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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.