Moderate heat stress prevented the observed biomass and yield stimulation caused by elevated CO₂ in two well-watered wheat cultivars

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Abstract

Key message  Heat stress (HS) under well-watered conditions was not detrimental to leaf photosynthesis or yield but modified the elevated CO₂ response of photosynthesis and yield in two contrasting wheat cultivars.

Abstract  Climate change is increasing the frequency of extreme events such as heat waves, adversely affecting crop productivity. While positive impacts of elevated carbon dioxide (eCO₂) on crop productivity are evident, the interactive effects of eCO₂ and environmental stresses are still unclear. To investigate the interactive effects of elevated CO₂ and heat stress (HS), we grew two contrasting wheat cultivars, early-maturing Scout and high-tillering Yitpi, under non-limiting water and nutrients at ambient (aCO₂, 450 ppm) or elevated (eCO₂, 650 ppm) CO₂ and 22 °C in the glasshouse. Plants were exposed to two 3-day HS cycles at the vegetative (38.1 °C) and/or flowering (33.5 °C) stage. At aCO₂, both wheat cultivars showed similar responses of photosynthesis and mesophyll conductance to temperature and produced similar grain yield. Relative to aCO₂, eCO₂ enhanced photosynthesis rate and reduced stomatal conductance and maximal carboxylation rate ($V_{cmax}$). During HS, high temperature stimulated photosynthesis at eCO₂ in both cultivars, while eCO₂ stimulated photosynthesis in Scout. Electron transport rate ($J_{max}$) was unaffected by any treatment. eCO₂ equally enhanced biomass and grain yield of both cultivars in control, but not HS, plants. HS reduced biomass and yield of Scout at eCO₂. Yitpi, the cultivar with higher grain nitrogen, underwent a trade-off between grain yield and nitrogen. In conclusion, eCO₂ improved photosynthesis of control and HS wheat, and improved biomass and grain yield of control plants only. Under well-watered conditions, HS was not detrimental to photosynthesis or growth but precluded a yield response to eCO₂.

Keywords  Wheat · Elevated CO₂ · Photosynthetic acclimation · Temperature response · Heat stress · Grain yield

Introduction

Ongoing climate change is threatening the production of agricultural crops including wheat (Triticum aestivum) (IPCC 2014; Asseng et al. 2015; Mishra et al. 2021). By the end of this century, atmospheric carbon dioxide concentration ([CO₂]) is expected to reach 700 ppm, increasing surface temperatures by 1.1–2.6 °C (IPCC 2014). For every degree of the temperature increase, global wheat production is predicted to decrease by 6–10% (Asseng et al. 2015; García et al. 2015). Crop models are important tools for assessing the impact of climate change (Asseng et al. 2013). However, they largely lack the ability to consider genotype-specific responses to elevated [CO₂] (eCO₂) and their interaction with other environmental conditions. Hence, it is important to better understand how plants respond to eCO₂ interactions with the environment. Photosynthesis, a fundamental
process driving crop growth and yield, can partially explain the interactive effects of eCO$_2$ with environmental stresses and provide a mechanistic basis for crop models (Yin and Struik 2009).

During photosynthesis, ribulose-1, 5-bisphosphate carboxylase/oxygenase (Rubisco) catalyzes the carboxylation and oxygenation of ribulose-1, 5-bisphosphate (RuBP). eCO$_2$ increases photosynthetic rates ($A_{\text{net}}$) and reduces photorespiration and stomatal conductance ($g_s$). Generally, higher photosynthetic rates enhance the growth and productivity of plants leading to increased leaf area, plant size and crop yield (Krenzer and Moss 1975; Sionit et al. 1981; Hocking and Meyer 1991; Mitchell et al. 1993; Kimball et al. 1995; Mulholland et al. 1998; Cardoso-Vilhena and Barnes 2001; Högy et al. 2009; Kimball 2016; Fitzgerald et al. 2016; Kimball 1983). Following long term CO$_2$ enrichment, photosynthetic capacity defined as the rubisco activity or electron transport rate under high irradiance per unit leaf area, may diminish due to lower amount of Rubisco (Nie et al. 1995; Rogers and Humphries 2000; Ainsworth et al. 2003) or reduced activation of Rubisco (Delgada et al. 1994).

Optimum temperature range for wheat growth is 17–23 °C, with a minimum of 0 °C and maximum of 37 °C (Porter and Gawith 1999). Global warming involves a gradual increase in mean temperature as well as increased frequency and intensity of heat waves. Heat can adversely affect crop growth and disrupt reproduction depending on the timing, intensity and duration (Sadras and Drecceer 2015). Higher daytime temperatures (below damaging level) increase photosynthesis up to an optimum temperature, above which photosynthesis decreases mainly due to higher photorespiration (Berry and Bjorkman 1980; Long 1991). High night time temperatures increase respiration and reduce overall photosynthetic carbon gain (Prasad et al. 2008). At the whole plant level, high temperatures accelerate growth (Fischer 1980) and shorten crop duration (Hatfield and Prueger 2015), hence reducing grain yield due to insufficient time to capture resources. Losses due to short crop duration are usually higher than benefits of growth stimulation at high temperature (Wardlaw and Moncur 1995).

The severity of the damage caused by abrupt temperature increases above the optimum range (termed heat stress, HS) depends on the magnitude and duration of HS as well as the developmental stage of the plant (Wahid et al. 2007). HS may reduce photosynthesis due to reduced chlorophyll content, impaired photosystem II and lower Rubisco activation (Berry and Bjorkman 1980; Eckardt and Portis 1997). Furthermore, HS can directly damage cells and increase grain abortion resulting in reduced growth, biomass and grain yield (Stone and Nicolas 1996, 1998; Wardlaw et al. 2002; Farooq et al. 2011). Around anthesis, HS (> 30 °C) reduces seed setting due to lower pollen viability, leading to poor fertilization, abnormal ovary development and slower pollen growth (Balla et al. 2019).

The interactive effects of eCO$_2$ and HS on plant growth and yield can be positive, negative or neutral (Wang et al. 2008, 2011). Plants may acclimate to changes in growth temperature and shift the optimum temperature for photosynthesis, which can maximize the photosynthetic rate at the growth temperature (Yamori et al. 2014). Elevated CO$_2$ increases the temperature optimum of photosynthesis (Long 1991; Alonso et al. 2009) by reducing photorespiration and improving tolerance to photoinhibition (Hogan et al. 1991). In addition, differences in plasticity of photosynthetic parameters with respect to growth temperature have been found responsible for differences in photosynthetic temperature acclimation (Yamori et al. 2010) and respiratory temperature acclimation can generate apparent acclimation of photosynthetic processes (Way and Yamori 2014). The impact of HS on photosynthesis will depend on whether Rubisco, electron transport or end-product synthesis is limiting at eCO$_2$ (Sage and Kubien 2007). Enhanced growth and leaf level intrinsic water use efficiency (iWUE) by eCO$_2$ may help compensate for the negative impact of HS; conversely, heat-induced shortening of the grain-filling stage and grain abortion could limit the benefits of eCO$_2$ (Lobell and Gourdji 2012). In addition, decreased $g_s$ under eCO$_2$ may limit transpirational cooling and therefore exacerbate HS. Thus, HS counteracts the positive effect of eCO$_2$ on yield components and may aggravate the negative effect of eCO$_2$ on grain quality due to the high sensitivity of wheat to temperature stress especially during anthesis and grain-filling stage (Wang and Liu 2021).

Many studies have investigated the response of wheat to eCO$_2$ in enclosures and in the field (Wang and Liu 2021). However, only a few studies have considered eCO$_2$ interaction with temperature increases in wheat (Rawson 1992; Delgado et al. 1994; Morison and Lawlor 1999; Jauregui et al. 2015; Cai et al. 2016) and rarely with HS (Coleman et al. 1991; Wang et al. 2008). Studies considering HS have addressed mainly the biomass or yield aspects and not the physiological processes such as photosynthesis (Stone and Nicolas 1994, 1996, 1998). Interactive effects of eCO$_2$ and HS on photosynthesis have been reported in a limited number of studies (Wang et al. 2008, 2011; Macabuhay 2016; Macabuhay et al. 2018; Chavan et al. 2019). Macabuhay et al. (2018) studied interactive effects of eCO$_2$ and (experimentally imposed) heatwaves on wheat (cv Scout and Yitpi) grown in a dryland cropping system and concluded that eCO$_2$ may moderate some effects of HS on grain yield but such effects strongly depend on seasonal conditions and timing of HS. In another glasshouse experiment on the interactive effects of severe HS (achieved by increasing RH to lower transpirational cooling) and eCO$_2$ in wheat (cv Scout), we found that eCO$_2$ mitigated the negative impacts of HS at anthesis on photosynthesis and biomass, but grain
yield was reduced by HS in both CO₂ treatments (Chavan et al. 2019). However, HS can occur throughout plant growth, including during vegetative, flowering or grain filling stages. Moreover, irrigation and relative humidity during HS plays an important role in how plants handle HS and plants may cope well with HS in well-watered conditions. In addition, different crop genotypes may respond variably to the interaction of eCO₂ with HS.

Here, we build on our previous work by comparing the interactive effects of eCO₂ and HS in two commercial wheat cultivars. In this study, we investigated the impact of HS during well-watered conditions at ambient RH. Scout and Yitpi have similar genetic background but distinct agronomic features. Scout is a mid-season maturity cultivar with very good early vigor that can produce leaf area early in the season. Scout has a putative water-use efficiency (WUE) gene, which has been identified using carbon isotope discrimination (Condon et al. 2004). Yitpi is a good early vigor, freely tillering, late flowering and long maturity cultivar (Seednet 2005; Pacificseeds 2009; Bahrami et al. 2017).

Although Scout is known to be a high yielding variety with very good grain quality and high reproductive sink (Pacific seeds 2009), we hypothesized that Yitpi will produce higher grain yield due to its ability to initiate more tillers and its longer time to flower and mature (Hypothesis 1). Fast growing plants with high sink capacity show a greater eCO₂-induced growth stimulation (Poorter 1993) and less photosynthetic acclimation (Delgado et al. 1994) compared to slow growing counterparts with low sink capacity. Consequently, we hypothesized that Yitpi will show greater photosynthetic, growth and yield response to eCO₂ due to its greater vegetative sink capacity (tillering) relative to Scout with restricted tillering (Hypothesis 2). The greater growth stimulation at eCO₂ may buffer Yitpi against HS damage compared to Scout. Thus, HS may decrease yield in Scout more than Yitpi and aCO₂ more than eCO₂ (Hypothesis 3). HS is more damaging at the reproductive relative to the vegetative developmental stage (Farooq et al. 2011). Hence, we expect less damage in plants exposed to HS at the vegetative stage relative to the flowering stage (Hypothesis 4).

To test these hypotheses, Scout and Yitpi were grown at controlled ambient or elevated CO₂ conditions and subjected to one or two heat stresses at the vegetative (HS1) and/or flowering (HS2) stage. Plant growth, biomass and leaf photosynthetic parameters were measured at different time points across the life cycle of the plants.

## Materials and methods

### Plant culture and treatments

The experiment was conducted in the glasshouse facility located at the Hawkesbury campus of Western Sydney University (WSU). Seeds of commercial winter wheat cultivars Scout and Yitpi were procured from Agriculture Victoria (Horsham). Cultivars were selected based on their use in the Australian Grains Free Air CO₂ Enrichment (AGFACE) project investigating climate change impacts on wheat growth and yield (Houshmandfar et al. 2017). For germination, 300 seeds of each cultivar were sterilized using 1.5% NaOCl₂ for 1 min followed by incubation in the dark at 28 °C for 48 h in petri plates. Sprouted seeds were planted in germination trays using seed raising and cutting mix (Scotts, Osmocote®) at ambient CO₂ (aCO₂, 400 μL L⁻¹), temperature (22/14 °C day/night), relative humidity (RH, 50–70%) and natural light (midday average 500 μmol m⁻² s⁻¹) (Figure S1). The growth stages are denoted by decimal code (DC) according to (Zadoks et al. 1974) along with the time points hereafter. Two-week-old seedlings (DC12) were transplanted to individual cylindrical pots (15 cm diameter and 35 cm height) using sieved soil collected from local site. At transplanting stage (T0) pots were distributed into two aCO₂ (400 μL L⁻¹) and two eCO₂ (650 μL L⁻¹) chambers (Figure S1B). Some plants were exposed to one or two HS cycles at the vegetative (HS1, 10 weeks after planting, WAP, DC 32) and/or the flowering (HS2, 15 WAP, DC 63) stages for 3 days with temperature ramp up from 14 °C night temperature (8 pm to 6 am) to 38 °C or 33 °C during mid-day (10 pm to 4 pm) respectively at 60% daytime RH (Figures S1, S2). The two HS cycles created four sets of heat treatments at each CO₂ concentration as follows: (1) Control—plants were not exposed to HS at any stage, (2) HS1—plants were exposed to HS at vegetative (DC32) stage only, (3) HS2—plants were exposed to HS at reproductive (DC63) stage only and (4) HS1 + 2—plants were exposed to both the heat stresses HS1 and HS2 (Fig. 1).

Thrive all-purpose fertilizer (Yates) was applied monthly throughout the experiment to maintain similar nutrient supply in all treatment combinations. Pots were regularly swapped between left and right benches as well as between front and back for randomization within chamber. Pots and treatments were also swapped between the two ambient and two elevated CO₂ chambers for randomization among chambers.
Growth and biomass measurements

The full factorial experimental design included four chambers (two chambers for each CO2 treatment) and five destructive harvests at time points T0 (2 WAP, DC12), T1 (6 WAP, DC28), T2 (10 WAP, DC35), T3 (17, DC65) and T4 (25 WAP, DC90) (Fig. 1). Ten plants per treatment per cultivar were measured and harvested at each time point except for T4 where plants exposed to only HS1 were not harvested. Morphological parameters were measured followed by determinations of root, shoot and leaf dry mass. Samples were dried for 48 h in the oven at 60 °C immediately after harvesting. Leaf area was measured at time point T1, T2 and T3 using a leaf area meter (LI-3100A, LI-COR, Lincoln, NE, USA). Plant height, leaf number, tiller number and ear (grain inflorescence) number along with developmental stage information (booting (DC45), half-emerged (DC55) or fully emerged (DC60)) were recorded at time points T2 and T3).

Leaf gas exchange measurements

The youngest fully developed leaf (which was the flag leaf at T3) was used to measure gas exchange parameters. Steady state leaf gas exchange measurements were performed at time points T1, T2 and T3 using a portable open gas exchange system (LI-6400XT, LI-COR, Lincoln, USA) to measure light-saturated (photosynthetic photon flux density (PPFD) = 1500 µmol m⁻² s⁻¹) photosynthetic rate (Asat), stomatal conductance (gs), ratio of intercellular to ambient
CO₂ (C/Cₐ), leaf transpiration rate (E), dark respiration (Rₑ) and dark- and light-adapted chlorophyll fluorescence (Fᵥ/Fₘᵥ, respectively). Dark adapted leaf measurements were conducted by switching off light for 15 min. Steady state leaf gas exchange measurements were also performed during (3rd day of HS) and after heat shock (next day after HS) along with recovery stage (5 days after HS). Plants were moved to a neighboring chamber with ambient CO₂ levels for short time (20–30 min for each plant) where air temperature was separately manipulated to achieve the desired leaf temperature. The LI-COR 6400-40 leaf chamber fluorimeter (LCF) was used to measure gas exchange parameters at a PPFD of 1500 μmol m⁻² s⁻¹ at two reference CO₂ (CO₂R) concentrations (400 and 650 μL L⁻¹) and two leaf temperatures (25 and 35 °C). Photosynthetic down regulation or acclimation was examined by comparing the measurements at common CO₂ (ambient and elevated CO₂ grown plants measured at 400 μL L⁻¹ CO₂ partial pressure) and growth CO₂ (aCO₂ grown plants measured at 400 μL L⁻¹ CO₂ partial pressure and eCO₂ grown plants measured at 650 μL L⁻¹ CO₂ partial pressure).

Dark respiration (Rₑ) was measured after a dark adaptation period of 15 min. Intrinsic water use efficiency (iWUE) was calculated as A_sat (μmol m⁻² s⁻¹)/gₑ (mol m⁻² s⁻¹). The response of A_sat to variations in sub-stomatal CO₂ mole fraction (Ci) (A-Ci response curve) was measured at T3 in 8 steps of CO₂ concentrations (50, 100, 230, 330, 420, 650, 1200 and 1800 μL L⁻¹) at leaf temperature of 25 °C. Measurements were taken around mid-day (from 10 am to 3 pm) on attached last fully expanded or flag leaves of the main stems. Before all leaf gas exchange measurements, the leaf was allowed to stabilize for 10–20 min until it reached a steady state of CO₂ uptake and stomatal conductance. Ten replicate plants per treatment were measured except for plants exposed only HS1 at T3 were not measured.

**Mesophyll conductance and temperature response**

Mesophyll conductance (gₘ) was determined by concurrent gas exchange and stable carbon isotope measurements using portable gas exchange system (LI-6400-XT, LI-COR, Lincoln, NE, USA) connected to a tunable diode laser (TDL) (TGA100, Campbell Scientific, Utah, USA) for the two wheat cultivars grown at ambient atmospheric CO₂ levels. A_sat and ¹³CO₂/¹²CO₂ carbon isotope discrimination were measured after T1 at five leaf temperatures (15, 20, 25, 30 and 35 °C) and saturating light (1500 μmol quanta m⁻² s⁻¹). Leaf temperature sequence started at 25 °C decreasing to 15 °C and then increased up to 35 °C. A-Ci response curves were measured at each leaf temperature. Dark respiration was measured by switching light off for 20 min at the end of each temperature curve.

Measurements were made inside a growth cabinet (Sanyo) to achieve desired leaf temperature. The photosynthetic carbon isotope discrimination (Δ) to determine gₘ was measured as follows (Evans et al. 1986):

\[
\Delta = \frac{1000e(\delta^{13}C_{sam} - \delta^{13}C_{ref})}{1000 + \delta^{13}C_{sam} - e(\delta^{13}C_{sam} - \delta^{13}C_{ref})}
\]

where,

\[
e = \frac{C_{ref}}{C_{sam} - C_{ref}}
\]

C_ref and C_sam are the CO₂ concentrations of dry air entering and exiting the leaf chamber, respectively, measured by the TDL. gₘ was calculated using correction for ternary effects (Farquhar and Cernusak 2012; Evans and Von Caemmerer 2013) following the next expression:

\[
g_{m} = \frac{1 + \Gamma (b - a - \frac{eR_{d}}{A + R_{d}} \Delta) \Gamma}{(\Delta - \Delta_{o} - \Delta_{e} - \Delta_{f})}
\]

where, \(\Delta_{o}\) is the fractionation that would occur if the gm were infinite in the absence of any respiratory fractionation (e=0), \(\Delta_{e}\) and \(\Delta_{f}\) are fractionation of ¹³C due to respiration and photorespiration respectively (Evans and Von Caemmerer 2013).

\[
\Delta_{o} = \frac{1}{1 - t} d' \Gamma \left(1 + t \frac{b - a'}{1 - \Gamma} \frac{C_{i}}{C_{a}} \right)
\]

\[
\Delta_{e} = \frac{1 + t}{1 - t} \left(\frac{eR_{d}}{A + R_{d}} \frac{C_{i} - \Gamma a}{C_{a}} \right)
\]

\[
\Delta_{f} = \frac{1 + t}{1 - t} \left(\frac{\Gamma a}{C_{a}} \right)
\]

where,

\[
t = \frac{(1 + a') E}{2g_{ac}^{'}}
\]

The constants used in the model were as follows: E denotes transpiration rate; g_{ac}' is total conductance to CO₂ diffusion in the boundary layer (ab = 2.9%e) and in air (a = 4.4%e); a’ is the combined fractionation of CO₂ across boundary layer and stomata; net fractionation caused by RuBP and PEP carboxylation (b = 27.3%e) (Evans et al. 1986); fractionation with respect to the average CO₂ composition associated with photorespiration (f = 11.6%e) (Lanigan et al. 2008) and we assumed null fractionation associated with mitochondrial respiration in light (e = 0).
Nitrogen and carbon estimation

Leaf discs were cut from the flag leaves used for gas exchange measurements at time points T2 and T3 which were then oven dried at 60 °C for 48 h. Leaf discs were processed for nitrogen (N) and carbon (C) content using an elemental analyzer (Dumas method). N and C were also estimated from other plant components including leaf, stem, root and grain harvested at T1, T3 and T4. Ground samples were processed for C & N with a CHN analyzer (LECO TruMac CN-analysyer, Leco corporation, USA) using an automated dry combustion method (Dumas method). Leaf N per unit area (Narea) was calculated as N (mmol g−1) x LMA (g m−2). Photosynthetic nitrogen use efficiency (PNUE) was calculated as N (μmol m−2)/leaf Narea (mmol m−2). Protein content was estimated using N and multiplication factor of 5.7 (Mosse 1990; Bahrami et al. 2017). N utilization efficiency was calculated as grain yield per total plant N.

Statistical and temperature analysis

All data analyses and plotting were performed using R computer software (R Core Team 2022). The effect of treatments and their interactions was analyzed using linear modeling with ‘anova’ in R. Significance tests were performed with anova and post hoc Tukey test using the ’glht’ function in the multcomp R package. Coefficient means were ranked using anova and post hoc Tukey test using the ‘glht’ function in the multcomp R package. Coefficient means were ranked using the ‘glht’ function in the multcomp R package. Coefficient means were ranked using the ‘glht’ function in the multcomp R package.

\[
R_d = R_{25} \cdot Q_{10}^{[(T-25)/10]} \quad (9)
\]

A peaked function (Harley et al. 1992) derived Arrhenius function was used to fit the temperature dependence of Jmax, and is given by the following equation:

\[
f(T_k) = \frac{E_a \cdot (T_k - 298)}{R \cdot 298 \cdot T_k} \left[ 1 + \exp \left( \frac{298 \cdot (S - H_d)}{T_k \cdot R \cdot 298} \right) \right] \left[ 1 + \exp \left( \frac{298 \cdot (S - H_d)}{T_k \cdot R \cdot 298} \right) \right] \quad (10)
\]

where, Ea is the activation energy and k25 is the Jmax value at 25 °C. Hd is the deactivation energy and S is the entropy term. Hd and ΔS together describe the rate of decrease in the function above the optimum. Hd was set to constant 200 kJ mol−1 to avoid over parametrization. The temperature optimum of Jmax was derived from Eq. 10 (Medlyn et al. 2002) and written as follows:

\[
T_{opt} = \frac{H_d}{\Delta S - R \cdot \ln \left( \frac{E_a}{(H_d - E_a)} \right)} \quad (11)
\]

The temperature response of A_sat was fit using a simple parabola equation (Crous et al. 2013) to determine temperature optimum of photosynthesis:

\[
A_{sat} = A_{opt} - b \cdot (T - T_{opt})^2 \quad (12)
\]

where, T is the leaf temperature of leaf gas exchange measurement for A_sat. T_opt represents the temperature optimum and A_opt is the corresponding A_sat at that temperature optimum. Steady state gas exchange parameters g_m, g_v, C_i and J_max to V_cmax ratio were fit using nls function with polynomial equation:

\[
y = A + Bx + Cx^2 \quad (13)
\]

Results

Two commercial wheat cultivars Scout and Yitpi were grown under aCO2 or eCO2 (daytime average of 450 or 650 μL L−1, respectively; 65% RH and 22 °C), natural sunlight and well-watered conditions (Figure S1). Both aCO2 and eCO2 grown plants were exposed to two 3-day HS cycles.

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at the vegetative (HS1, 10 WAP, DC32, daytime average of 38 °C) and flowering stage (HS2, 15 WAP, DC63, daytime average of 33.5 °C), while daytime RH was maintained at 60%. HS2 was lower in intensity relative to HS1 due to the cool winter conditions. Both HS cycles had similar overall effects on growth and yield parameters, refuting our fourth hypothesis that HS during the reproductive stage is more damaging. Hence, we mostly compare the control plants to those exposed to both heat stresses. Grain filling started 17 WAP (DC65) and final harvest occurred 25 WAP (DC90) (Fig. 1).

**Photosynthetic temperature responses of the two wheat cultivars at aCO₂**

A-Cₐ curves together with gₐ were measured at five leaf temperatures to characterize the thermal photosynthetic responses of the two wheat cultivars grown at aCO₂ (Fig. 2; 35 °C) in plants grown at aCO₂. Scout and Yitpi are depicted using circles with solid cultivars and triangles with broken cultivars respectively. Data in panels (a–f) and (h) are fit using nonlinear least square (nls) function in R.
Overall, both cultivars had similar photosynthetic temperature responses. $A_{sat}$ and $g_s$ increased with leaf temperature up to an optimum ($T_{opt}$) around 23.4 °C and decreased thereafter, while $C_i$ slowly decreased with temperature. Mesophyll conductance ($g_m$) increased up to 25 °C then plateaued (Fig. 2b). Scout had slightly higher $A_{sat}$, $g_s$ and $g_m$ than Yitpi at most leaf temperatures (Fig. 1a–d). $R_d$ linearly increased with temperature, and both cultivars had similar $Q_{10}$ ($R_d$) for dark respiration. Letters indicate significance of variation in means.

### Table 1 Summary of modelled parameters for temperature response of photosynthesis

| Parameter | Constant | Scout | Yitpi |
|-----------|----------|-------|-------|
| $A_{sat}$ (µmol m$^{-2}$ s$^{-1}$) | $T_{opt}$ (°C) | 23.4 ± 1 a | 23.4 ± 0.7 a |
| $A_{opt}$ | 24.6 ± 1 a | 22 ± 0.6 b |
| $g_m$ (mol m$^{-2}$ s$^{-1}$ bar$^{-1}$) | $T_{opt}$ (°C) | 27.9 ± 2.2 a | 32.5 ± 6.9 b |
| $g_m$ at 25 °C | 0.31 ± 0.01 a | 0.25 ± 0.01 b |
| $g_m$ at $T_{opt}$ | 0.30 ± 0.01 | 0.25 ± 0.01 |
| $V_{cmax}$ (µmol m$^{-2}$ s$^{-1}$) | $V_{cmax}$ at 25 °C | 192.7 ± 17.1 a | 198.4 ± 17.7 a |
| $E_aV$ (kJ mol$^{-1}$) | 43.3 ± 8.74 a | 46.4 ± 8.7 a |
| $J_{max}$ (µmol m$^{-2}$ s$^{-1}$) | $J_{max}$ at 25 °C | 187.9 ± 13.1 a | 186.1 ± 5.7 a |
| $T_{opt}$ (°C) | 29.6 ± 0.3 a | 30.5 ± 0.3 a |
| $J_{max}$ at $T_{opt}$ | 205.7 ± 10.2 | 215.4 ± 13.4 |
| $E_aJ$ (kJ mol$^{-1}$) | 37.7 ± 13.2 a | 41.1 ± 5.8 a |
| $\Delta S_J$ (J mol$^{-1}$ K$^{-1}$) | 648.3 ± 5.3 a | 647 ± 2.4 a |
| $H_d$ (kJ mol$^{-1}$) | 200 |
| $R_d$ (µmol m$^{-2}$ s$^{-1}$) | $R_d$ at 25 °C | 1.25 ± 0.02 a | 1.25 ± 0.02 a |
| $EaR$ (kJ mol$^{-1}$) | 30.9 ± 1.6 a | 33.2 ± 1.7 a |
| $Q_{10}$ | 1.51 ± 0.03 a | 1.56 ± 0.04 a |

Summary of coefficients derived using nonlinear least square fitting of CO2 assimilation rates and maximal rate of RuBP regeneration ($J_{max}$) determined using A-C$_i$ response curves and dark respiration measured at five leaf temperatures 15, 20, 25, 30 and 35 °C. Values are means with standard errors. Derived parameters include temperature optima ($T_{opt}$) of photosynthesis ($A_{opt}$), activation energy for carboxylation ($E_aV$); activation energy for RuBP regeneration ($E_aJ$), entropy term ($\Delta S_J$) and $T_{opt}$ and corresponding value for $J_{max}$ with deactivation energy ($H_d$) assumed constant; and activation energy ($EaR$) and temperature coefficient ($Q_{10}$) for dark respiration. Letters indicate significance of variation in means.

#### eCO2 stimulated photosynthesis and reduced stomatal conductance in both wheat cultivars

Overall, the two wheat cultivars had similar $A_{sat}$, $g_s$, iWUE ($A_{sat}/g_s$), $R_d$, $Fv/Fm$, $V_{cmax}$ and $J_{max}$ measured under most conditions (Figs. 1, 2, 3, 4; Tables S1, S2, S3). Under control (non-HS) conditions, eCO2 enhanced $A_{sat}$ measured at growth CO2 ($A_{growth}$) and 25°C and reduced $g_s$ in both cultivars at T1, T2 and T3 (Figs. 3, S2; Tables S1, S2, S3). When measured at common CO2 and 25 °C, eCO2-grown plants had lower $A_{sat}$ (−12% at T2, p < 0.001) and $g_s$ (−10% at T2, p < 0.001) relative to aCO2. This photosynthetic downregulation was more persistent in Yitpi compared to Scout (Fig. 3; Tables S1, S2, S3).

#### High temperature during HS enhanced photosynthesis under eCO2

The two HS cycles did not reduce $A_{growth}$ measured at 25°C during or after HS (Fig. 3a–d; Tables S1, S2, S3). During both HS1 and HS2, eCO2 stimulated $A_{growth}$ measured at 25°C in Scout but not Yitpi. Relative to 25 °C, $A_{growth}$ increased at 35 °C in Scout (10–14%) and Yitpi (12–18%) grown at eCO2 but not at aCO2. Immediately after the recovery from HS, $A_{growth}$ was upregulated in eCO2-grown Scout (Figs. 3a–d, S3). During both HS cycles, dark-adapted $Fv/Fm$ measured at 25 °C tended to be lower in Yitpi grown at eCO2 relative to aCO2. In both cultivars, $Fv/Fm$ decreased at 35 °C relative to 25 °C, indicating transient damage to PSII due to HS at both CO2 treatments (Fig. 3e–h; Tables S1, S2, S3).

Following long-term recovery from HS1 and/or HS2, the eCO2 stimulation of $A_{growth}$ was still marginally apparent in all T3 plants, being the strongest in eCO2-grown Yitpi (Fig. 5a, b; Tables S1, S2, S3). The reduction of $g_s$ at eCO2 was weak in all plants (Fig. 5c, d; Tables S1, S2, S3). Hence, iWUE was stimulated by eCO2 in all treatments, while PNUE was unaffected (Fig. 5e–h; Tables S1, S2, S3). There
was a good correlation between $A_{growth}$ and $g_s$ ($r^2 = 0.51$, $p < 0.001$) across all treatments (Fig. 6a).

$V_{cmax}$ and $J_{max}$ were derived from A-C response curves measured at 25 °C during the recovery stage after HS2. For control and HS plants, growth at eCO2 marginally reduced $V_{cmax}$ in Scout (−14%, $p = 0.09$) and Yitpi (−15%, $p = 0.06$) but had no effect on $J_{max}$. HS had no effect on $V_{cmax}$ or $J_{max}$ in either cultivar (Fig. 5i–l; Tables S1, S2, S3). $V_{cmax}$ and $J_{max}$ correlated well ($r^2 = 0.75$, $p < 0.001$) across treatments (Fig. 6b).

**Yitpi produced more tillers and grains than Scout**

When compared at aCO2, the two wheat cultivars differed in phenology and growth habit. Scout developed faster and flowered earlier than Yitpi. At T2, 43% of tillers had ears in Scout compared to 11% in Yitpi (Figure S3). At T2, Scout was 74% (p < 0.001) taller than Yitpi but at T3 both cultivars had similar height (Fig. 7i, j; Tables S4, S5). In contrast, Yitpi accumulated more biomass relative to Scout by producing more tillers. At T3, Yitpi had 42% (p < 0.005) more total plant biomass, 130% (p < 0.001) more tillers, 254% (p < 0.001) larger leaf area, 128% (p < 0.001) more leaves and 61% (p < 0.001) larger leaf size compared to Scout (Fig. 7; Tables S4, S5).

At the final harvest (T4), Yitpi had more plant biomass (84%, p < 0.001), tillers (88%, p < 0.001) and number of grains (54%, p < 0.001). Conversely, Scout had larger grain size (+31%, p < 0.001), a higher proportion (100%) of its tillers developed ears and more ears filled grains compared to higher tillering Yitpi (88%). Hence, both cultivars had relatively similar grain yield (g/plant) (Fig. 8a–f; Tables S4, S6). Higher (178%, p < 0.001) harvest index (HI) in Scout was due to early maturity and consequent leaf senescence leading to loss of biomass at final harvest (Tables S5). The final harvest was undertaken four weeks after all ears had matured on Scout to give ample time for grain filling in Yitpi (Fig. 8; Tables S4, S6).
eCO₂ similarly stimulated wheat biomass and grain yield under non-HS conditions

The increase in plant biomass at eCO₂ depended on the growth stage (Figs. 6, 7; Tables S4, S5). However, the overall stimulation was not different between the two cultivars as evident from the non-significant eCO₂ x cultivar interaction at all harvests (Table S4). By T3 (anthesis), when both cultivars were still within the exponential growth stage, eCO₂ stimulated plant biomass of Yitpi (+29%, p < 0.001) and Scout (+9%, p < 0.001) under control conditions. The number of tillers, total leaf area, mean leaf size or leaf mass area were not significantly affected by eCO₂ in either cultivar (Fig. 7; Tables S4, S5). eCO₂ increased allocation to stem relative to leaf biomass, particularly in Yitpi. Accordingly, there was a strong correlation across treatments between

![Fig. 4: Response of photosynthesis and chlorophyll fluorescence to HS in Scout and Yitpi grown at aCO₂ or eCO₂. CO₂ assimilation rates (a-d) and dark-adapted chlorophyll fluorescence, Fv/Fm (e-h) were measured at growth CO₂ and 25 °C in Scout (Circles) and Yitpi (Triangles). Open and closed symbols represent control and HS plants, respectively. In addition, plants were measured at 35 °C (*) during both HS cycles.](image-url)
stem and leaf biomass ($r^2 = 0.83$, $p < 0.001$) and between total biomass and leaf area ($r^2 = 0.83$, $p < 0.001$) in Scout but not in Yitpi. However, the two cultivars followed common relationship for root versus shoot biomass ($r^2 = 0.41$, $p < 0.001$) and leaf area versus leaf number ($r^2 = 0.82$, $p < 0.001$) across all treatments suggesting no effect of cultivar, eCO2 or HS on these common allometric relationships (Figure S4; Table S5).

At the final harvest T4 (seed maturity), eCO2 enhanced biomass and equally stimulated grain yield by increasing grain number in both cultivars (+64% in Scout and +50% in Yitpi) under control conditions only (Fig. 8a–d; Tables S4, S5, S6). Harvest index was not directly affected by any treatments but showed a significant interaction ($p < 0.05$) between CO2 and cultivar, such that HI was higher in Yitpi under eCO2 (Tables S5 and S6).

**eCO2 did not stimulate the grain yield of HS plants**

At T3, moderate HS (34–38 °C) applied under well-watered conditions and 60% RH during the vegetative (HS1 applied after T1) and flowering (HS2 applied after T2) stages had no significant impact on plant biomass of either wheat cultivar or CO2 treatment. By T4, there were significant HS × CO2 × cultivar interactions ($p < 0.01$) for biomass and grain yield. HS1 + 2 reduced the biomass and grain yield of eCO2-grown Scout relative to aCO2-grown counterparts. Unlike control plants, the biomass and yield of HS plants were not enhanced by eCO2 (Fig. 8; Tables S4, S5).

**eCO2 reduced grain N in Yitpi but not in Scout**

Neither eCO2 or HS had a significant effect on flag leaf N content in either cultivar at T2 or T3, but eCO2 reduced aggregate leaf N content (−18%) at T3 in Yitpi only (Cultivar × CO2 $p < 0.05$) (Table S7). Yitpi had higher grain N content (+26%) than Scout in control plants grown at aCO2 (Fig. 8g, h; Table S6). In control plants, eCO2 significantly reduced grain protein content in Yitpi (−18%, $p < 0.05$) but not in Scout due to significant cultivar × CO2 interaction ($p < 0.01$), while HS had no effect on protein content in either cultivar (Fig. 8g, h; Table S6).
Discussion

Two wheat cultivars with contrasting morphology and phenology, but similar photosynthesis and grain yield

The effects of future climate conditions, including eCO₂, will depend on the environmental conditions (e.g., water and heat stress) and the crop’s agronomic features. Here, we compared the interactive effects of eCO₂ and HS on two commercial wheat cultivars, Scout and Yitpi, with contrasting phenology and growth habit. Plants were grown under well-watered and fertilized conditions to remove any confounding effects of water or nutrient limitations on the eCO₂ or HS responses. RH was kept constant to minimize the negative impact of dry air during HS. Finally, we compared the effects of applying HS at the vegetative and flowering stages.

Free tillering Yitpi produced substantially more tillers, leaf area and biomass relative to the faster developing Scout. Accordingly, our first hypothesis predicted that Yitpi will have higher grain yield. The results only partially supported this hypothesis, because relative to Yitpi, Scout had higher harvest index (HI) due to its early maturing and senescing habit. While Yitpi initiated more tillers, a lower proportion of these tillers produced ears and filled grains. In contrast, Scout produced less tillers but flowered earlier which allowed enough time for all its tillers to produce ears and fill bigger grains by the final harvest. Hence, both cultivars had relatively similar yields due to bigger grain size in Scout and higher grain number in Yitpi. It is worth noting that some field trials have reported slightly higher grain yields in Scout than Yitpi (National variety trial report, GRDC, 2014). Our results are consistent with a previous study using different wheat cultivars with contrasting source-sink relationships which reported that the freely tillering cultivar “Silverstar” translated into more spikes while restricted tillering cultivar “H45” had more and heavier kernels per spike than “Silverstar” (Tausz-Posch et al. 2015). Thus, early vigor and maturity compared to high tillering capacity seem to be equally beneficial traits for high grain yield in the Australian environment.

The two wheat cultivars showed similar photosynthetic traits and response to temperature and eCO₂. The temperature response of \( \varphi_{\text{m}} \) as well as the values recorded at 25 °C (0.25–0.31 mol m\(^{-2}\) s\(^{-1}\) bar\(^{-1}\)) for Scout and Yitpi (Fig. 2b) were similar to what has been reported for wheat (0.39) and other crop species (cotton = 0.73, soybean = 0.49 and rice = 0.67) (Von Caemmerer and Evans 2015; Jahan et al. 2021). In contrast to our expectations that Scout would have higher WUE due to its selection based on a carbon isotope discrimination gene (Condon et al. 2004), both wheat cultivars showed similar iWUE under most measurement and growth conditions in this study (Fig. 5e, f; Table S2).
Rubisco activation or other regulatory mechanisms without affecting Rubisco content (Delgado et al. 1994). In the current study, eCO₂ similarly increased $A_{\text{growth}}$ (+21%) measured at growth CO₂ and reduced both $A_{\text{sat}}$ (−12%) measured at common CO₂ (Fig. 3, T2) and $V_{\text{cmax}}$ (Fig. 5i, j) in both cultivars. In contrast, flag leaf N (and possibly Rubisco) was not significantly affected in either cultivar (Table S6). Hence, the wheat cultivars have likely undergone a photosynthetic downregulation (less rubisco activation)—rather than acclimation (reduction in rubisco content)—in response to eCO₂ (Delgado et al. 1994; Leakey et al. 2009). These results partially countered our second hypothesis suggesting that Yitpi will show less photosynthetic acclimation due to its higher sink capacity. The interaction of eCO₂ with plant traits are complex. On the one hand, eCO₂ is expected to cause less feedback inhibition on photosynthesis in plants with high sink capacity (Ainsworth et al. 2004). On the other, fast-growing plants show a proportionally larger response to eCO₂ (Poorter and Navas 2003). Hence, high tillering in Yitpi and fast development in Scout both led to a relatively small observed photosynthetic downregulation in response to growth at eCO₂. This allowed a sustained photosynthetic stimulation, which in turn led to a significant biomass and yield enhancement by CO₂ enrichment in both wheat cultivars (Figs. 6, 7). Photosynthetic responses of wheat in current study are in agreement with earlier enclosure studies.
which generally have higher response to eCO₂ than the FACE studies (Kimball et al. 1995, 1999; Hunsaker et al. 1996; Osborne et al. 1998; Long et al. 2006; Cai et al. 2016).

**Elevated CO₂ stimulated grain yield similarly in both wheat cultivars**

In disagreement with our second hypothesis, eCO₂ similarly stimulated plant biomass and grain yield in early-maturing Scout and high tillering Yitpi (Figs. 6, 7; Table S4, S5). In Scout, the biomass stimulation was associated with increased tillering (one extra tiller per plant). In contrast, Yitpi produced many tillers at aCO₂ and the additional fixed carbon at eCO₂ was allocated to the existing tillers. At seed maturity, eCO₂ stimulated grain yield similarly in both cultivars as a result of the trade-off between grain yield components (Dias de Oliveira et al. 2015). In particular, eCO₂ stimulated grain number in both cultivars, while grain size increased in Scout only (Fig. 8; Table S6). Generally, eCO₂ stimulates grain yield by increasing the number of tillers and consequently, ears per plant (Zhang et al. 2010; Bennett et al. 2012) as a result.
of increased carbon supply due photosynthetic stimulation by eCO2, which has also been reported in FACE studies (Högy et al. 2009; Tausz-Posch et al. 2015; Fitzgerald et al. 2016). However, in our study, the increase in grain yield at eCO2 was mainly due to the increase in the number of grains per ear. In line with our results, Tausz-Posch et al. (2015) reported comparable grain yield stimulation by eCO2 in two different wheat cultivars with contrasting source-sink relationships. Moreover, grain yield of twenty wheat cultivars that differed in tillering propensity, water soluble carbohydrate accumulation, early vigor and transpiration efficiency responded similarly to eCO2 in glasshouse settings (Ziska et al. 2004; Bourgault et al. 2013).

Elevated CO2 reduced grain N in Yitpi only

Overall, there is a negative relationship between grain yield and quality (Taub et al. 2008; Pleijel and Uddling 2012). Hence, increased grain yield at eCO2 results in lower grain N and hence protein content (Seneweera and Conroy 1997; Bahrami et al. 2017). In our study, eCO2 reduced grain N in Yitpi under control conditions. Scout was characterized by having larger grains which accumulated less N than Yitpi. Moreover, eCO2 reduced total leaf N (−18%) at T3 and grain N (−17%) at T4 in Yitpi but not in Scout. This is consistent with the results from FACE study with same cultivars which reported −14% reduction in N content by eCO2 in above ground dry mass in Yitpi but not in Scout under well-watered conditions (Bahrami et al. 2017). The higher biomass accumulation in free tillering Yitpi may have exhausted the nutrient supply or nitrogen uptake may have slowed down (Carreras Navarro et al. 2020), such that further biomass stimulation by eCO2 lead to a significant dilution in N content (Taub and Wang 2008).

Wheat cultivars with early vigour such as Scout have greater root biomass accumulation as well as greater early N uptake which may have avoided a negative effect of eCO2 on leaf and grain N (Liao et al. 2004; Bahrami et al. 2017). Accordingly, Scout maintained a higher N utilization efficiency (grain yield per total plant N) relative to Yitpi under all treatments (Table S6). Increased grain yield is strongly associated with higher grain number per unit area (Zhang et al. 2010; Bennett et al. 2012) which dilutes the amount of N translocated per grain. Quality deterioration due to lower protein via reduced N is of critical concern in future high CO2 climate considering that even additional supply of N does not prevent N dilution in grain under eCO2 (Tausz et al. 2017). In addition, eCO2 has strong detrimental effect on other nutrient availability and remobilization from leaves to grains (Tcherkez et al. 2020).

HS had little effects on wheat photosynthesis or yield at aCO2

One of the key finding of this study was that the application of HS events (HS1, HS2 or HS1 + 2) was not detrimental to aCO2-grown wheat plants (Figs. 5, 7; Tables S4, S5, S6). Thus, our hypothesis that HS will reduce photosynthesis, biomass and yield at aCO2 was rejected. This finding is in contrast to previously reported studies where HS reduced the grain yield and negatively affected the growth and development in wheat (Stone and Nicolas 1996, 1998; Farooq et al. 2011; Coleman et al. 1991). During heat waves in the field, the vapor pressure deficit (VPD) increases and soil moisture decreases leading to lower stomatal conductance and consequently lower transpiration rate. Thus, plants are unable to cool down and leaf temperatures rise beyond optimum levels causing damage. The negligible effect of HS in our study could be explained by the ability of well-watered plants to maintain leaf temperature below damaging levels due to transpirational cooling (Perera et al. 2019; Deva et al. 2020) even with air temperatures reaching up to 38 °C. At moderate (~60%) relative humidity, there is sufficient water vapour gradient to sustain high transpiration rates when soil water is available, as was the case in our experiment. In most cases, gs was not significantly affected (Tables S1 and S2), and even slightly higher at T3 in HS-pants relative to the control (Fig. 5c, d). Well-watered crops can maintain grain-filling rate, duration and size under HS (Dupont et al. 2006), and high temperatures can increase crop yields if not exceeding critical optimum growth temperature (Welch et al. 2010). Also, in the current study, the night temperatures were not increased during HS which favors plant growth by reducing respiratory losses (Prasad et al. 2008).

In particular, HS did not elicit a direct negative impact on photosynthesis or chlorophyll fluorescence in either cultivar or CO2 treatment. During HS, high temperature transiently reduced maximum efficiency of PSII (Fv/Fm) in both cultivars and CO2 treatments (Fig. 4e–h). However, unchanged Fv/Fm measured at 25 °C confirmed that photosynthesis did not suffer long-term damage during or after HS. Moreover, HS was not severe enough to negatively affect A growth measured at 25 °C. These results are corroborated by the insensitivity of Vcmax and Jmax to HS (Fig. 5i–l), but contrast with previously reported studies where HS reduced photosynthesis in wheat at the vegetative (Wang et al. 2008) and the flowering (Chavan et al. 2019; Balla et al. 2019) stages. HS lowers membrane thermostability by inducing reactive oxygen species (ROS) and altering the membrane protein structures, which lead to changes in the fluidity of the thylakoid membrane and separation of light harvesting complex from the photosystems (Wahid et al. 2007; Poudel 2020). We were unable to measure leaf temperatures in the current study, but we speculate that, in well-watered wheat plants.
growing at moderate RH, leaf temperatures might not have increased beyond damaging levels to the membranes during the HS events.

Repeated HS may result in priming which involves pre-exposure of plants to a stimulating factor such as HS (Wang et al. 2017) and enable plants to cope better with later HS events (Balla et al. 2021). However, there was no difference between HS applied at the vegetative (HS1) and/or flowering stage (HS2) in rejection of our fourth hypothesis, and this may additionally be due to the short term duration of the two HS cycles (3 days each). Hence, our study demonstrated the benign effect that HS has on crop yield when separated from water stress and plants are able to transpire.

**HS precluded an eCO2 response in biomass and grain yield**

In our study, the impact of HS depended on the wheat cultivar and growth CO2 (Tables S1 and S4). Elevated CO2 and temperature interactions can be complex, dynamic and difficult to generalize as they can go in any direction depending on plant traits and other environmental conditions (Rawson 1992). Plant development is generally accelerated by increased temperature; eCO2 can accelerate it further in some instances or may have neutral or even retarding effects in other cases (Rawson 1992).

While eCO2 stimulated wheat biomass and grain yield under control (non-HS) conditions, HS precluded a yield response to eCO2 in Yitpi and reduced biomass and yield in eCO2-grown Scout relative to aCO2-grown counterparts (Fig. 8). These results are in contrast with previous studies that reported similar wheat yield reduction at ambient or elevated CO2 in response to severe (Chavan et al. 2019) or moderate HS (Zhang et al. 2018). The results also partially refuted our third hypothesis that HS may decrease yield more at aCO2 than eCO2, while partially agreeing that HS will have a more negative impact on Scout relative to Yitpi, albeit for different reasons than what we originally suggested. The negative effect of HS on Scout biomass and grain yield at eCO2 occurred despite the eCO2 stimulation of Agrowth under HS (T3, Fig. 5). However, over the long term, Agrowth was stimulated in eCO2-grown Yitpi and not Scout (Fig. 5).

Lack of a biomass stimulation despite high photosynthetic rates during HS under eCO2 could be due to the short duration of HS (3 days), which may not have been long enough to stimulate biomass gain. In addition, nutrient limitation at eCO2 may have restricted the eCO2 growth response. Typically, eCO2 studies show reduced N content in wheat and other crops (Taub and Wang 2008; Leakey et al. 2009; Bahrami et al. 2017). Hence, the wheat plants may have exhausted available nutrients due to increased demand by growing sinks at eCO2, which may limited further stimulation by high temperature. HS may be more damaging at eCO2 due to reduce transpirational cooling as a result of reduced gs at eCO2, leading to higher leaf temperatures. However, Agrowth increased in response to high temperature (35 °C) under eCO2 but not under aCO2 during HS (Fig. 4a–d), which refutes the suggestion of HS-damage to photosynthesis.

Higher gs during HS at moderate RH in well-watered conditions may increase Agrowth by increasing C in both aCO2 and eCO2 grown plants. Furthermore, lower photorespiration under eCO2 allows additional increase in Agrowth with temperature when measured at 35 °C relative to 25 °C (Long 1991). Under aCO2, photorespiration increases with temperature reducing Agrowth measured at 35 °C relative to 25 °C. Our results also point to a shift in Topt of photosynthesis (~24 °C at aCO2) to higher temperatures for plants grown at eCO2 (Sage and Kubien 2007). This would come about as a result of lower photorespiration at eCO2 as well as the slight upregulation of photosynthetic rates observed in eCO2-grown Scout at the recovery stage of HS (Fig. 4a, c). However, at T3, Agrowth was similar between aCO2 and eCO2 grown plants (Fig. 5a) indicating the short-term nature of this photosynthetic upregulation.

**Conclusions**

The two wheat cultivars, Scout and Yitpi differed in growth and development but produced similar grain yield. Under control conditions, eCO2 stimulated biomass and yield similarly in both cultivars. HS was not damaging to photosynthesis, growth, biomass or grain yield under well-watered and moderate RH conditions. However, HS interacted with eCO2, leading to similar or lower biomass and grain yield at eCO2 relative to both aCO2 in plants exposed to HS. This interactive effect precluded the positive effects of eCO2 in HS-plants. eCO2 improved photosynthetic rates in control and HS plants. Also, high temperature stimulated photosynthesis under eCO2 but not under aCO2 during HS which suggests increased optimum temperature of photosynthesis at eCO2. We speculate that in the current study, HS plants were able to cool down using high transpiration which helped to maintain lower leaf temperatures despite high air temperatures during HS. The current study provides important insights into the effect of short-term moderate temperature increases in well-watered conditions under future elevated CO2, potential role of transpirational cooling during HS and interactions between HS and eCO2 which will be useful in breeding cultivars for future climate and improving crop model accuracy to predict crop performance in future high CO2 environment with frequent heat waves.
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Author contributions All authors conceived the project. SGC maintained the plants and collected the data. SGC and RAD analysed the data. SGC and OG prepared the manuscript with input from other co-authors.

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Data availability All data supporting the findings of this study are available within the paper and within its supplementary materials published online. Reuse of the data is permitted after obtaining permission from the corresponding author.

Code availability Software application and codes used are all publicly available.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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