 environment, and assesses the impact of heat stress in combination with FACE conditions and water availability on wheat growth and yield, by utilising the AGFACE facility at Horsham, Victoria.

Methods

Heat chambers were used to examine the impact of simulated heat waves on wheat production and were applied at one of two stages (6 days pre- and post-anthesis) during 2011. The target temperature was 36 to 38°C in the crop canopy, applied for 6 to 8 hours and thereafter reduced to ambient temperature during the night time over three days. Heat chambers consisted of right-angle hollow section (RHS) frame boxes (1200mm W × 800mm D × 500 mm H) that were clad with Sun Tuff Greca Laserlite®. Electric fan heaters (1200W) were mounted at the top of the chambers with the temperature controlled by a thermocouple.

Power in the field was supplied using mobile diesel generators. Mixing of outside air was allowed from the base of the chamber. The Australian Grains Free Air CO_2 Enrichment (AGFACE) experiment in Horsham, Australia (Mollah *et al.* 2009) provided the facility to test the impact of simulated heat waves on wheat crops (Fig 1). The AGFACE experiment comprised two atmospheric daytime CO_2 levels (ambient, 365 and elevated, 550 ppm) under two water supply regimes (rain-fed and irrigation).

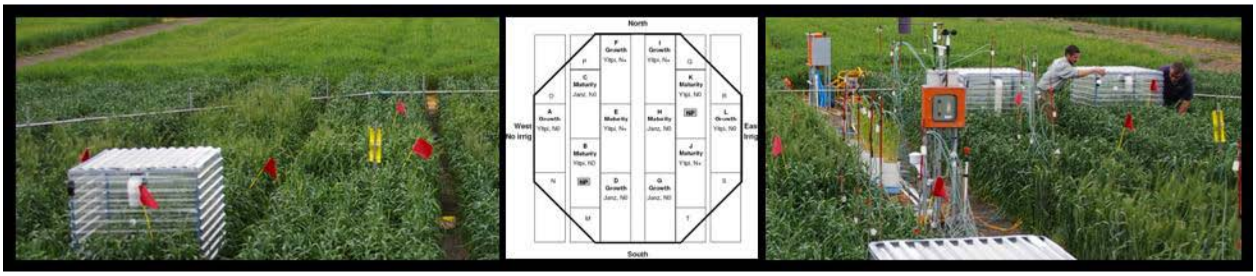

Figure 1. Design and layout of heat chambers within an AGFACE ring.

Results and Discussion

Heat chamber performance

The performance of the chambers in applying elevated temperature to the crop canopy is presented in Fig 2. For the pre-anthesis heating, temperatures were raised 7 to 10°C above ambient conditions, but were under the targeted 36-38°C. In contrast, temperatures during the post-anthesis heating phase reached the target temperature range despite a large variation in ambient temperature. We attribute the variation in performance between the pre- and post-anthesis heat treatments to several factors: a) shorter crop canopy during the pre-anthesis phase increased the amount of mixing with cooler outside air; and b) stronger wind conditions, particularly on day three in the pre-anthesis phase limited the heating capacity of the chambers. The effect of the passive chambers on heating the air was greatest in the pre-anthesis phase. In preparation for subsequent heat stress studies we have made engineering modifications to improve temperature control.

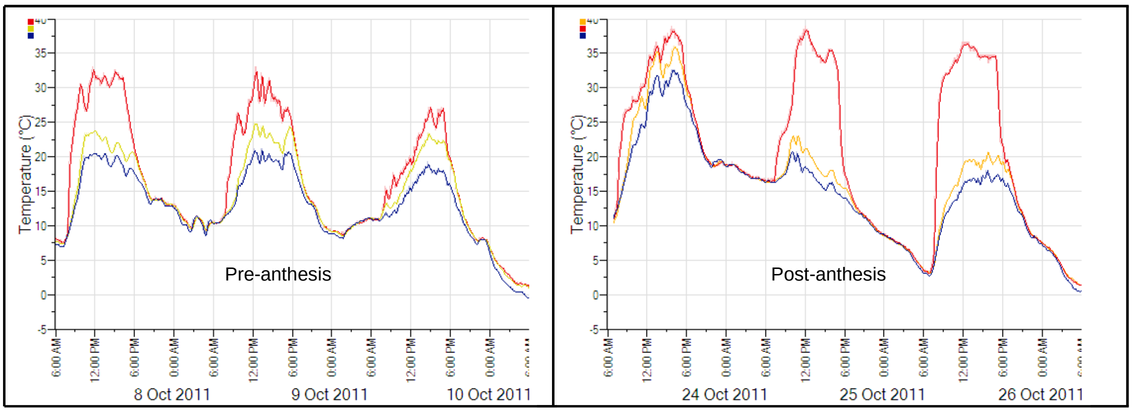

Figure 2. Temperature comparison of ambient air (blue trace: bottom) compared with heat chambers (red traces: top) were applied to wheat (*cv.*Yitpi) over three days at four days pre- and post-anthesis. Heating effect of passive chambers (no heater unit) is also presented (yellow traces: middle).

Chamber [CO_2] and relative humidity

Within the heat chambers the concentration of CO_2 was not greatly different from the free air eCO_2 environment (Fig 3). For days two and three (8 and 9 October) the CO_2 concentration was greater than the target 550 ppm. The higher concentration of CO_2 exists due to the proximity of loggers (and experimental plots) to the periphery of the rings and active legs that are triggered under upwind conditions. This CO_2 concentration pattern is an artefact of design (Mollah et al., 2009). Overnight, when CO_2 injection is turned off, the ambient CO_2 concentration was close to 380 ppm but was slightly higher within the chambers due to transpiring crops. The heat chambers caused the relative humidity during the day time to be reduced by 10 to 15%.

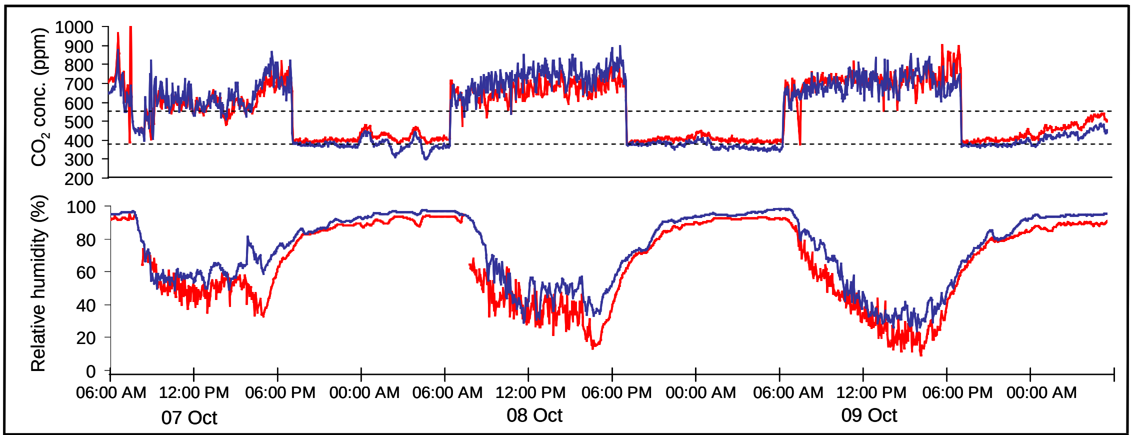

Figure 3. Comparison of CO_2 concentration (ppm) and relative humidity (%) between free-air and within the heat chamber during the applied heat treatment within an elevated CO_2 ring. Red and blue traces are heat chamber and ambient environment, respectively, where pre-anthesis traces are presented.

Crop growth

Elevated CO_2 (eCO_2) produced a 17% increase in wheat yield compared with ambient CO_2 conditions, where under eCO_2 grain number increased 14% and there was a 2% increase in kernel size, (Table 1) however, there was no interactive effect of CO_2 and heat (pre- or post-anthesis) on yield components. For wheat crops that were irrigated there was a 5% increase in wheat grain number and yield compared with rain-fed crops, and a 2% increase in kernel size however, no interactive effect of water supply and heat shock (pre- or post-anthesis) on yield components.

Table 1. The effect of CO_2 and water supply on yield components of wheat grown in the AGFACE trial.

	CO_2		Water supply	
	Ambient	Elevated	Rain-fed	Irrigated
Grain number (grains/m^2)	16970	19290	17695	18564
lsd (*P*<0.01)	1277		1277	
Yield (t/ha)	7.0	8.2	7.4	7.8
lsd (*P*<0.01)	0.5		0.5*	
Kernel size (mg/1000)	41.6	42.4	41.6	42.4
lsd (*P*<0.01)	0.7		0.7	

*(*P* = 0.10)

Pre-anthesis heat stress had no effect on grain number, kernel size or yield of wheat in this experiment. In contrast, where crops were exposed to a post-anthesis heat wave there was a 12 and 13% reduction in grain number and yield respectively (Table 2). There was no compensatory increase in kernel size for crops with a reduced grain number due to heat stress. The control chamber, where temperature briefly exceeded 35°C during the first day caused grain number to be reduced by 8%, however; this did not translate to a significant yield penalty.

Table 2. The effect of heat stress on yield components of wheat grown in the AGFACE trial. Impact of heat-stress for 3 days post-anthesis are presented where a control is compared with a blank chamber (passive heating effect) and a heated (heated chamber) environment.

	Post-anthesis heat shock		
	Control	Blank	Heated
Grain number (grains/m^2)	20099	18470	17768
lsd (P<0.01)		1018*	
Yield (t/ha)	8.33	7.67	7.25
lsd (P<0.01)		0.80	
Kernel size (mg/1000)		41.4	
lsd (P<0.01)		ns	

*(*P* = 0.10)

The limited effect of heat stress on wheat growth during the pre-anthesis test period may be due to the temperature shock over three days (*ca* 30°C) being insufficient to cause abortion of florets. When target temperatures (36-38°C) were reached during post-anthesis exposure this caused a 13% reduction in yield. By comparison, heat stress studies on barley with a target temperature of 40°C for 5 days caused a 36% reduction in grain number (Savin *et al.* 1996). Similarly, for wheat, heat stress of 35°C for 12 days, reduced grain number by 41% (Wollenweber *et al.* 2003), whereas exposure for one day at this temperature reduced yield by 18 to 35% across a range of cultivars (Talukder *et al.* 2010). In the latter study, yield loss was due to a parallel reduction in kernel size, whereas in our study reduced grain number limited yield. This difference may be due to changes in post-anthesis growing conditions where in the current study photosynthesis and grain fill were unlikely to be limited by water supply.

Variation in chamber performance between the pre- and post-anthesis heat stress testing meant we were unable to infer an effect of heat stress timing on wheat growth. We were not able to demonstrate a link between atmospheric CO_2 level and the impact of heat stress and suspect that large intra-site variability in soil type and plot edge effect limited the ability to identify such interactions (control plot standard deviation of the mean (7.7 t/ha) 1.6). In summary, the minimum temperature required to induce a heat stress effect experimentally in cereals is likely to be around 35°C, where duration of exposure appears to have an accumulative effect of yield reduction. Under natural field conditions the effects of associated drying winds during a heat wave is likely to exasperate the impact of high temperature, an effect which is not considered in these studies. The information gathered through our broader research program on extreme weather events and crop production will be used to: a) understand the mechanisms of heat wave tolerance of crops in terms of grain-set, yield and quality for the purpose of improving the capacity of crop simulation models to account for the effect of heat waves on yield prediction and b) identify variation of crops for tolerance to heat waves during reproductive growth and develop suitable screening technologies for breeding programs.

Conclusions

Imposed heat stress six days after anthesis on wheat grown in the AGFACE facility caused grain number to be reduced by 12%, and a parallel reduction in grain yield of 13%. In contrast no yield penalty occurred for heat exposure six days prior to anthesis possibly due to target temperatures not being reached during this phase. The impact of heat stress in the post-anthesis phase was not influenced by atmospheric CO_2 concentration or water supply, although high spatial variability may be masking such interactions.

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