Heat shock response in wheat under Free Air CO_2 Enrichment

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Abstract

Heat waves have the potential to significantly reduce grain production and quality of rain-fed cropping systems. Along with expected increases in global atmospheric CO_2 concentration and average ambient temperature, due to climate change, there will also be an increase in the frequency of heat waves combined with increasingly severe terminal drought for many arable regions. In the development of adaptive management strategies, simulation modelling provides a potentially powerful tool to investigate the effects of climate and weather variables on wheat production. Many contemporary models used throughout the world do not adequately account for heat shock response of wheat during the reproductive and grain filling phase and data supporting the development of detailed heat shock modules is valuable, particularly under varying CO_2 environments. For the current study, two wheat varieties (cv. Scout & Yitpi) were exposed to heat stress (36 to 38 °C over 3 consecutive days) at two growth stages around anthesis with atmospheric CO_2 concentrations of 385 and 550 ppm using Free Air CO_2 Enrichment (FACE). Elevating CO_2 increased average yield by 31% which was attributed to a significant increase in grain number (27%). Kernel size also increased by 7% across both cultivars, although this was only significant for cv. Scout. Heat applied five days prior to anthesis caused grain number to decline by 0.21% per °C.hr (>32°C) for cv. Scout, which translated to a yield decrease of 0.22% per °C.hr (>32°C). For cv. Yitpi, there was no effect of pre-anthesis heat on yield components, although there was a consistent trend of increasing kernel size across both cultivars. When heat stress occurred 15 days after anthesis, grain number was unaffected for either cultivar; however, there was a consistent, non-significant trend of decreased kernel size. No interaction of heat and CO_2 concentration were observed. Crop canopy temperature (screen) was equivalent across ambient and elevated CO2 conditions; however, spike temperature was 1°C cooler under eCO_2. The screen temperature of the canopy compared to the 1.2 m standard (BoM), the canopy temperature was constantly 1°C hotter, which has implications for phenology prediction within crop models. The current work contributes to our experimental understanding of the effects of heat shock to wheat growth under different CO_2 growing conditions and supports the development of robust heat shock modules for incorporation into crop models.

Keywords

Crop models, heat shock, FACE, AGFACE, terminal drought

Introduction

For field crops grown in Mediterranean-type environments, heat waves have the potential to significantly reduce grain quality and production. Higher global atmospheric CO_2 concentrations are anticipated and in many semi-arid regions such as southern Australia this will lead to reduced growing season rainfall and increases in the frequency of heat waves (IPCC, 2012). Wheat is considered most sensitive to sudden heat stress (above 31ºC) if it occurs during the reproductive and grain-filling phase (Wardlaw and Wrigley, 1994). For example, yield was reduced by 18-35% for 35ºC heat stress imposed over a single day (Talukder et al., 2010). To investigate the effects of future climate and weather variables on wheat production and to aid the development of adaptive management strategies, simulation modelling provides a powerful tool for resolving these dilemmas (Jamieson and Semenov, 2000). Currently, few crop models comprehensively account for the response of wheat to extreme heat during the reproductive and grain filling phase (Barlow et al., 2014) which highlights the need for algorithms which describe the crop response to extreme heat events (Zheng et al., 2012). In the development of such algorithms, the generation of data defining wheat response to heat shock, particular under elevated atmospheric CO_2 is warranted. This paper reports on the response of heat shock under elevated CO_2 conditions to develop heat shock algorithms for incorporation into contemporary crop simulation models.

Methods

Heat chambers were used to examine the impact of simulated heat waves on wheat production and were applied at one of two stages (five days pre- and 15 days post-anthesis) for wheat grown at the Australian

Grains Free Air CO_2 Enrichment (AGFACE) experiment in Horsham, Australia (Mollah et al., 2009) during 2014. The AGFACE experiment comprised two atmospheric daytime CO_2 levels (ambient, 385 and elevated, 550 ppm). Prior to sowing 34 mm was applied to experimental plots. Between sowing (29 May 2014) and anthesis (07 Oct 2014) there was 94 mm rainfall and 59 mm of supplemental irrigation and in the post-anthesis phase up to harvest (19 Nov 2014) 1 mm rainfall and 60 mm of irrigation. For the heat shock treatments, target temperature was 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 (1200mmW×800mmD×500mmH) 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 situated in the crop canopy. Mixing of outside air was allowed from the base of the chamber. For monitoring temperature, screens were erected at canopy and 1.2 m within ambient and elevated CO_2 treatments and temperature was logged at five minute intervals using a combination of TinyTag Ultra 2 sensors, TGU-4017 (temperature) and TGU-4500 (temperature and relative humidity). For spike temperature, thermocouples were attached to the glume of main spikes, mid-head on the southern side.

Results and Discussion

Heat chamber performance

The performance of the heat chambers in elevating canopy temperature of wheat is presented in Fig 1. For the pre-anthesis heat treatment, average temperature across the three days (6 hours per day) was 36°C, compared with an average ambient air temperature of 20°C for the same period. For the post-anthesis heating, average canopy temperature was 38°C and the ambient air temperature for this period was 31°C. Variation in chamber performance between the pre- and post-anthesis heat treatments, where higher peak temperatures were achieved during the post-anthesis heat treatment may be due to several factors: a) the greater latent heat associated with the relative lush state of the crop canopy during the pre-anthesis phase; and b) cooler ambient air conditions in the pre-anthesis phase limiting the heating capacity of the chambers. For the design of heat chamber used, the concentration of CO_2 within the heat chamber positioned in the FACE ring is equivalent to free air eCO_2 environment (Nuttall et al., 2012). Relative humidity of the ambient air during the pre-anthesis phase was between 30 & 55% over the three day whereas within the heat chambers this decreased to circa 28%. During the post-anthesis heat treatment the relative humidity of the ambient air and heat chamber were similar, between 20 & 30%.

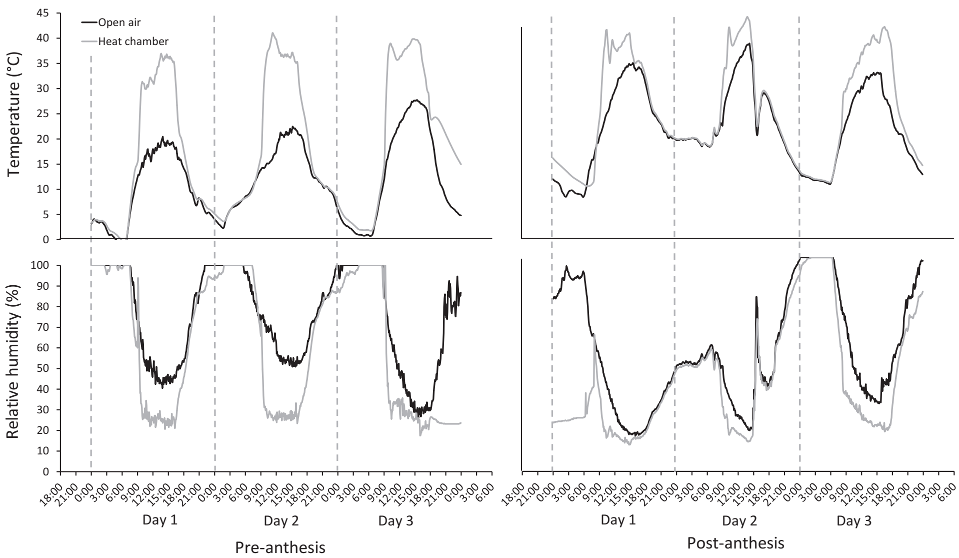

Figure 1. Crop canopy temperature and relative humidity for open air and heat chambers during the application of heat shock to wheat. Heat (target 38°C) was applied at two growth stages (5 days pre- and 15 days post-anthesis) for six hours per day over three consecutive days. Pre-anthesis heat was applied from 01 Oct 2014 to 03 Oct 2014 and post-anthesis heat applied from 21 Oct 2014 to 23 Oct 2014.

Wheat growth

Elevated CO_2 significantly increased yield by 29 and 44% for Scout and Yitpi respectively (Table 1). The increase in yield was due to large and significant increases in grain number of 22 and 32% for Scout and Yitpi respectively under eCO_2. For both cultivars grown under eCO_2, kernel size increased by 7%, although this increase was only significant for cv. Scout.

For heat shock there was a significant difference between cultivar response. For cv. Scout, heat applied five days prior to anthesis reduced grain number and grain yield by 18% while kernel size did not change significantly. When Scout was exposed to heat shock 15 days after anthesis, there was a significant reduction in yield of 14%, although yield components did not change significantly In contrast, for cv. Yitpi, heat at either stage had no significant impact on crop yield components, although for post-anthesis heat stress kernel size was reduced by 9% (non-significant). The limited response of Yitpi may be due to delayed development (4 days) compared with Scout. Of note is that there was no interaction between CO_2 level and the heat shock response in terms of overall yield and yield components for either of the cultivars.

Table 1. The response of wheat to FACE and heat shock. The yield components of two cultivars, Scout and Yitpi are presented.

		Scout				Yitpi			
		Grain no. (grains/m2)	**Kernel size (mg/1000)**	**Yield (t/ha)**	**HI**	**Grain no. (grains/m2)**	**Kernel size (mg/1000)**	**Yield (t/ha)**	**HI**
CO2	**Ambient**	4849	35.6	1.7	0.35	4936	34.3	1.6	0.35
	Elevated	5924	38.2	2.2	0.35	6498	36.8	2.3	0.31
	lsd (P<0.05)	360	1.9	0.2	ns	1169	ns	0.5	ns
Heat	**Ambient**	5867	37.1	2.2	0.37	5829	35.8	2.0	0.35
	Pre-anthesis	4826	38.3	1.8	0.35	5326	38.3	2.0	0.33
	Post anthesis	5465	35.2	1.9	0.35	5997	32.5	1.9	0.30
	lsd (P<0.05)	440	2.3	0.2	ns	ns	4.2	ns	ns

Heat load and crop response

For the pre- and post-anthesis heat treatments the corresponding heat load applied to crops (above 32°C) was 68 and 118°C.hr. In contrast, the open-air conditions over the same period were 0 and 13 °C.hr respectively. With regard to crop response of wheat (cv. Scout) to heat shock, this equated to a 0.21% reduction in grain number per C.hr (above 32°C), when heat stress occurred five days pre-anthesis. When heat stress occurred 15 days after anthesis the impact on grain number was limited (non-significant) to a 0.06% reduction per C.hr (above 32°C), and kernel size also decreased 0.04% per C.hr (above 32°C). Overall, pre- and post-anthesis heat shock reduced the yield of cv. Scout by 0.22 and 0.16% per C.hr (above 32°C) respectively. For cv. Yitpi, no significant reduction in grain number or yield due to heat treatment was observed, although a substantial (non-significant) reduction in kernel size due to post-anthesis heat equated to a 0.08% reduction in grain weight per C.hr (above 32°C).

FACE and screen position effect on apparent temperature

For crops grown under contrasting CO_2 concentration at ambient temperature, canopy temperature measured within a screen was equivalent at both five days pre- and 15 days post-anthesis (Fig 2 a) with no deviation from the 1:1 line between ambient and elevated CO_2 environments. While spike temperatures, were on average 1^{o}C cooler where crops were growing under high CO_2 conditions. This is contrary to expectations where the reduced transpiration of high CO_2 crops may translate to a hotter canopy. These results may reflect larger crop canopies and greater leaf area with eCO_2 condition resulting in greater net cooling with post-anthesis irrigation ensuring sufficient water to maintain adequate transpiration. There may also be more available soil water later in the season under eCO_2 crops (Leakey et al., 2009).

The temperature at the crop canopy (within a screen) compared with screen temperature at 1.2m above the soil surface was consistently 1oC hotter at the crop canopy, this pattern being consistent both at five days pre- and 15 days post-anthesis (Fig 2 *b*). Such variation in apparent temperature has implications for the application of BoM derived temperature data for driving wheat phenology within crop models where canopy temperature is not explicitly calculated. If consistent rules can be established between measured BoM screen temperature data and crop canopy temperature, this will assist in improving simulated phenology of crop models.

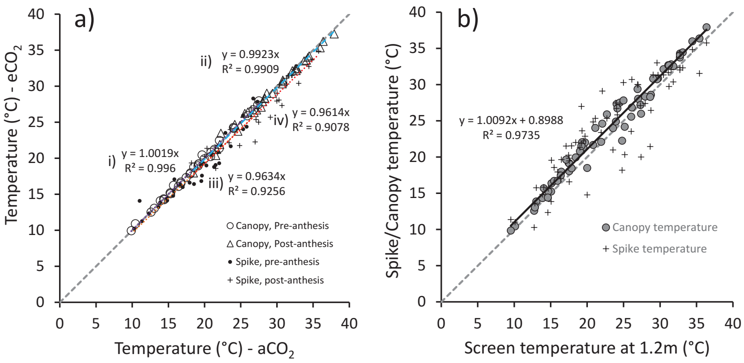

Figure 2 a) Comparison of wheat canopy and spike temperature for crops grown under ambient and elevated CO_2 conditions. Regression functions i, ii, iii and iv describe pre-anthesis canopy, post-anthesis canopy, pre-anthesis spike and post-anthesis spike temperatures respectively, b) Comparison of screen temperature measured at 1.2 m, wheat canopy and wheat spike. Temperature data are for three consecutive days, 5 days pre- and 15 days post-anthesis, expressed as hourly means of temperature recorded at 5 minute intervals between 0800 and 1800H. Regression function describes screen and crop canopy temperature. Broken line is 1:1.

Conclusions

The current study provides response data of wheat to heat shock under contrasting CO_2 conditions and compares crop canopy temperatures across CO_2 and height factors. Typically pre-anthesis heat shock limited yield potential through grain number reduction, with a tendency for some compensation in kernel size where grain number is reduced. For post-anthesis heat stress, the reduction in kernel size limited yield. For CO_2 interaction with heat stress, next steps require a meta-analysis over different seasons to verify these single year observations. Overall, such data help support the development of algorithms for use in crop models which have the broader utility for developing adaptive management strategies for maintaining yield and quality of wheat production amid the impacts of climate change.

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