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Comparison of sensitive stages of wheat, barley, canola, chickpea and field pea to temperature and water stress across Australia

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ABSTRACT

Winter crops are the backbone of Australian agriculture. This study reports the first comparative analysis of the impact of temperature and water stress on yields of wheat, barley, canola, chickpea and field pea across four major production zones in Australia (North, East, South and West) using the 2009-2013 National Variety Trials (NVT). Developmental windows of 100 °Cd centred at flowering were used to sample rainfall, vapour pressure deficit (VPD), potential evapotranspiration, water supply/demand ratio, average minimum (Tmin) and maximum (Tmax) temperature, number of days below 0 °C and above 30 °C, incident radiation, photothermal quotient (PTQ) and PTQ corrected by VPD. Flowering was estimated for a mid-season cultivar for each trial using a simulation model (APSIM). There was a consistent negative association between Tmax and yields in all crops, from early in the season in the South and after flowering in the West. Our study supports that high temperature in the non-stressful range is associated with yield reduction with crop specific effects. Days exceeding 30 °C were unlikely before flowering; wheat and chickpea were sensitive to temperatures above 30 °C from early and late in grain filling respectively. Chickpea was sensitive to low temperatures from flowering. Canola was overall the most sensitive to water stress. Unequivocally, the interaction between temperature and water stress exhibited strong regional differences. In the West, with Mediterranean rainfall pattern, high Tmin before flowering was associated with higher yields in wheat, barley, canola and chickpea, indicating a role in promoting early growth and water use and reducing evaporation. In the North, crops depend on initial soil moisture, and high yields were associated with lower Tmin, likely slowing growth and early water use and lessening terminal stress. These relationships need direct experimental confirmation to show causality but there is room for large scale studies to uncover seasonal and regional patterns and highlight targets for research, breeding and management options aimed at improving yield under climate change.

1. Introduction

Winter/spring grown cereals, oilseeds and pulses are important crops in many farming systems and pillars of food security worldwide (Erskine et al., 2011; Fischer et al., 2014; Hartman et al., 2011; Shiferaw et al., 2013). The role of these crops in production systems relies on strong evidence about the nature and quantitative impact of environmental drivers on grain yield and quality. The quality of this information is critical, as it underpins predictions of performance under future climate scenarios (Challinor et al., 2014; Gourdji et al., 2013; Semenov et al., 2012), practical decisions about substitution or land use intensification options (Rial-Lovera et al., 2017; van Ittersum et al., 2013) and choice of genotype by management packages in a complex socio-economic environment (Peltonen-Sainio et al., 2017; Rodriguez et al., 2017).

Driven by climates and soils, much of Australia's agriculture has evolved into cereal-based systems, mainly wheat and barley, in rotation with pulses and more recently canola (Sadras and Dreccer, 2015). These cropping systems stem from the founder crops in the Levante (Abbo et al., 2003) and are currently widespread in other parts of the world with similar soil and climate constraints, including the Mediterranean basin and parts of the North American Great Plains (Fischer et al., 2014). Although these crops are grown in a relatively similar window in the Australian cropping belt and belong to the same photosynthetic

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pathway classification (C_3), differential responses to environmental factors, particularly temperature, have been documented during the critical period for yield formation (Sadras and Dreccer, 2015).

Climate projections indicate that global mean temperatures will rise by 0.4 to 1.6 °C by 2046-2065 and 2.6-4.8 °C by 2081-2100, depending on the emission scenario considered, with the potential to reduce crop production without adaptation (IPCC, 2014). Heat events will be more common and severe in the future. Battisti and Naylor (2009) predicted a > 90% probability that by the end of the 21 st century growing season temperatures in the tropics and subtropics will exceed the most extreme seasonal temperatures recorded from 1900 to 2006, whereas in temperate regions, the hottest seasons on record will represent the future norm in many locations. Changes in precipitation will not be uniform (IPCC, 2014), but for Australia (Reisenger et al., 2014), annual average rainfall is likely to decline in a large part of the cropping belt in the winter half of the year, a trend already observed in historical data (Cai and Cowan, 2008). Impact estimates of temperature and rainfall on yield are usually based on indirect methods linking crop performance and weather using regression (Tack et al., 2015), more sophisticated statistical models (Lesk et al., 2016) and/or dynamic process-based crop simulation (e.g. Asseng et al., 2015). For instance, Lesk et al. (2016) utilised superposed epoch analysis to conclude that, over the period 1964-2007, extreme drought and heat events substantially damaged cereal national agricultural production across the globe by 9-10%. Arnell et al. (2013) calculated a drop in productivity of spring wheat of ca. 30%-60% by 2100, depending on the level of temperature rise, based on a simple simulation model operating at large scale. Asseng et al. (2015), using a crop modelling ensemble in a range of locations, concluded that global wheat production was estimated to fall 6%°C^{-1} temperature rise, though a large discrepancy has been pointed out when models simulate dry and hot environments such as Australia (Asseng et al., 2013).

If extreme weather scenarios were realised, Australia could become a net importer of wheat (Howden et al., 2010). For a range of intermediate scenarios, shifts in the cultivated area and substitution amongst the major winter/spring grains may occur. While comparative approaches between crops have provided insights on crop physiology (e.g. Andrade and Satorre, 2015; Dreccer et al., 2000; Vega et al., 2001), they are rarer in the study of climate change impacts (Anwar et al., 2015). Numerous global impact studies have focused on wheat as a winter/spring crop, and maize, rice and soybean as summer options (Arnell et al., 2013; Challinor et al., 2014; Gourdji et al., 2013), with little attention to pulses, oilseeds or even barley. Among the few exceptions, Anwar et al. (2015) explored the impact on phenology and yield of wheat, barley, lupin, canola and field pea in four Australian locations, whilst Peltonen-Sainio et al. (2009) and Rodriguez et al. (2014) looked at opportunities for substitution at regional and farm level respectively.

National Variety Trials (NVT) are an extensive source of data that can be used to explore the relation between recently released germplasm and vulnerability to weather conditions. Tack et al. (2015), using regressions between winter wheat yield data from variety trials in Kansas and on-site weather data grouped chronologically, concluded that during spring, heat events caused the greatest reduction in yield but these could be partially offset by higher spring rainfall. Linking yield and weather using chronological time does not allow to exploit the physiological framework around the definition of yield components. For instance, in wheat, the yield component most closely associated with yield is grain number, defined in a window approximately 300 °Cd before and 100 °C days after flowering (Fischer, 1985) which encompasses spike growth, floret survival and grain set.

This study used data from the National Variety Trials to explore associations between yield and weather variables, particularly temperature and water, across the Australian cropping belt. Our work fills two gaps. First, we focused not only on wheat, but also on crops that have received little attention including barley, canola, chickpea and field pea. Second, we used a comparative approach to illuminate physiological aspects that are overlooked in single-crop studies. Overall, the data are analysed to learn about the adaptive potential of the different crops as they are exposed to a variety of weather and soil conditions across the continent using a phenology centred analysis.

2. Materials and methods

To establish associations between yield and weather in crop-specific developmental windows, we advanced an approach with three elements: (1) yield measured in Australia's National Variety Trials, a program of comparative crop variety testing with standardised management and data collection, (2) weather records, and (3) modelled crop phenology. To analyse the crop stages more vulnerable to each weather variable by crop and by region, environmental variables were sampled around predicted flowering date for a mid-season maturity type using the crop simulation model APSIM (Holzworth et al., 2014). The model was also used to calculate a water stress index based on the plant-soil water balance (Chapman et al., 2000). The association between yield and weather was carried out with the method proposed by Mercau et al. (2001).

2.0.1. Overview of regional climate, soil and cropping systems

Our analysis focused on four geographical regions (Fig. 1). The North has a summer rainfall pattern dominated by large rainfall events, the East has a uniform rainfall pattern, and the South and West have a winter rainfall pattern dominated by small rainfall events (Gentilli, 1971; Sadras and Rodriguez, 2007). In a study of locations spanning from North to South, Sadras and Rodriguez (2007) showed that annual median rainfall declined from 600 mm in the North to ca. 400 mm in the South but in season rainfall was about 30% vs. 70% of annual rainfall in the North and South respectively. Rodriguez and Sadras (2007) went further to show latitudinal trends, with the North presenting higher mean temperature, higher vapour pressure deficit, a lower fraction of diffuse radiation and lower daily PAR due to day length. Dominant soils are deeper and have higher water holding capacity and fertility in the North compared to the South and West region (ABARE-BRS, 2010; Fischer, 2009). Cereals constitute the backbone of Australian farming, and are grown in rotation with legumes and canola, particularly in the winter-rainfall environments of the south-east and western grain belt (Fischer, 2009). Canola and field pea are less cultivated in the North due to negative effects of high temperatures on production and quality (Sadras and Dreccer, 2015), while chickpea is less abundant in the East due to the dominance of acid soils and potential for disease.

2.1. Yield data and weather records

Yield data for wheat, barley, canola, chickpea and field pea were sourced from National Variety Trials (NVT, www.nvtonline.com.au) between 2009 and 2013, organised per geographical region as shown in Fig. 1. The 5-year period allows for seasonal variation whilst meeting the assumption of negligible yield change with technology (Calvino and Sadras, 1999) and keeps the comparison consistent among crops that have been in NVT for a different length of time. A longer time series would have been required to capture decadal trends of rainfall in Australia (Meinke et al., 2005), but this could have compromised the assumption of constant technology. Temperature, rainfall, global radiation and air vapour pressure data were obtained from patched point data sets (Jeffrey et al., 2001), while soil characteristics for each location were selected from the APSOIL database www.apsim.info/Products/APSoil.aspx.

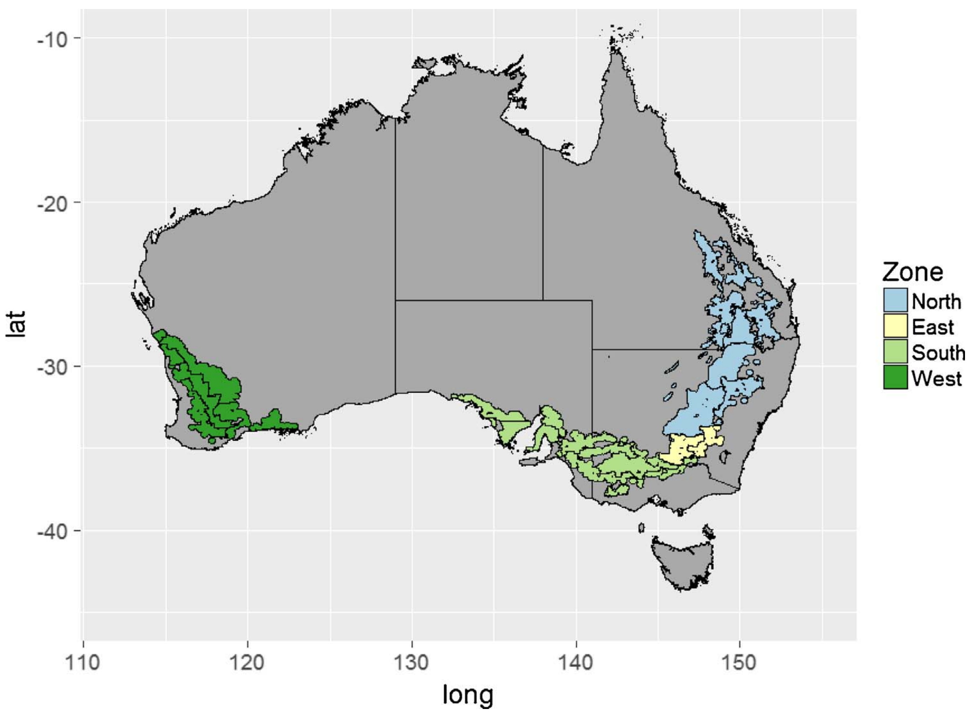

Fig. 1. Geographical regions as defined in http://www.nvtonline.com.au/ using the regional map from Chenu et al. (2013).

2.1.1. A phenology centred approach to link yield and weather

There was limited information on crop phenology from NVT datasets. Thus, simulated flowering dates of an intermediate maturity cultivar for each crop were obtained for each trial using the Agricultural Production Systems sIMulator (APSIM version 7.7, https://www.apsim.info/Products/Downloads.aspx) (Holzworth et al., 2014), sown at the NVT trial date and without water or N limitation. An intermediate maturity cultivar was chosen since the relation between yield of different entries classified in terms of maturity and trial mean was unique, spanned across the whole yield range (Appendix A Fig. A1) and entries of intermediate maturity were more common. The ability of APSIM to simulate crop phenology has been validated in different environments in the cropping region for wheat (Zheng et al., 2013 and references therein), barley (Salo et al., 2016), canola (Farre et al., 2002), field pea (Sadras et al., 2012) and chickpea (Chauhan et al., 2008). The cultivar phenology parameterisation had been validated for APSIM 7.7 for sensitivity to photoperiod, vernalisation and thermal time from floral initiation to flowering (Appendix A Table A1). Thermal time was calculated as the sum of the average daily temperature with base temperature of 0 °C across crop types and stages. Weather records and derived indices were sampled every 100 °Cd around flowering from sowing to simulated maturity or 700–800 °Cd depending on the crop, using algorithms in R (R Development Core Team 2010) based on Dreccer et al. (2007). Rainfall (mm), maximum (Tmax) and minimum temperature (Tmin) (°C) and global radiation (MJ m^{-2} d^{-1}) were taken directly from weather files. Temperature data were used to derive diurnal amplitude (Tmax-Tmin) and the number of days with potential for damage by frost (Days < = 0 °C) or heat (Days > = 30 °C). For heat, other thresholds were explored, e.g. Tmax > 35 °C but the low frequency of these events prevented a thorough analysis. Global radiation was converted to photosynthetically active radiation (PAR) by multiplying by 0.47 (Pinker and Laszlo, 1992). The vapour pressure deficit (VPD, kPa) and potential evapotranspiration (ET, mm d^{-1}) were calculated as described in Dreccer et al. (2007). Briefly, ET was calculated following Priestley and Taylor (1972) with the parameters used by the Australian Bureau of Meteorology (Wang et al., 2001). The vapour pressure deficit (VPD, kPa) was calculated as the difference between the air vapour pressure (VP) from the SILO database and the calculated saturated vapour pressure. The latter was based on Tmax and Tmin following Goudriaan and Van Laar (1994), calculated as a weighted average with more emphasis on Tmax (Jeffrey et al., 2001), (Eq. 1).

$$VPD = 0.75 \times 610.7 \times e^{\left(\frac{17.4 \times Tmax}{239+Tmax}\right)/1000} + 0.25 \times 610.7 \times e^{\left(\frac{17.4 \times Tmin}{239+Tmin}\right)/1000} - \frac{VP}{10} \quad (1)$$

The photothermal quotient (PTQ, MJ m^{-2} °Cd^{-1}) (Fischer, 2016; Nix, 1976) was used to compare the potential of different environments for yield, in this case using incident rather than intercepted radiation. It was calculated as the ratio between incident photosynthetically active radiation PAR (MJ m^{-2} d^{-1}) and daily mean temperature (°C) from start to end of each 100 °Cd interval:

$$PQ = \frac{\sum_{start}^{end} PAR}{\overline{T}_{start-end}} \quad (2)$$

The photothermal quotient corrected by the mean vapour pressure deficit (VPD, KPa) (Rodriguez and Sadras, 2007) was also calculated from start to end of each 100 °Cd interval:

$$PQ_{vpd} = \frac{\sum_{start}^{end} PAR}{\overline{T}\cdot\overline{VPD}} \quad (3)$$

Lastly, the water supply vs. demand ratio (SDR) (Chapman et al., 2000), was calculated using APSIM water supply (mm d^{-1}) based on the amount of water available for extraction in the rooted soil profile and the water demand (mm d^{-1}) as the ratio between daily crop growth rate and atmospheric demand (VPD) vs a transpiration efficiency coefficient adjusted by CO_2 concentration, as explained in Chenu et al. (2013). For these simulations, the starting soil water was reset on 1 January each year at 15% maximum available water relative to the lower limit of the soil, distributed evenly in the profile (Sadras et al., 2012). All weather indices were expressed as means for the 100 °Cd interval except for rainfall which was cumulative and the number of days of extreme temperature.

2.1.2. Data treatment and statistical methods

Yield analyses were based on site averages of Best Linear Unbiased predictors for individual genotypes for wheat, barley and field pea. The decision to use site averages was based on data exploration revealing that (i) the magnitude of yield variation between trials far outweighed the genotypic variation within a trial and (ii) the close association between yield of maturity groups and the environmental site mean (Appendix A Fig. A1). In canola and chickpea, separate trials were run for different crop types within the same site and sowing date. In canola, the types included conventional, triazine tolerant, imidazoline tolerant and Roundup Ready; in chickpea, kabuli and desi types. While smaller than the yield differences between extreme environments, chickpea and canola crop types presented yield variation relative to the trial site mean at particular yield ranges as observed by Zhang et al. (2016) in canola and Purushothaman et al. (2014) in chickpea. Hence, the yield data representing a particular site for canola and chickpea corresponded to the trial mean of the type that reached the highest yield, so that the performance in a given environment would not be limited by the potential of the germplasm. For each crop and region, the 10th and 90th yield percentile was calculated. The association of each of these yield categories with the corresponding weather variables mentioned above was compared using a t-test as in Mercau et al. (2001), performed per 100 °Cd interval.

Principal components analysis (PCA) based on 9 standardised descriptors of the environment as described previously were performed from emergence to flowering and grain filling, to analyse their relationships in the locations where yields were in the 10th and 90th percentile across all regions. PCA is a multi variate method of analysis that explains the variance-covariance structure of p variables with k linear combinations of original variables, where k is smaller than p. The weather descriptors were Tmax, Tmin, Days < = 0 °C, Days > = 30 °C, PAR, ET, VPD, cumulative rainfall (Rain), PTQvpd and SDR. The first two principal components are presented. The biplots show the relationship between trials of contrasting yield levels (scores), Low-10th percentile and High-90th percentile, among weather descriptors (loadings) and the relationship between trials and weather descriptors. Weather descriptors have a more positive correlation when the angle between vectors is more acute. Trials where certain conditions were prevalent are located on and towards the end of the vector, whereas those lacking that condition are in the space opposite to that vector. Trials that are poorly explained by the weather descriptors are close to the origin.

3. Results

3.1. Frequency distribution of yield and sowing date

Yield mean, median and thresholds used for low (10th percentile) and high (90th percentile) yielding conditions are presented in Table 1. The higher frequency of trials of a crop in a particular region reflects the actual cropping system (section 2.1). In general, the South and the West had the larger number of trials, followed by the North; the East had the lowest. The South and West had the highest number of trials of wheat, barley and canola while the South had the largest number of chickpea and field pea trials. The low number of trials, once crop type was taken into account, precluded quantile analysis of canola yields in the North and chickpea in the South; field pea did not have enough trials in the North. Caution is needed when interpreting the results of chickpea in the West and canola and field pea in the East, based on a small number of trials (ca. 30).

The distribution of sowing dates is shown in Table 2. The mean sowing dates were close among regions for wheat, barley, canola and chickpea. Field pea trials had a spread of 15 days between East and West and also the widest distribution, with early crops sown in the beginning of April and late ones up to end of June. In our sample of NVT crops, chickpea was sown later than most other crops (Table 2) but within acceptable margins for expression of yield potential (Whish, pers. comm.). High yielding crops (90th percentile) of wheat in the West and canola in the South were sown significantly earlier than low yielding ones (10th percentile).

Table 1
Number of trials analysed and mean, median, 10th and 90th percentile grain yield of wheat, barley, chickpea, field pea and oil yield of canola per region.

Crop	NVT Region	Number of trials	Yield (t ha^{-1})			
			Mean	Median	10th percentile	90th percentile
Wheat	North	130	3.4	3.4	2.1	4.7
	East	36	3.5	3.6	2.0	5.2
	South	230	3.4	3.3	1.5	5.0
	West	200	2.8	2.7	1.3	4.0
	Total	623				
Barley	North	42	3.7	3.8	2.7	4.9
	East	39	3.3	3.3	1.7	4.7
	South	146	3.6	5.1	2.1	5.1
	West	75	3.5	3.0	1.5	4.5
	Total	302				
Canola	North	-[a]	–	–	–	–
	East	33	0.8	0.8	0.6	1.2
	South	71	0.9	0.9	0.6	1.3
	West	81	0.8	0.8	0.4	1.2
	Total	185				
Chickpea	North	47	2.1	1.9	1.0	3.3
	East	-[a]	–	–	–	–
	South	77	1.9	1.7	0.9	3.1
	West	33	1.3	1.0	0.6	2.6
	Total	157				
Field pea	North	-[a]	–	–	–	–
	East	27	2.0	2.0	1.2	2.8
	South	107	2.5	2.4	1.4	3.5
	West	51	1.9	1.8	0.7	3.0
	Total	185				

[a] insufficient data.

3.2. Common features of high and low yielding sites across regions before and after flowering

Weather variables and derived indices can be correlated, due to causality or co-occurrence. A multivariate analysis revealed the main weather descriptors that discriminated low and high yielding conditions (Fig. 2). From emergence to flowering, the first principal component explained 51 to 60% of the variation in the data while the second was responsible for 18 to 27%. Two groups of variables tended to have high loadings on the first principal component. PAR, Tmax, VPD and ET were positively correlated (in absolute value) and contrasted with PTQvpd, the photothermal quotient corrected by VPD, rainfall and the water supply/demand ratio (SDR). Considering some of the formulas, it is not surprising that PAR and ET or Tmax and VPD are positively correlated or that PTQvpd is negatively correlated to Tmax and VPD. In all crops, most high yielding sites were characterised by high rainfall, SDR and PTQvpd and lower Tmax and VPD before flowering. SDR had more bearing on the first and rainfall on the second principal component. In wheat and chickpea, some high yielding sites also featured high PAR and ET. Tmin and the number of days below 0 °C tended to be negatively correlated and had a stronger bearing in the second principal component, helping discriminate within low or high yielding trials. Chickpea was an exception, as some high yielding trials had higher Tmin from emergence to flowering.

During grain filling, the first principal component explained more than before flowering, 63-74%, with PTQvpd negatively correlated to Tmax, number of days above 30 °C and VPD. The second principal

Table 2
Mean, median, 10th and 90th percentile of sowing date, and mean sowing dates and simulated flowering dates associated with 10th and 90th percentile (p) of grain yield of wheat, barley, chickpea, field pea and oil yield of canola per region and probability of those values being different after ANOVA.

			Sowing date			Sowing dates associated with yield category			Simulated flowering dates associated with yield category		
Crop	Region	Mean	Median	10th p	90th p	10th p	90th p	p-Val.	10th p	90th p	p-Val.
Wheat	North	31-May	31-May	10-May	18-Jun	27-May	6-June	NS[a]	30-Aug	11-Sep	NS
	East	25-May	28-May	12-May	5-Jun	4-Jun	21-May	NS	27-Sep	8-Oct	NS
	South	26-May	27-May	12-May	10-Jun	23-May	21-May	NS	15-Sep	17-Sep	NS
	West	27-May	28-May	13-May	12-Jun	30-May	12-May	*	15-Sep	3-Sep	**
Barley	North	3-Jun	2-Jun	15-May	21-Jun	6-Jun	24-May	NS	11-Sep	26-Sep	NS
	East	29-May	29-May	19-May	13-Jun	31-May	25-May	NS	11-Oct	14-Oct	NS
	South	27-May	28-May	11-May	14-Jun	24-May	27-May	NS	28-Sep	5-Oct	NS
	West	27-May	27-May	15-May	11-Jun	26-May	28-May	NS	29-Sep	30-Sep	NS
Canola	North	–[b]	–	–	–	–	–	–	–	–	–
	East	11-May	8-May	2-May	26-May	7-May	10-May	NS	2-Sep	9-Sep	***
	South	15-May	14-May	2-May	30-May	22-May	14-May	*	7-Sep	6-Sep	NS
	West	13-May	13-May	5-May	22-May	14-May	13-May	NS	27-Aug	26-Aug	
Chickpea	North	29-May	6-Jun	3-Apr	22-Jun	12-Jun	9-Jun	NS	31-Aug	2-Sep	NS
	East	–[b]	–	–	–	–	–	–	–	–	–
	South	5-Jun	1-Jun	20-May	26-Jun	8-Jun	7-Jun	NS	7-Sep	8-Sep	NS
	West	4-Jun	30-May	25-May	28-Jun	1-Jun	26-May	NS	31-Aug	6-Aug	*
Field pea	North	–[b]	–	–	–	–	–		–	–	–
	East	11-May	26-May	2-Apr	15-Jun	19-May	1-Apr	NS	8-Sep	30-Jul	NS
	South	15-May	26-May	2-Apr	17-Jun	18-May	5-Jun	NS	30-Aug	14-Sep	NS
	West	26-May	1-Jun	2-Apr	25-Jun	5-Jun	20-May	NS	7-Sep	7-Aug	NS

[a]P < ‘***’ 0.001, ‘**’ 0.01, ‘*’ 0.05; NS non-significant
[b]not calculated due to insufficient data.

component explained 12-23% of the variation in the data, generally dominated by Tmin, water SDR and rainfall. The discrimination between high and low yielding conditions by the first principal component was not as clear during grain filling as it was from emergence to flowering. In fact in canola, chickpea and field pea the second principal component tended to contribute more to the discrimination.

To tease out the impact of weather during the crop cycle and its impact in different locations, an analysis of the association between yield and individual weather variables was carried out per crop and region sequentially from emergence to maturity. Because of the association and co-occurrence of some of these variables (Fig. 2), it is important to interpret the results with caution.

3.3. Relationships between weather variables and yield

3.3.1. Rainfall, evapotranspiration, vapour pressure deficit and water supply/demand ratio

The *expectation* is that greater yields will be associated with lower water stress due to higher rainfall and lower VPD. For the series analysed (2009-2013), the *findings* confirm that for wheat, barley and canola; high yields were associated with significantly higher rainfall particularly in the South and West (Fig. 3). There was little or no association between yield and rainfall in the pulses. High ET was significantly and consistently associated with lower yields in wheat, barley and canola in the South and West and chickpea in the West but did not define high and low yielding environments in the North (Appendix B, Fig. B1). Low yields were more consistently related with higher VPD, either throughout the cycle (e.g. wheat in the South or West) or during grain filling (e.g. canola in the West) (Fig. 4). The associations between yield and either rainfall or VPD were stronger in the South and West, and less significant in the North and East. In wheat, barley and canola in the South, rainfall was higher before flowering and so was its impact, whereas the opposite was apparent in the West, where impact was more noticeable during grain filling, when VPD was also higher. In wheat but more markedly in barley in the East, high ET during the critical period for grain number formation was associated with higher yields, linked to a higher radiation (section 3.5).

The simulated water supply/demand ratio (Fig. 5) integrates the supply (initial soil water plus in-season rainfall) with the simulated crop demand, and can be used as an indicator of water stress. The higher the water supply/demand ratio, the lower the water stress. As *expected*, water stress increased during the season, particularly in low yielding crops, but different patterns of association with yield emerged across regions and crops. Regionally, in the North and to some extent the East, the associations were more frequent during grain filling but were generally weak. This is possibly related to the significant role of initial soil water under the summer rainfall pattern of the North and North E, and would explain the lack of association between low yields and low rainfall, high ET and VPD in the North (Figs. 3–5). The association between yield and water supply/demand ratio was stronger in the South and West. Wheat experienced almost no stress between establishment and early vegetative growth, but stress increased during tillering and stem elongation and continued throughout the season, particularly in the South and West. In barley, the association between water stress and low yield was stronger in the South compared to the West and was confined to pre-flowering stages. While in the South, high yielding barley crops experienced no water stress until shortly before flowering, in the West, even high yielding crops experienced some degree of water stress from shortly after emergence, coinciding with low rainfall and marginally higher evapotranspiration. Interestingly, water stress increased during barley grain filling and did not help to discriminate high from low yielding crops. In canola, yield was unrelated to water stress until ca. 300 °Cd before flowering, its influence growing steadily during flowering and grain filling. In any region, low yielding canola crops experienced the lowest water supply/demand ratio compared to other crops, whereas high yielding wheat crops were the least stressed. In chickpea, associations between water stress and yield emerged ca. 300–400 °Cd after flowering, consistently across regions. Water stress in field pea was low for this data set and unrelated to yield.

3.4. Temperature

Higher average temperature was associated with lower yield, except for chickpea before flowering in the West and field pea in the East (Appendix B Fig. B2). Useful information was unlocked when the analysis was repeated with maximum, minimum and threshold temperatures. The *expectation* was that high maximum temperatures (Tmax),

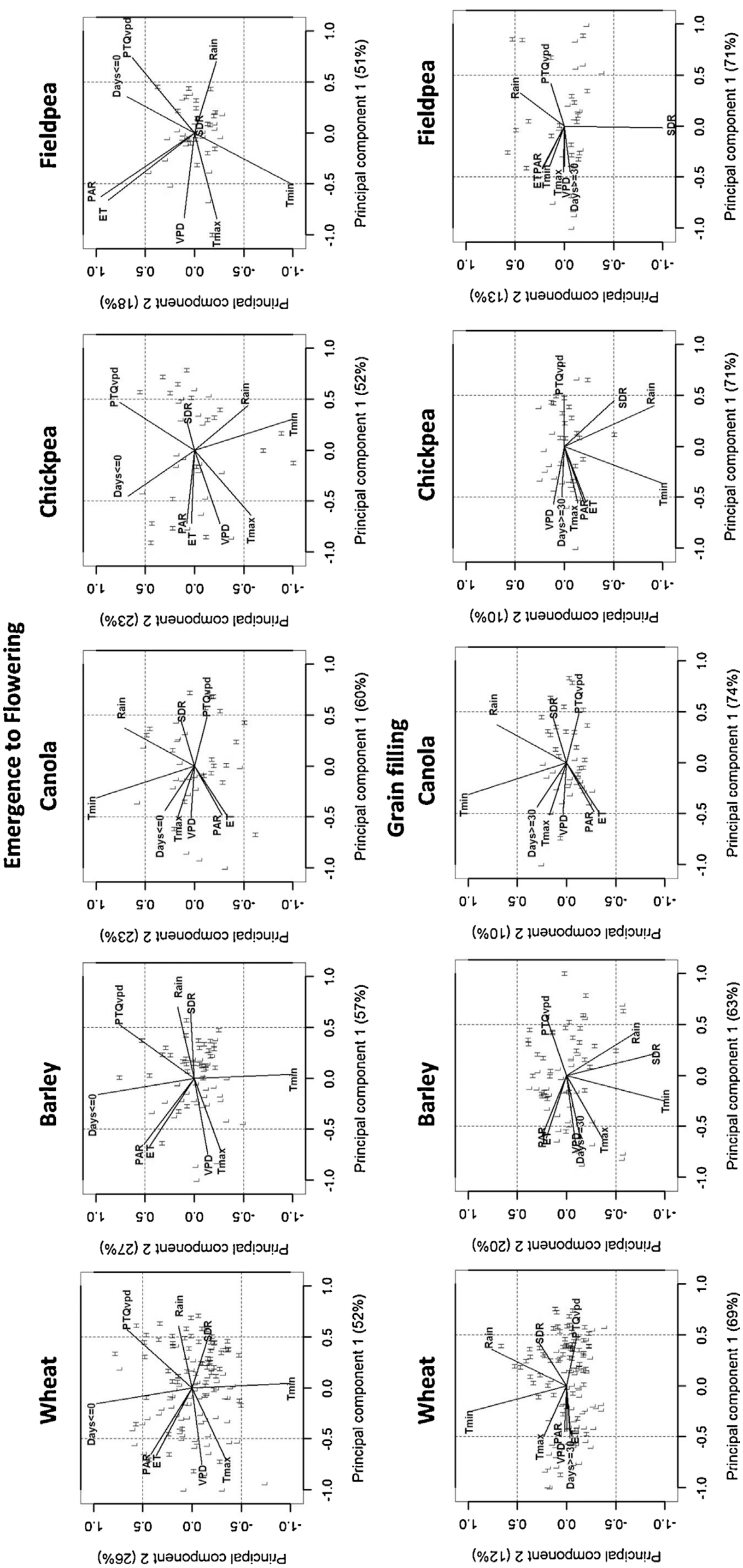

Fig. 2. Biplot of trials clustered per yield level (High (90th percentile): H, Low (10th percentile): L) as characterised by environmental descriptors (loadings) from emergence to flowering and during grain filling. Environmental descriptors are maximum temperature (Tmax), minimum temperature (Tmin), number of days above 30 °C (Days > =30), number of days below 0 °C (days < =0), vapour pressure deficit (VPD), photosynthetically active radiation (PAR), potential evapotranspiration (ET), cumulative rainfall (Rain), water supply/demand ratio (SDR) and photothermal quotient corrected by VPD (PTQvpd).

particularly in the stressful range, e.g. above 30 °C, would be associated with low yields. More generally, the *findings* indicated that there was a strong and consistent association between high Tmax and lower yields (Fig. 6). Wheat and barley conformed to a pattern where higher Tmax was weakly related to low yields in the North, practically unrelated in the East, strongly throughout the cycle in the South and more

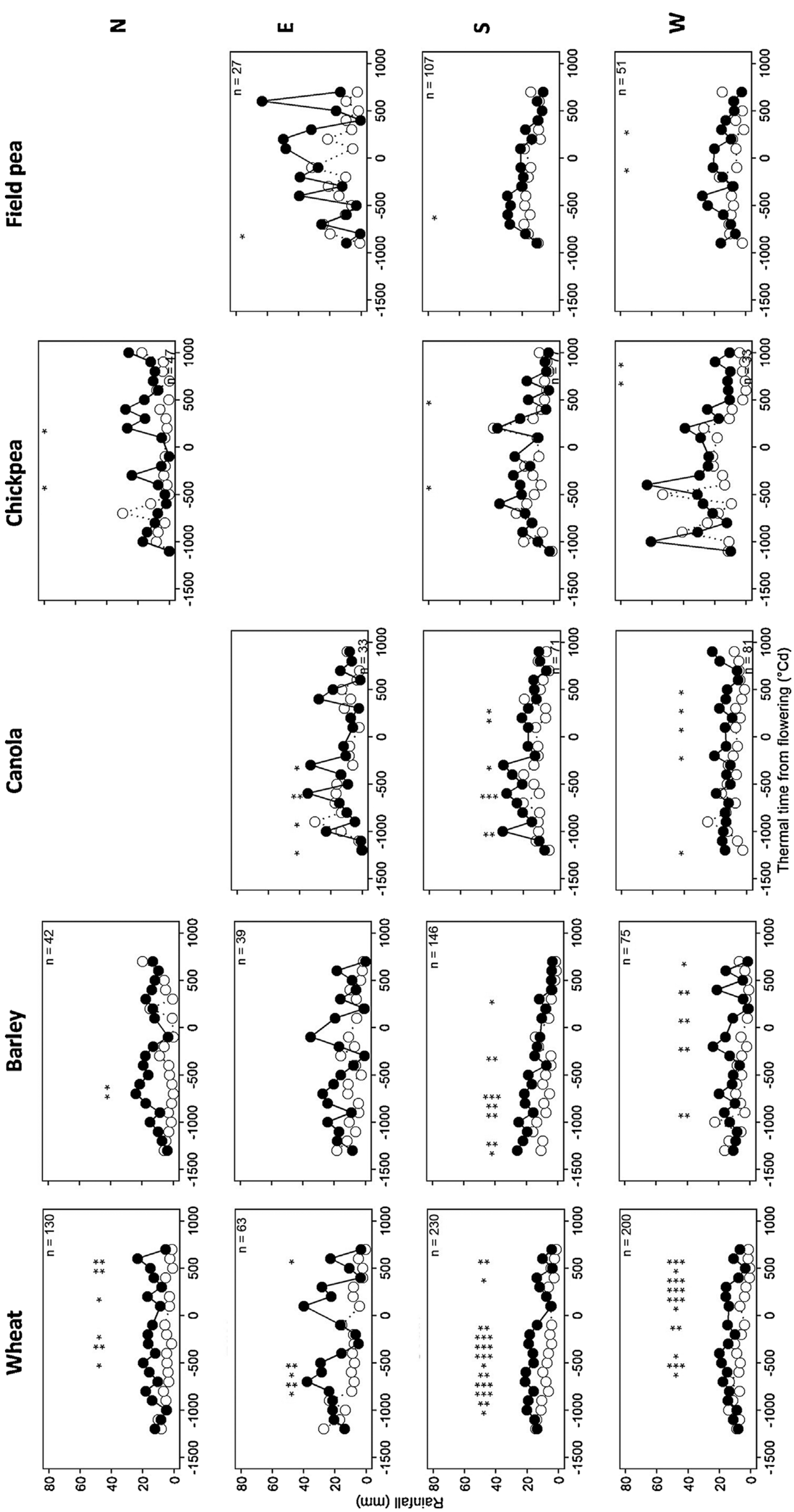

Fig. 3. Cumulative rainfall per 100 °Cd interval associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at $P < 0.0001$ (***), $P < 0.01$ (**) and $P < 0.05$ (*).

influential towards flowering and grain filling in the West. In the West, this may reflect the fact that low yielding wheat had also been sown later (Table 2). Canola had a weak association between low yield and higher Tmax during grain filling in the East, and was similar to wheat and barley in the South and West. In chickpea, higher Tmax during grain filling had a consistent negative impact on yield, but the effect was less significant than in other crops. Interestingly, higher Tmax early in the cycle was positively associated with field pea yield in the East, a

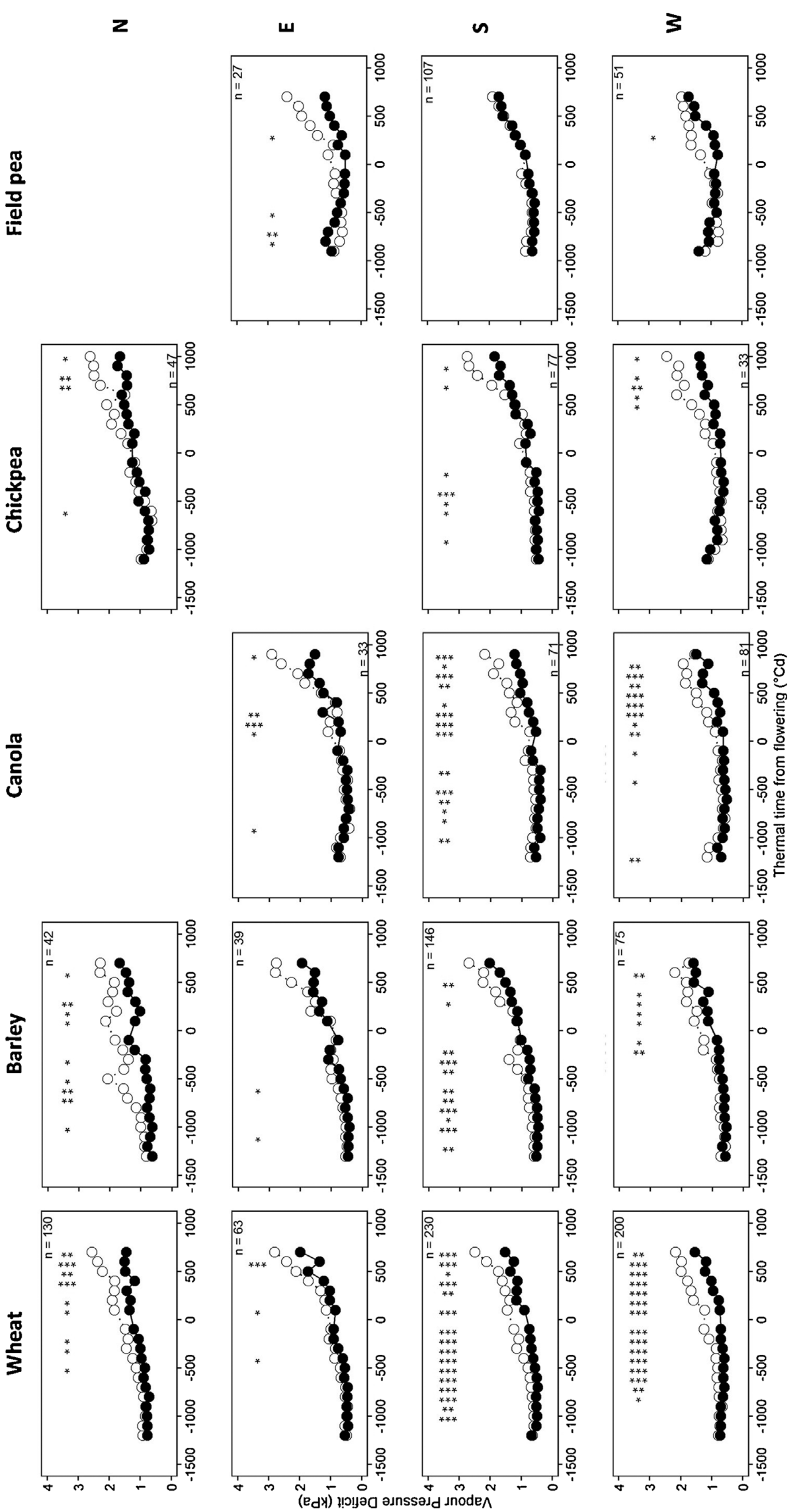

Fig. 4. Vapour pressure deficit associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at $P < 0.0001$ (***), $P < 0.01$ (**) and $P < 0.05$ (*).

similar trend was observed for chickpea and field pea in the West albeit non-significant.

Maximum temperatures exceeding 30 °C were unlikely before flowering (Appendix B Fig. B3). In wheat, there was a significant association between the number of days above 30 °C during grain filling and low yields in the North, South and West. A similar trend was observed in canola in the South and West and chickpea in the North and West. Low yielding chickpea experienced the higher number of days above 30 °C during grain filling in the West.

The *findings* regarding minimum temperature (Tmin) were different

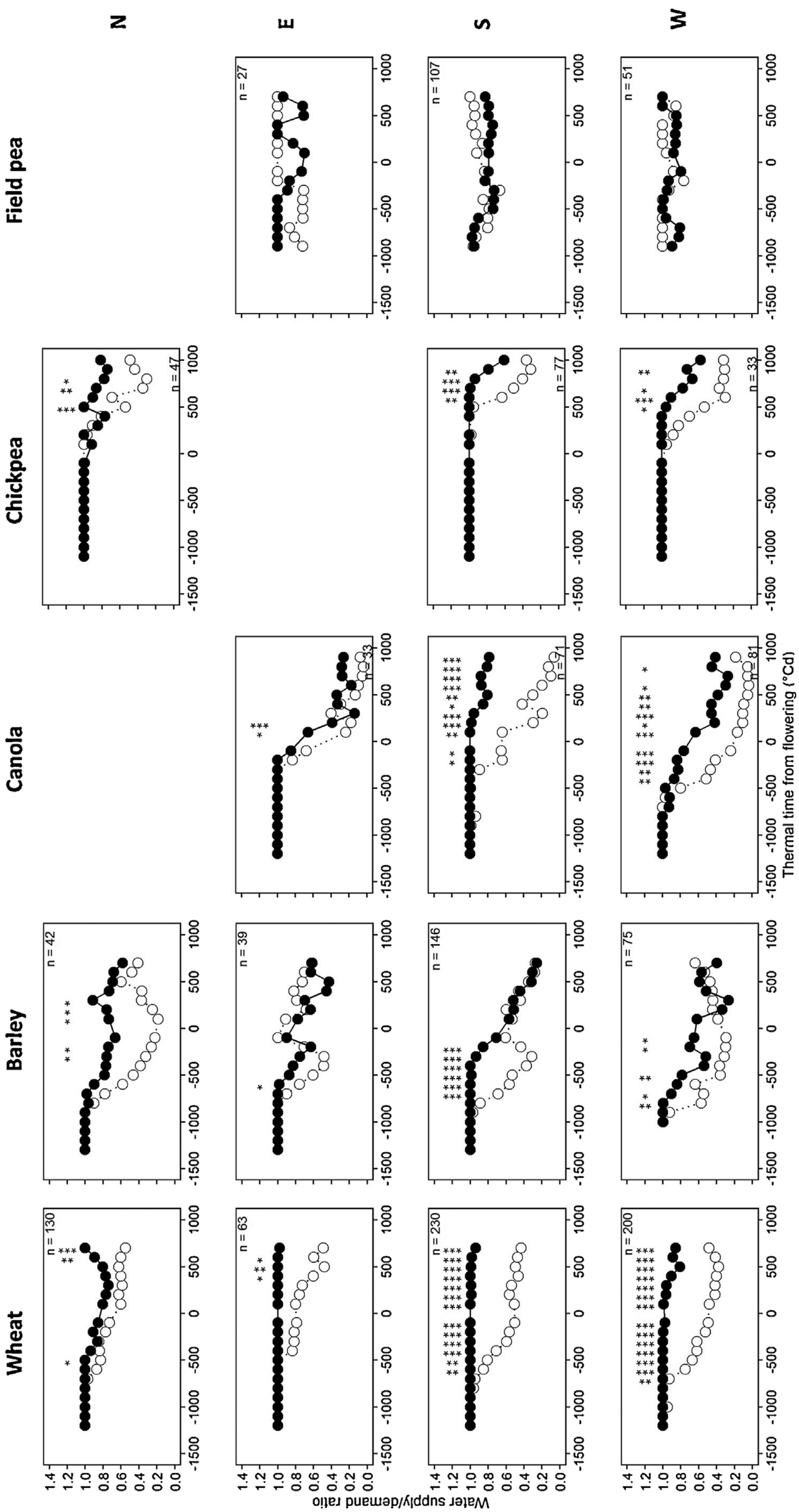

Fig. 5. Water supply/demand ratio associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at $P < 0.0001$ (***), $P < 0.01$ (**) and $P < 0.05$ (*).

between regions and, sometimes, for crops and crop stages within a region (Fig. 7). For all crops in the West, a lower Tmin during tillering and stem elongation in the cereals and before flowering in canola, chickpea and field pea, was associated with lower yields. For wheat and barley in the North and the East and canola in the East, lower yields were more often associated with a higher Tmin before flowering. By contrast, after flowering, higher Tmin was associated with lower yields across crops and regions where a significant effect was detected (e.g.

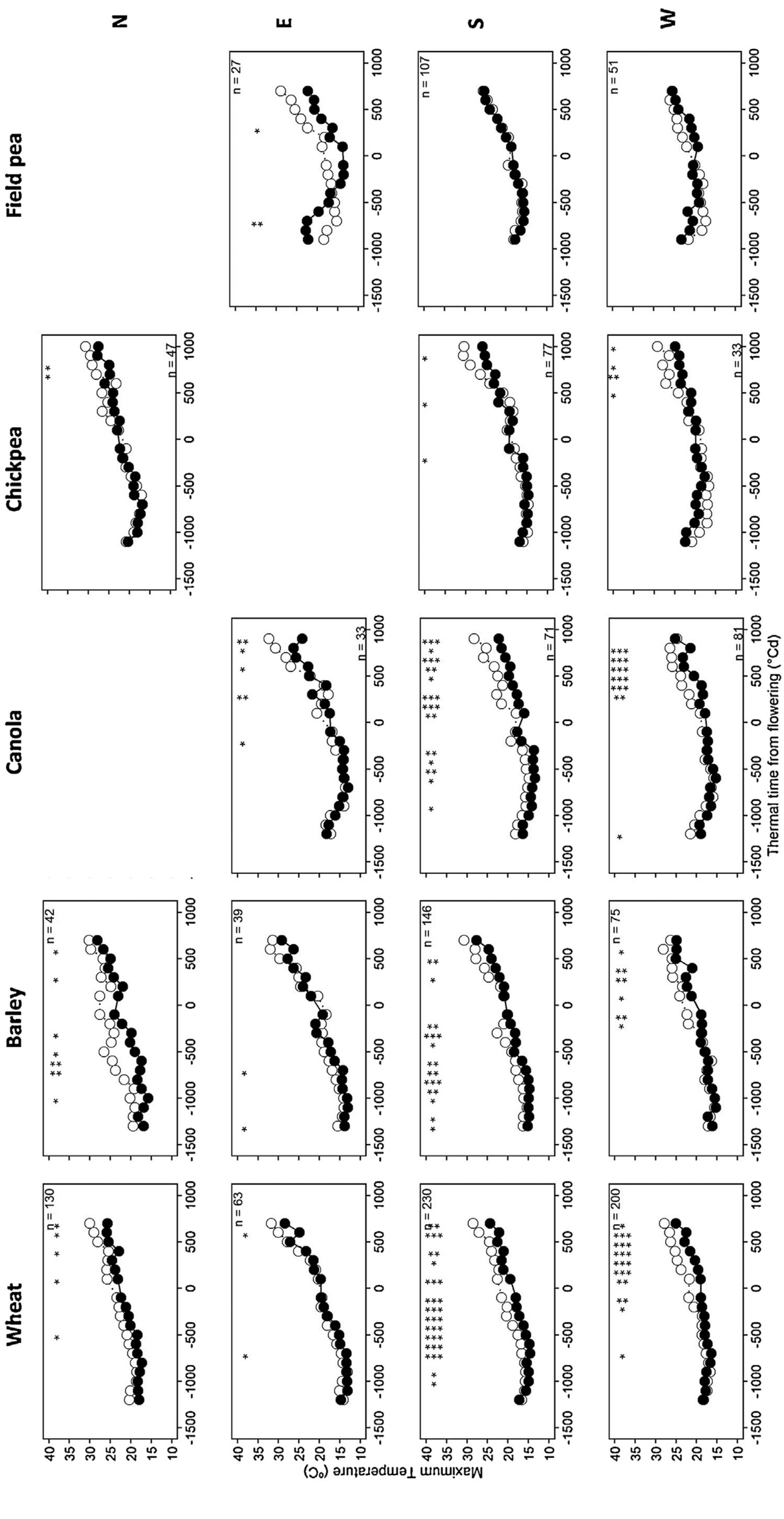

Fig. 6. Maximum temperature associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at P < 0.0001 (***), P < 0.01 (**) and P < 0.05 (*).

chickpea in South and West). Temperatures below 0 °C occurred more frequently before flowering and were inspected for their potential to cause frost damage (Appendix B Fig. B4). Only in the West did temperatures below 0 °C before flowering have a weak but negative impact on yield of wheat and canola, a similar but non-significant trend was observed for chickpea.

A corollary of the influence of Tmax and Tmin was that greater diurnal amplitude throughout the crop cycle was consistently

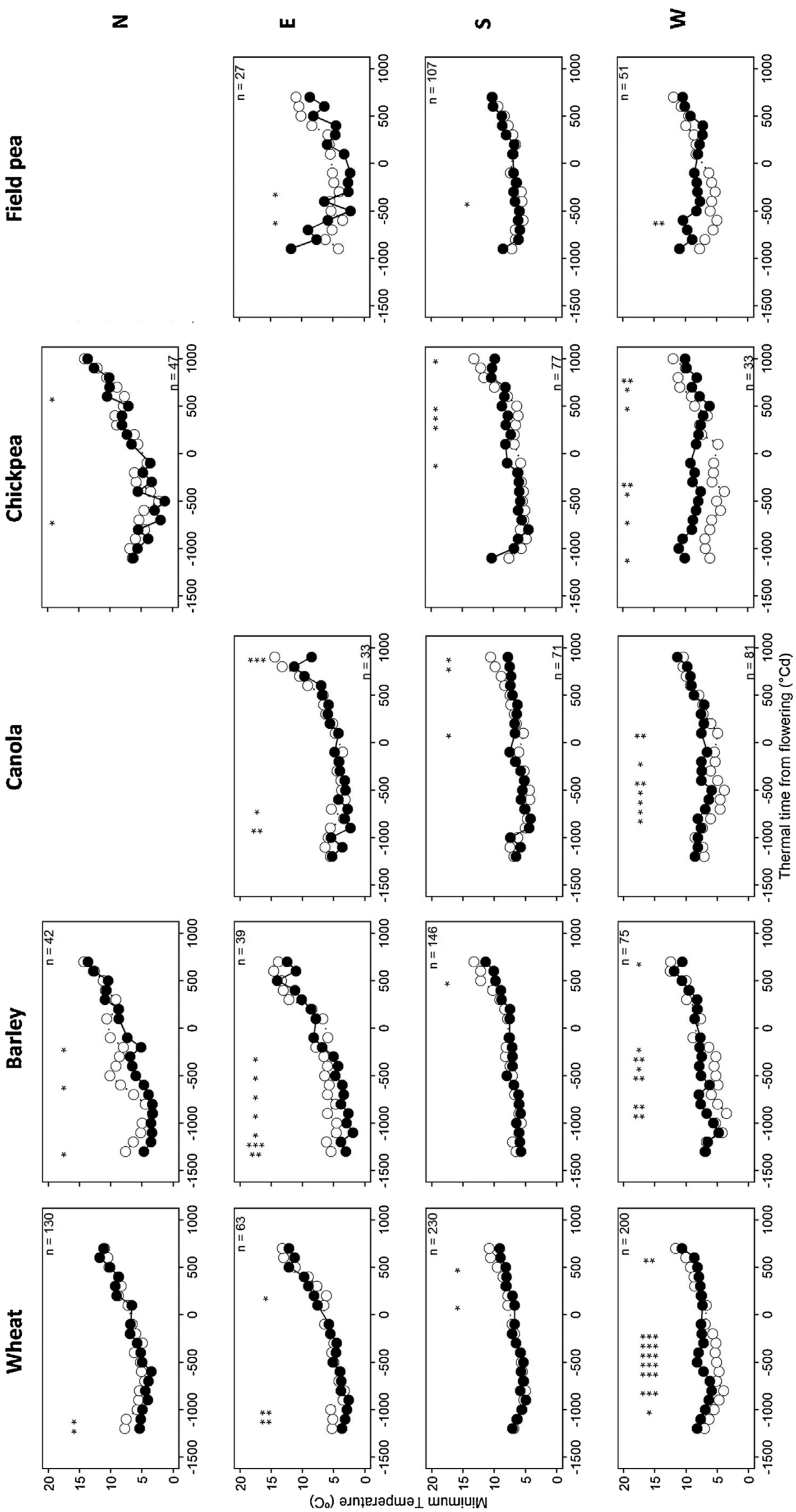

Fig. 7. Minimum temperature associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at $P < 0.0001$ (***), $P < 0.01$ (**) and $P < 0.05$ (*).

associated with lower yields for wheat, barley and canola in the South and West, chickpea in the South and wheat in the North during grain filling (data not shown). The overall impact of extreme temperatures on yield was stronger for heat than for the frost thresholds.

3.5. Radiation and the photothermal quotient

The *expectation* was that higher radiation during the season would be associated with higher yields. This was true for wheat and barley

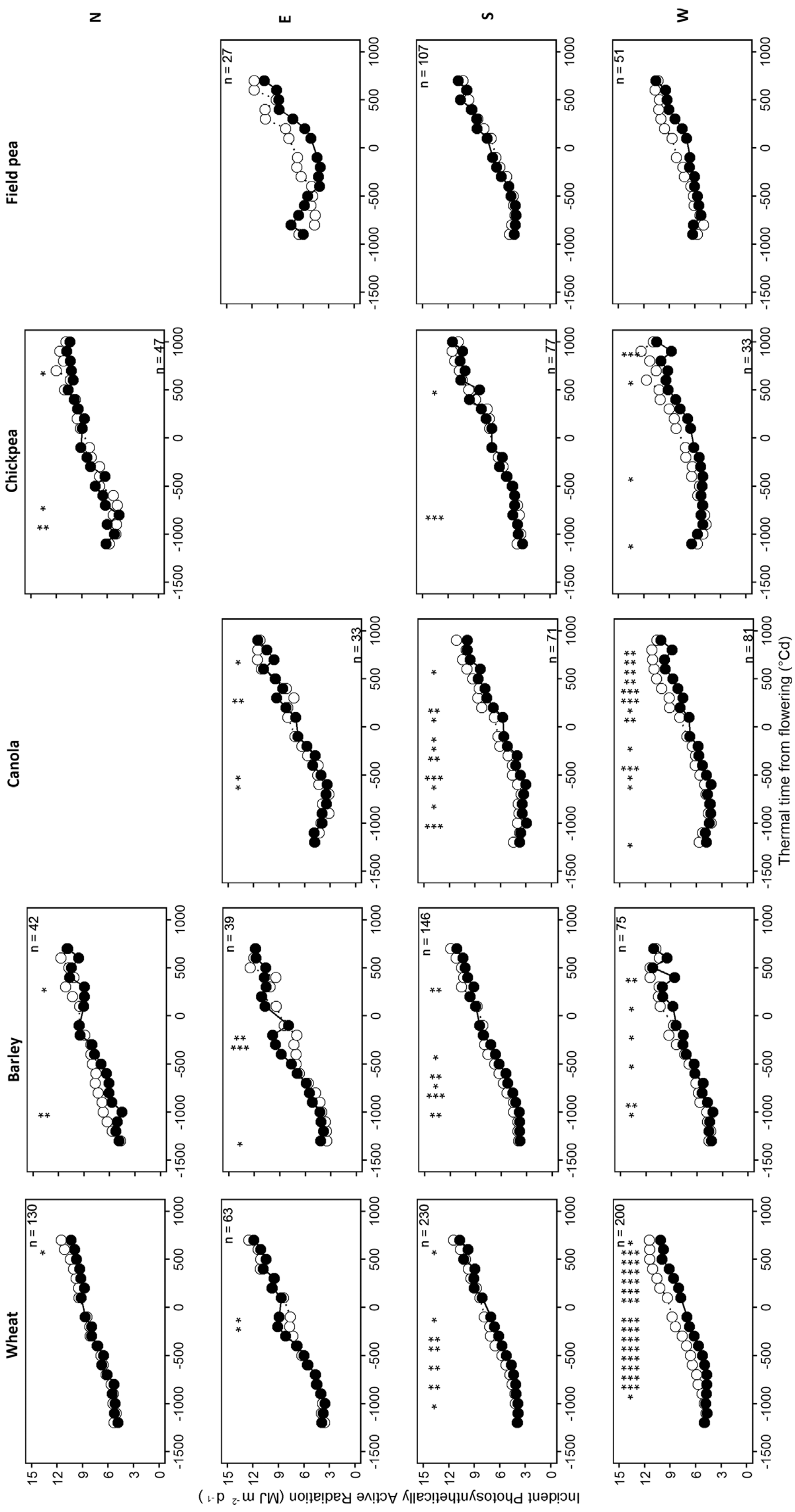

Fig. 8. Incident PAR associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at P < 0.0001 (***), P < 0.01 (**) and P < 0.05 (*).

immediately before flowering in the East and occasionally during early growth in chickpea (Fig. 8). However, this was more the exception than the rule. The *findings* showed that more frequently, higher incident PAR was associated with lower yields, for all crops in the South and West. Similar, non-significant trends were observed for field pea in the East and West.

A high ratio between radiation and temperature or photothermal quotient (PTQ), is an indicator of high yield potential, as high radiation promotes

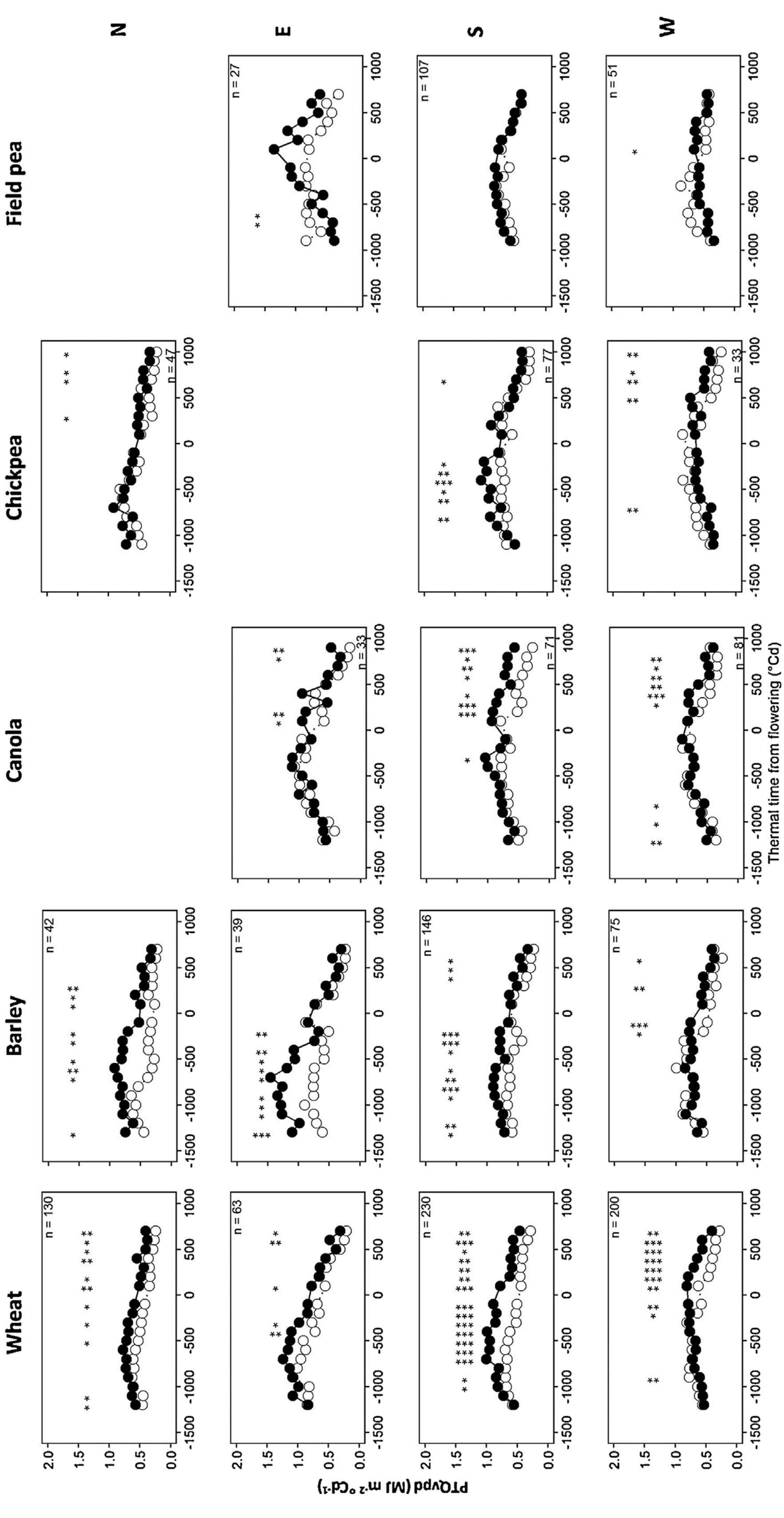

Fig. 9. Photothermal quotient corrected by VPD associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at $P < 0.0001$ (***), $P < 0.01$ (**) and $P < 0.05$ (*).

growth and cooler temperatures prolong the growth phases. There were two types of association between yield and PTQ. In the East, where water stress was not the dominant feature (Fig. 5), higher yields were associated with a higher PTQ around or before flowering in wheat and barley (Appendix A Fig. B5). By contrast, in the West, a higher PTQ before flowering was consistently associated with lower yields in all crops.

The association with yield was more often significant and consistently in the same direction between crops and regions when PTQ was corrected by

VPD, as a measure of environmental demand (Fig. 9). In contrast to PTQ, there is a trend for PTQvpd to decline during the season as temperature and VPD increase. Higher crop yields were related to a higher PTQvpd across regions, except for chickpea in the West before flowering. In the South, the association with a high PTQvpd was clear from emergence, whereas in the West it was mostly noticeable from flowering onwards. Overall, PTQvpd was a more consistent indicator of environmental potential for higher yields, characteristic of trials with similar or lower radiation, lower temperature and VPD and higher water supply/demand ratio.

4. Discussion

The purpose of this study was to explore the relationship between weather and yield in the Australian cropping belt and identify the stages of vulnerability of different crops with emphasis on temperature and water stress. The vulnerable stages emerge from the convergence of crop-specific sensitive developmental windows (Sadras and Dreccer, 2015), and the environment-dependent likelihood of thermal and water stress (Chenu et al., 2013; Sadras et al., 2012). Our comparative approach revealed interesting contrasts and similarities between crops and regions that can be used to think about the adaptive potential of the system and inform decision making.

4.1. Particulars of National Variety Trials data and weather analysis method

NVT are a rich source of information, growing crops and measuring yield using a common protocol, but sources of variation need to be acknowledged. Given the scale of trial coverage, weather and labour-bound windows of opportunity, timely operations are not always possible, e.g. sowing dates may not maximise yield in particular sites or seasons. Location-wise, representative sites are generally chosen in a given region and fertilisation reflects local best practice, yet regional intrinsic soil properties (e.g. duplex soils, subsoil toxicity, etc.) cannot be avoided. Despite these constraints, multi-location data can still be explored for impact analysis as they are as a whole (combination of years and sites) relevant to conditions in the cropping belt. The NVT 2009-2013 yields in this study are consistent with those summarised by Hochman et al. (2016) in an agronomic yield gap study using actual farm yield data and simulated water-limited yields. For instance, the 10th percentile yields of wheat and canola (at 40-50% oil) in the NVT were close or slightly above the actual yield bracket in the yield gap study, while the 90th percentile was slightly above the simulated water limited yields.

Amongst weather impact analysis frameworks, the method proposed by French and Schultz (1984), where yield is a function of water use, has been extensively used to determine yield gaps by factors such as N fertility or subsoil toxicity (Grassini et al., 2009; Sadras and Angus, 2006). Known limitations to this approach are factors that can cause variation in yield at the same level of water supply, such as rainfall distribution with respect to crop stage, size of rainfall events, but also radiation and temperature (Sadras and Rodriguez, 2007; van Ittersum et al., 2013). Because rainfall distribution differs among regions, a flowering centred scale was favoured for comparative analysis of five crops. In addition, the close association between yield of different maturity groups and the environmental site mean (Appendix A Fig. A1) justifies using phenology simulated for a mid-season cultivar to capture large-scale patterns; very early or very late lines may show deviations from the trends presented. Lastly, the relationships found between weather variables and yield were agronomically robust but, because some weather variables are associated (Fig. 2) and have joint impact on crop growth and development, they need to be interpreted with caution. Hence, this analysis framework provides opportunities for guiding targeted experimental research required to unequivocally demonstrate cause and effect relations.

4.2. Performance of climate related indices for yield discrimination in different crops

The combination of stressful and non-stressful temperatures, the water supply/demand ratio, and the PTQvpd were identified as reliable weather indices for yield discrimination in their distinct categories: thermal, water-limited and potential yield. The most sensitive stages for yield definition were confirmed as stem elongation and shortly after flowering in wheat and barley (Fischer, 1985) with flow on and direct effects during grain filling, but extended to shortly after flowering in canola, when flowering and pod growth overlap (Kutcher et al., 2010), similarly to pulses (Sadras and Dreccer, 2015).

Regarding temperature, it was useful to make the distinction between non-stressful temperatures, with a continuous quantitative effect on growth and development vs. untimely stressful temperatures that can disrupt critical processes, e.g. reproduction (Sadras and Dreccer, 2015). Our analysis detected different trends for maximum and minimum temperatures effects and isolated the impact of critically low (below 0 °C) or high (above 30 °C) temperatures. Higher maximum temperature within the optimal range had the potential to discriminate low yielding trials from very early in the season in wheat, barley and canola in the South and after flowering in the West, with some impact in the North and with more significant impact than days above 30 °C. Warmer temperatures shorten crop cycles in calendar days, reducing resource capture for grain number formation and grain filling (García et al., 2015; Sparks et al., 2005). Despite being widespread, the impact of high but non-stressful termperatures is often overlooked as the effect is not as visually compelling as that of frost or heat shock at heading rendering sterile a spike cohort. A proposed solution to maintain cycle lenght in wheat is the exploitation of vernalisation genes in combination with early sowing (Zhang et al., 2016). There has not been yet a concerted effort to select for temperature responsiveness per se.

Temperatures above 30 °C increased their frequency and discriminating power later in the season, when they can negatively affect yield via grain weight in cereals (Dreccer et al., 1997; Savin et al., 1996), flower fertilisation (Kutcher et al., 2010; Lilley et al., 2015) and oil synthesis or oil/protein ratio (Aksouh-Harradj et al., 2006) in canola and flower fertilisation and pod development in chickpea (Devasirvatham et al., 2013; Devasirvatham et al., 2012). Amongst crops, maximum temperature above 30 °C during grain filling had a more significant impact in wheat, followed by canola, chickpea and barley. In chickpea, low yields were also associated with low minimum temperatures after flowering which negatively affect ovule viability, pollen growth and seed set (Srinivasan et al., 1999; Thakur et al., 2010). Clarke and Siddique (2004) proposed an average temperature of 15 °C or above to maintain reproductive functionality. Low yielding chickpea crops were below that temperature threshold before flowering and minimum temperature was slightly above 5 °C on average.

From the water stress related indices, cumulative rainfall per 100 °Cd was the least and water supply/demand ratio was the most reliable at discriminating high and low yielding conditions. The water supply/demand ratio was able to reconcile differences among crops and regions via the integration of simulated demand by the crop, differences in rainfall amount and seasonality, soil water storage capacity and plant available water at sowing (Chauhan et al., 2013; Chenu et al., 2011; Sadras et al., 2012). The latter is an important source of variation among regions with contrasting rainfall seasonality and soils, e.g. a large component of the water balance in the summer-rainfall North region but minor in the winter-rainfall South and West regions (Lawes et al., 2009; Sadras and Rodriguez, 2007; Whish et al., 2007). From the measures of evaporative demand, mean VPD separated high and low yield better than potential evapotranspiration based on radiation (Priestley and Taylor, 1972), however in regions where hot winds are common, the Penman-Monteith approach could also be tested (Goudriaan and Van Laar, 1994). A large influence of VPD on yield has also been shown in maize (Lobell et al., 2014). Interestingly, maximum temperature and VPD, discriminated between yield levels early in the season (between 200 to 800 °Cd before flowering), before a significant influence of the water supply/demand ratio could be detected. This early discrimination capability may be associated with direct effects of temperature and VPD on radiation use efficiency (Stockle and Kemanian, 2009) and maximum transpiration rate (Schoppach and Sadok, 2013). A comparison amongst high yielding crops (90th yield percentile) showed that wheat rarely experienced water stress during the cycle or across regions, chickpea only in late grain filling, whilst water stress from around flowering affected canola and earlier water stress reduced barley yield. In barley, water stress did not help separate high and low yielding crops during grain filling but, in terms of magnitude, canola was the crop reaching the lowest water supply/demand ratio. Water stress did not define yield levels in field pea, the range of yield was narrow with particularly low yield under favourable conditions (Sadras et al., 2012),

The interactions between water supply/demand ratio and temperature are channelled not only via the effect of temperature on VPD and the link to stomatal response but also via its effect on the rate and duration of growth and therefore seasonal pattern of water use (e.g. Peltonen-Sainio and Jauhiainen, 2011). Similar to wheat and other crops in the West, high yielding chickpea crops were associated with higher minimum temperature early in the season, possibly via increased ground cover and reduced direct evaporation from soils with limited water holding capacity, resulting in a more favourable water balance compared to low yielding crops. Chickpea has a higher temperature requirement (Abbo et al., 2003) than other crops in this study and higher minimum temperature would favour early growth. In contrast, low biomass resulting in lower demand before flowering would be an advantage if soil water can be stored for a period of greater environmental demand, e.g. late spring, and higher vulnerability, such as the flowering-pod setting interval in chickpea (Berger et al., 2004), a more likely scenario for any crop grown in the North than South or West. Breeding for early vigorous wheat has been proposed as an alternative for Mediterranean-type rainfall environments, following the barley ideotype (Rebetzke et al., 2017).

Finally, while some associations between weather variables and yield are straightforward agronomically, composite variables like PTQ need further interpretation. In wheat growing without water limitation, PTQ normalised by VPD was more useful than PTQ reconciling crops and regions and was associated with lower maximum temperatures and incident radiation. Lower incident radiation due to higher latitude or cloud cover is conducive to a higher fraction of diffuse radiation (Goudriaan and Van Laar, 1994) which is positively related to radiation use efficiency (Rodriguez and Sadras, 2007; Sinclair and Shiraiwa, 1993). This supports Rodriguez and Sadras (2007) who identified a negative relationship between the residuals of the relation between radiation use efficiency vs. fraction of diffuse radiation and VPD in a latitudinal transect across Australia hinting at the importance of this correction when spatial or temporal VPD variation is large.

4.3. Conclusions

The Grains Research and Development Corporation of Australia recently estimated annual economic losses attributable to heat stress at about AU$ 1.1 B (GRDC, 2015). This estimate is conservative because it does not account for yield reduction caused by non-stressful temperature shortening key phenophases, as highlighted in our study, nor does it account for potential impact on grain quality. Lesk et al. (2016) reported that the relative impact of climate extremes, i.e. severe drought and heat events, was more important in developed than developing countries, and hypothesised that larger monoculture areas and high risk strategies could partially drive substantial yield deficit. In this context, knowledge about the vulnerabilities and opportunities for crop diversification is crucial. The crops in this study already have clear differences in reproductive biology (e.g. wheat, barley, chickpea and field pea are self pollinated; canola is cross pollinated).

Using NVT data, our methodology proved useful in identifying differences between crops in their vulnerability periods and sensitivity to different environmental factors. The series explored covered the range of yields encountered in agronomic yield gap studies and established that all crops were sensitive to the impact of warming from early in the season. While wheat and chickpea were sensitive to temperatures above 30 °C from early and late in grain filling respectively, chickpea was sensitive to low temperatures from flowering and canola was overall the most sensitive to water stress. Furthermore, the interaction between early growth and drought has regional relevance. The results from this study provide new opportunities to design hypothesis-driven experiments, target genotypic variation for abiotic stress tolerance, crop positioning in the landscape and agronomy options to enrich the gamut of adaptation strategies to lessen the impact of climate change on crop productivity.

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Appendix A

Table A1
Cultivars simulated per region using phenology parameterisation from APSIM 7.7 for sensitivity to photoperiod (Rp), to vernalisation (Rv) and thermal time from floral initiation to flowering (TT_{FI-FL}).

Crop	Region	Intermediate Cultivar/Variety	Rp	Rv	TT_{FI-FL}
Wheat	North	Baxter	3.5	1.5	555
	East	Janz	2.9	2.2	458
	South	Janz	2.9	2.2	458
	West	Mace	3.5	3.0	475
Barley	All regions	Buloke	3.5	1.0	230
Canola	All regions	Hyola 50	–	–	250
Chickpea	All regions	Amethyst	–	–	450
Field pea	All regions	Excell	–	–	33

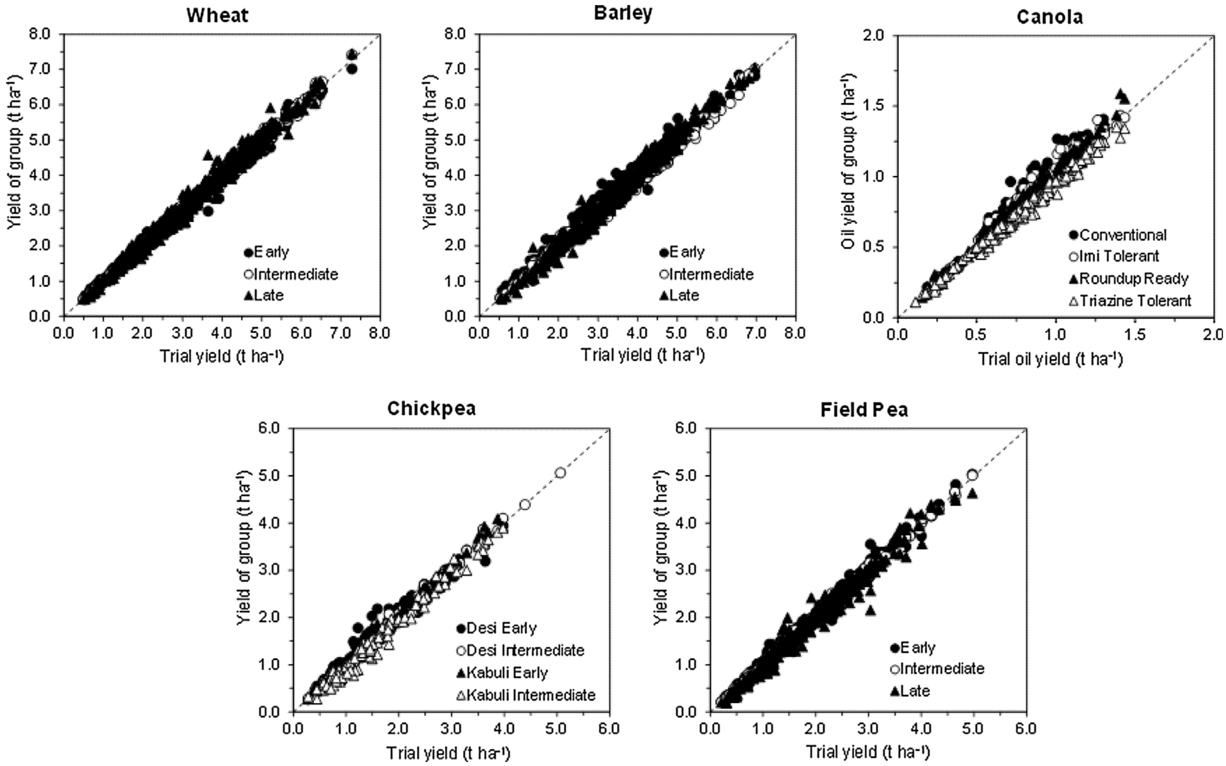

Fig. A1. Yield of different crop types within a crop as a function of trial average for wheat (n = 623), barley (n = 354), canola (n = 216), chickpea (n = 187), field pea (n = 278). Grouping is per maturity group in wheat, barley and chickpea, per maturity group within grain type in chickpea and including herbicide resistance in canola. In canola and chickpea not all crop groupings were present in all environments.

Appendix B

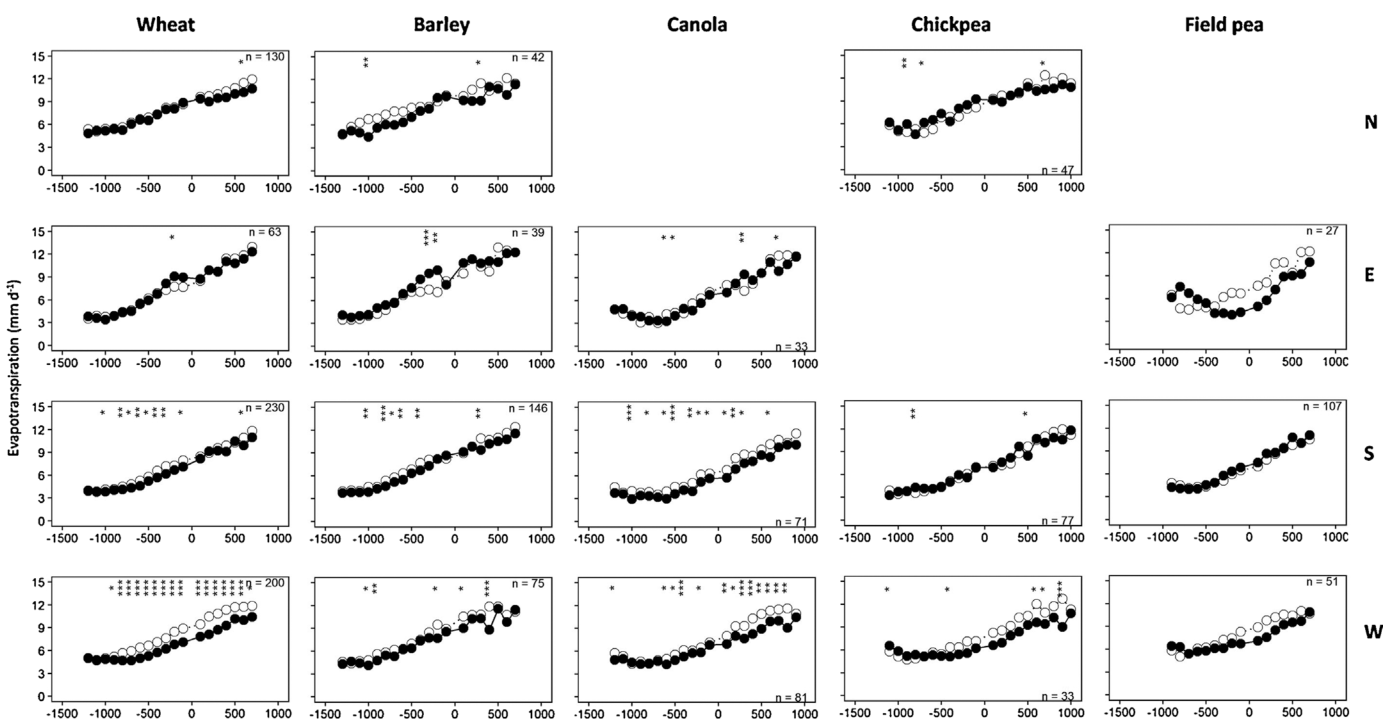

Fig. B1. Evapotranspiration associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at $P < 0.0001$ (***), $P < 0.01$ (**) and $P < 0.05$ (*).

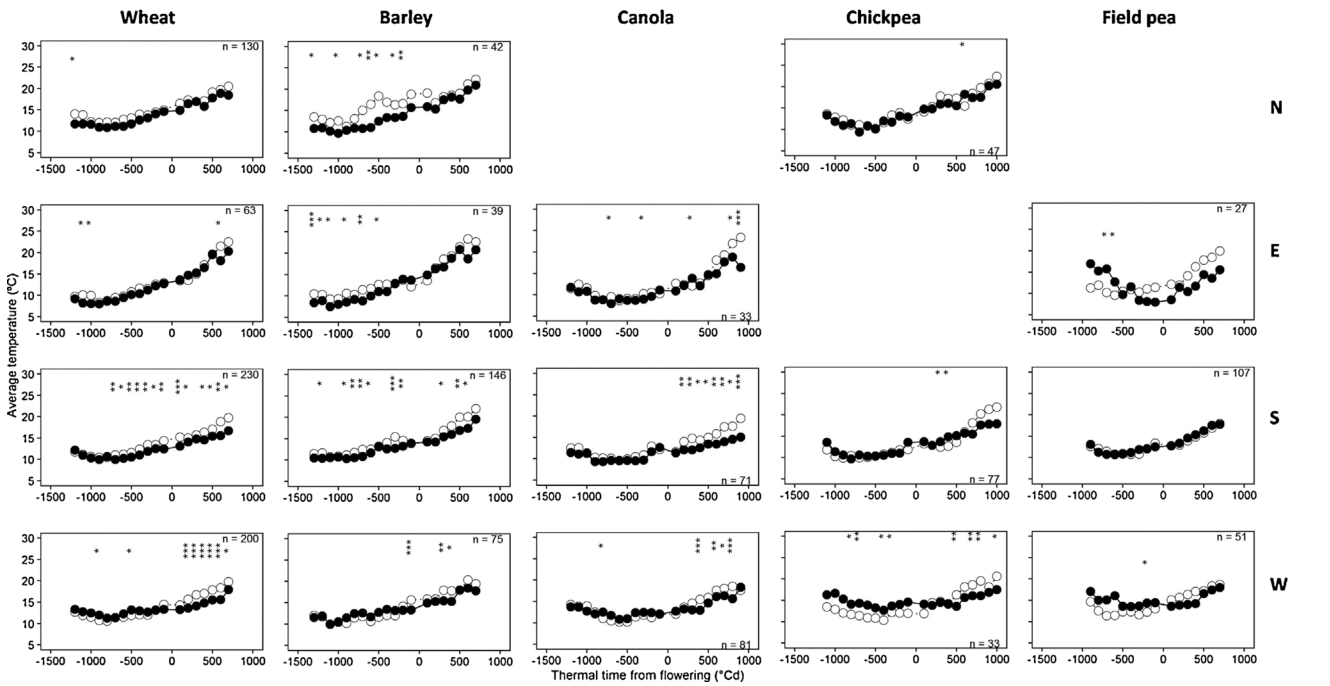

Fig. B2. Average temperature associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at $P < 0.0001$ (***), $P < 0.01$ (**) and $P < 0.05$ (*).

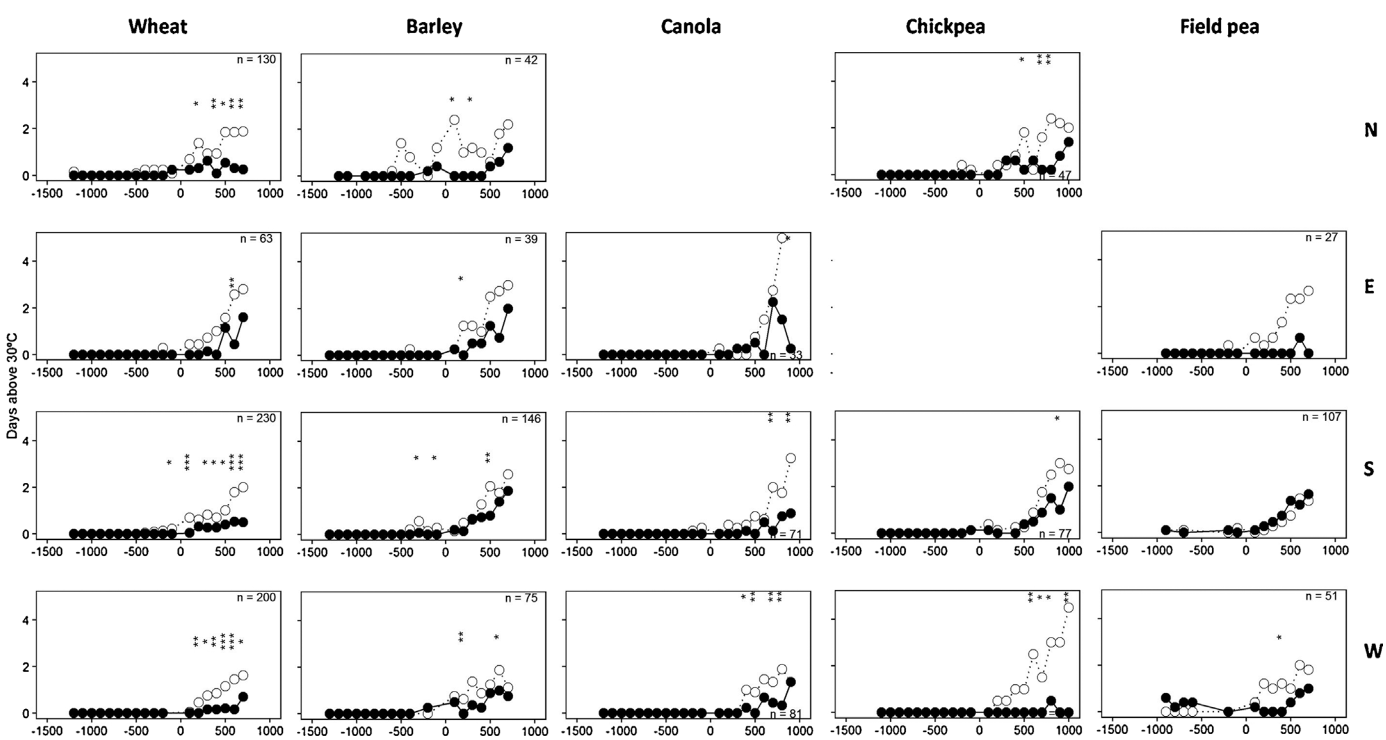

Fig. B3. Number of days with maximum temperature above or equal to 30 °C associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at $P < 0.0001$ (***), $P < 0.01$ (**) and $P < 0.05$ (*).

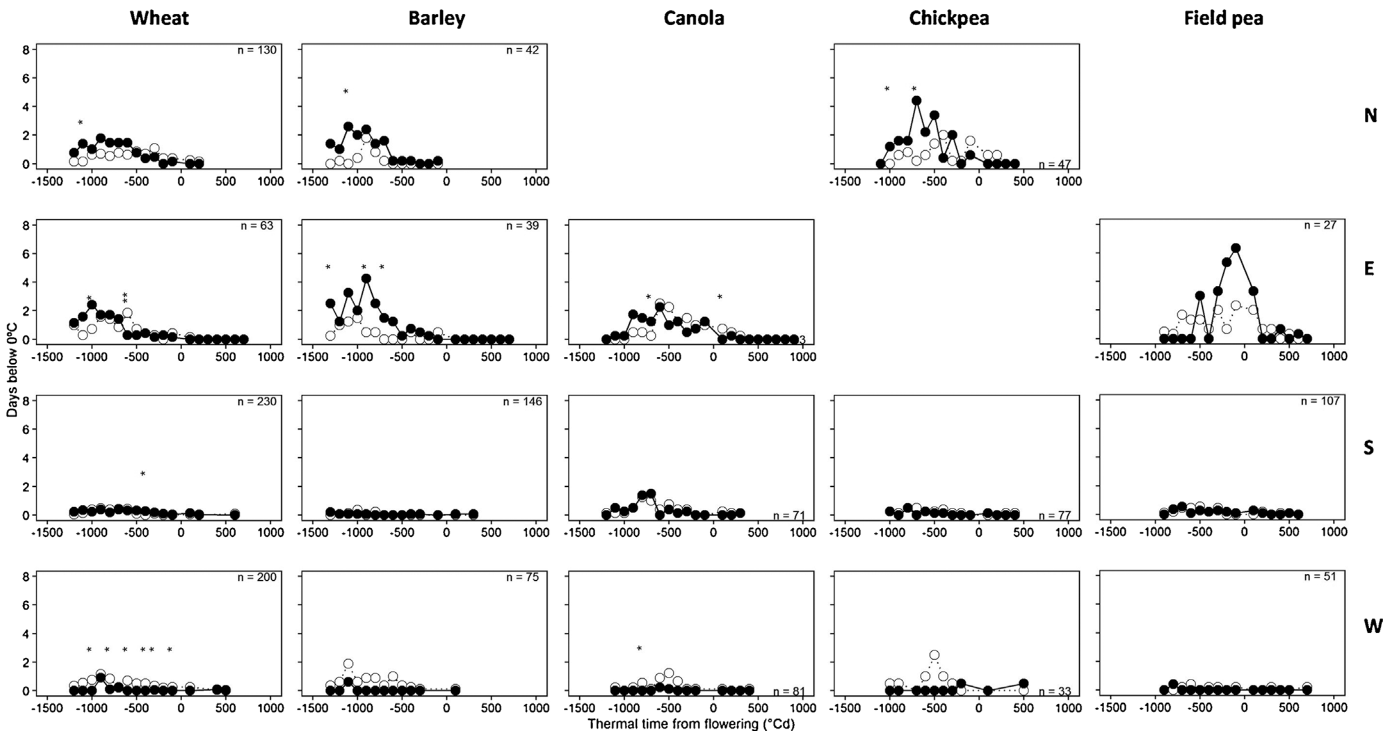

Fig. B4. Number of days with minimum temperature below or equal to 0 °C associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at $P < 0.0001$ (***), $P < 0.01$ (**) and $P < 0.05$ (*).

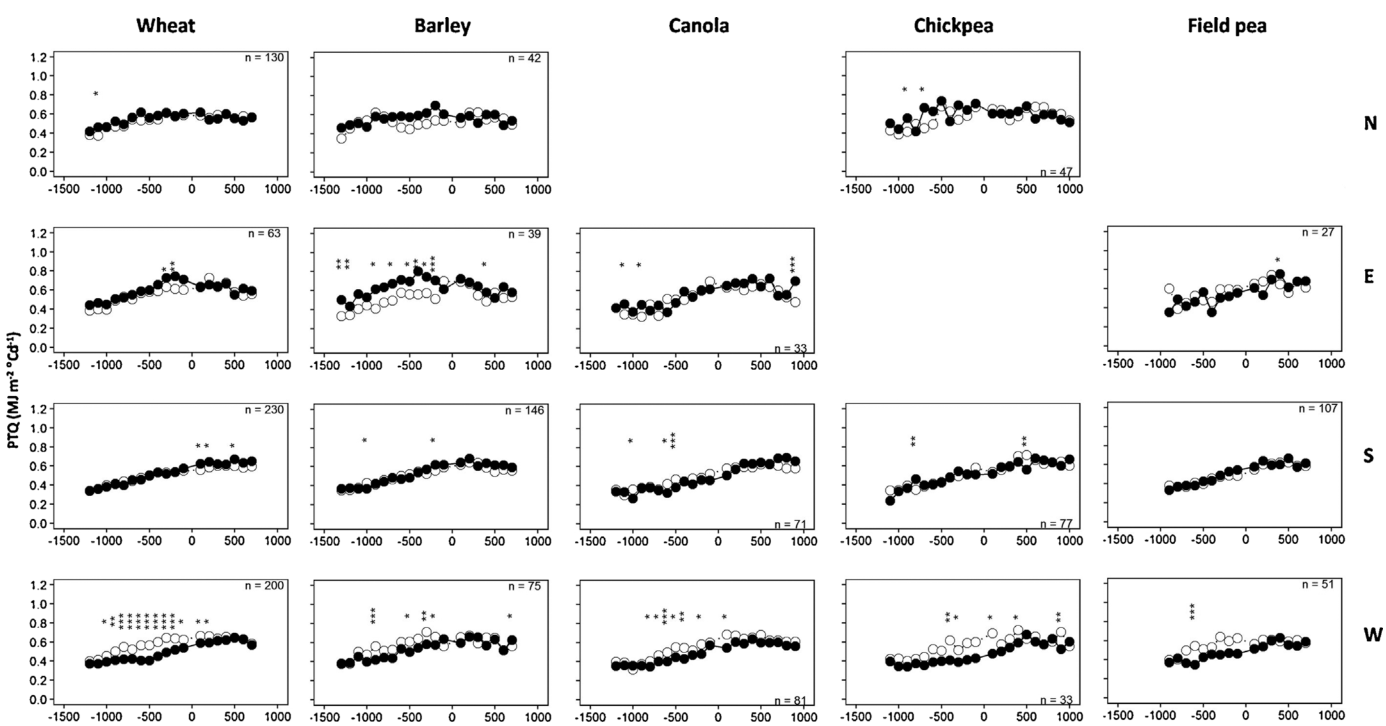

Fig. B5. Photothermal quotient associated with high (90th percentile, black symbols) and low (10th percentile, white symbols) yielding wheat, barley, canola, chickpea and field pea crops in different regions of Australia as a function of thermal time centered at flowering (x = 0 °Cd). Asterisks indicate significant differences at $P < 0.0001$ (***), $P < 0.01$ (**) and $P < 0.05$ (*).

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