European Journal of Agronomy 90 (2017) 152–161

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Modelling wheat yield change under CO_2 increase, heat and water stress in relation to plant available water capacity in eastern Australia

Bin Wang[a,b,*], De Li Liu[b], Senthold Asseng[c], Ian Macadam[d,e], Qiang Yu[a]

[a] School of Life Sciences, Faculty of Science, University of Technology Sydney, PO Box 123, Broadway, NSW 2007, Australia
[b] NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, NSW 2650, Australia
[c] Agricultural & Biological Engineering Department, University of Florida, 221 Frazier Rogers Hall, P.O. Box 110570, Gainesville, FL 32611-0570, USA
[d] Climate Change Research Centre and ARC Centre of Excellence for Climate System Science, University of New South Wales, Sydney, NSW 2052, Australia
[e] Now at Met Office, FitzRoy Road, Exeter, EX1 3PB, UK

ARTICLE INFO

Keywords:
GCMs
Heat stress
Water stress
Wheat yield
PAWC

ABSTRACT

Increasing heat and water stress are important threats to wheat growth in rain-fed conditions. Using climate scenario-based projections from the Coupled Model Intercomparison Project phase 5 (CMIP5), we analysed changes in the probability of heat stress around wheat flowering and relative yield loss due to water stress at six locations in eastern Australia. As a consequence of warmer average temperatures, wheat flowering occurred earlier, but the probability of heat stress around flowering still increased by about 3.8%–6.2%. Simulated potential yield across six sites increased on average by about 2.5% regardless of the emission scenario. However, simulated water-limited yield tended to decline at wet and cool locations under future climate while increased at warm and dry locations. Soils with higher plant available water capacity (PAWC) showed a lower response of water-limited yield to rainfall changes except at very dry sites, which means soils with high PAWC were less affected by rainfall changes compared with soils with low PAWC. Our results also indicated that a drought stress index decreased with increasing PAWC and then stagnated at high PAWC. Under high emission scenario RCP8.5, drought stress was expected to decline or stay about the same due to elevated CO_2 compensation effect. Therefore, to maintain or increase yield potential in response to the projected climate change, increasing cultivar tolerance to heat stress and improving crop management to reduce impacts of water stress on lower plant available water holding soils should be a priority for the genetic improvement of wheat in eastern Australia.

1. Introduction

Global Climate Models (GCMs) from the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model dataset point to a significant increase in mean temperature and marked shifts in the distribution of rainfall patterns (IPCC, 2013). In a warmer future climate, most GCMs also predict a substantial increase in the frequency and severity of extreme weather events (Alexander and Arblaster, 2009; Kharin et al., 2013). Changes in climate and extreme weather events are likely to affect agricultural crops (Barlow et al., 2015; Gornall et al., 2010; Moriondo et al., 2011; Porter and Semenov, 2005).

The occurrence of extreme high temperature during sensitive stages of crop development, such as the period around anthesis, could reduce grain yield due to its direct effect on grain number and grain weight (Stone and Nicolas, 1994; Talukder et al., 2014; Wollenweber et al., 2003). The individual grain mass and the grain set can be substantially reduced if a cultivar, sensitive to heat stress, is exposed to even a short period of high temperature around flowering (Talukder et al., 2010). For example, in a field experiment on the combine effects of CO_2 and temperature on the grain yield Nuttall et al. (2013) showed that a temperature of 36–38 °C around flowering (6 days after anthesis) could result in a high number of sterile grains (grain number reduced by 12%) and therefore 13% grain yield loss. A modelling study for the main wheat growing regions in Australia showed that variations in average growing-season temperature of 2 °C caused reductions in grain production of up to 50% (Asseng et al., 2011). Therefore, mitigating the impacts of heat stress on crop yield is one of crucial tasks for securing food under a future and variable climate.

Numerous simulation studies, linking projected climate data from climate models to crop models, have assessed the effects of heat and drought stress in combination or isolation on crop yield under future climate change in rainfed cropping systems (Deryng et al., 2014; Gourdji et al., 2013; Lobell et al., 2015; Semenov and Shewry, 2011). Using climate projections from the CMIP3 multi-model ensemble with

* Corresponding author at: NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, NSW 2650, Australia.
E-mail address: bin.a.wang@dpi.nsw.gov.au (B. Wang).

http://dx.doi.org/10.1016/j.eja.2017.08.005
Received 22 May 2017; Received in revised form 5 August 2017; Accepted 11 August 2017

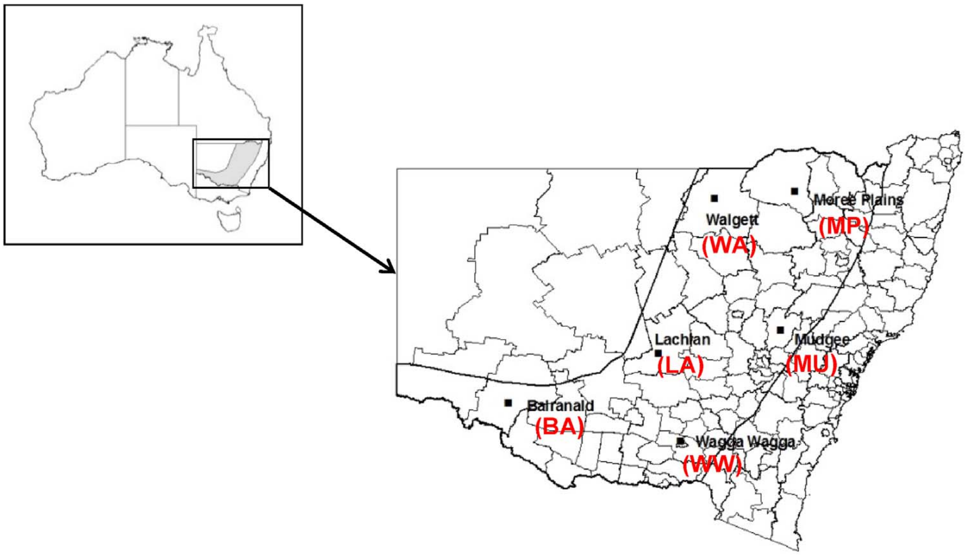

Fig. 1. The six selected sites (Walgett, Moree Plains, Lachlan, Mudgee, Balranald and Wagga Wagga) used in this study.

LARS-WG weather generator, Semenov and Shewry (2011) demonstrated that droughts would not increase vulnerability of wheat in Europe. It is noteworthy that relative yield losses from water stress were likely to decrease due to earlier maturity avoiding terminal drought stress. As drought could be associated with high temperature, crop experience heat and drought stress often simultaneously (Chung et al., 2014; Rezaei et al., 2015). However, Lobell et al. (2015) found that the significant direct damage to wheat crops from heat stress was increasing and estimated that aggregate yield impacts of heat stress might equal drought impacts for wheat by the mid-21st century in northeast Australia. The combination of increasing CO_2 and associated climate changes was likely to gradually reduce the drought impact in northeast Australia. However, previous analyses modelling the effect of water stress on wheat have been limited to using single soil types at specific sites. Furthermore, there are many uncertainties in these projections due to uncertainty in future greenhouse gas emissions. Finally, linking crop simulation models to projected climate data for the future from climate models at specific locations is not straightforward. Indeed, the spatio-temporal scale mismatches between GCMs and crop simulation models must be bridged through downscaling methods.

It is well-know that under the same climatic conditions, soil characteristics are the key to sustaining agricultural production. Soil can provide a buffer to store water and supply to the crop and therefore minimize the effects of severe drought. However, the soil's ability to support crop growth is largely dependent upon its water-holding and supply capacity. Soils with larger plant available water holding capacity (PAWC) are generally higher yielding as high PAWC can lead to more water use and reduce water leakage below the crop root zone, resulting in increased rainfall use efficiency and decreased offsite impacts (Morgan et al., 2003; Wang et al., 2009a; Wong and Asseng, 2006, 2007). Wong and Asseng (2006) showed a linear increased of measured wheat yield with soil PAWC of the top 100 cm of the soil profile in West Australia, which was consistent with crop model simulated results from Wang et al. (2009a). However, soil PAWC does not change the crop water use efficiency, but change the availability of water to crops (Wang et al., 2009a). Although efforts have been made to evaluate the impact of PAWC on crop yields, little evidence is available to prove how water stress responds to soil PAWC as a result of climate change.

The New South Wales (NSW) wheat belt contains 29.3% of the Australian wheat planted area and accounts for 28.7% of Australia's wheat production (averaged by 2003–2014) (http://www.abs.gov.au). It is among the most vulnerable regions in Australia due to its great reliance on climate. Extreme events in the NSW wheat belt have been predicted to increase in frequency, length and intensity by the end of the century (Alexander and Arblaster, 2009; Lewis and Karoly, 2013; Wang et al., 2016). However, it is not yet clear what the extent of yield losses resulting from water stress or heat stress will be under future climate change in this particular region. In addition, the lack of daily temperature and rainfall data for future climate has been a major obstacle to demonstrate the site-specific impact assessment of climate change on crop production. This study accounted for uncertainties in future climate conditions by considering two scenarios for future atmospheric greenhouse gas concentrations. We used a statistical downscaling method to downscale GCM projections from the CMIP5 ensemble to a local scale. The use of statistical downscaling in climate change studies allows exploration of the effect of changes in mean climate as well as changes in climatic variability and extreme events (Ahmed et al., 2013; Wang et al., 2016). A wheat simulation model was used to simulate impacts of climate change on wheat yield based on different soil types across a range of wheat cropping regions in eastern Australia.

The objectives of this study are to (1) quantify change in the probability of heat stress around flowering; (2) quantify the relative yield loss due to water stress across different soils. We focus on the analyses of two 30-year simulations: the first examines the time period 1961–1990 (referred to as 'present'), which was selected because a number of climate change indices were calculated using 1961–1990 as the base period (http://etccdi.pacificclimate.org/list_27_indices.shtml); the second the period 2061–2090 (referred to as 'future'), based on the latest greenhouse gas emissions and GCM projections. We here present a study in heat stress and water stress impacts on wheat involving 12 soil types for a great degree of soil variability and six represented sites across the NSW wheat growing area.

2. Materials and methods

2.1. Study sites, climate and soil data

The NSW wheat belt is located between the arid interior of Australia and the Great Dividing Range to the east. The topography is characterized by plains in the west and slopes in the east. The climate is Mediterranean (with winter-dominant rainfall) characterized by large inter-annual variations in rainfall. Six sites, representing different agro-climatic zones within the wheat belt, were selected for this study (Fig. 1). The principal characteristics of these sites are summarized in Table 1. The two northern sites (WA, MP) are relatively warm and the three western sites (WA, LA and BA) are relatively dry. Sites to the south and east are cooler and wetter, respectively.

Table 1
Average wheat growing season (April–November) mean temperature and total rainfall (1961–1990) at the six study sites.

Site	Acronym	Latitude	Longitude	Maximum T (°C)	Minimum T (°C)	Mean T (°C)	Rainfall (mm)
Walgett	WA	−29.66	148.12	23.9	9.6	16.7	268.2
Moree Plains	MP	−29.50	149.90	23.0	9.0	16.0	331.8
Lachlan	LA	−33.10	146.85	20.6	7.8	14.2	287.3
Mudgee	MU	−32.60	149.60	19.4	5.6	12.5	450.5
Balranald	BA	−34.20	143.50	20.7	7.6	14.1	212.9
Wagga Wagga	WW	−35.05	147.35	18.1	6.6	12.4	396.8

Daily climate data (maximum and minimum temperature, rainfall and solar radiation) for 1961–1990 for the six study sites were extracted from the SILO patched point observational dataset (PPD, http://www.longpaddock.qld.gov.au/silo/ppd/index.php) (Jeffrey et al., 2001). Daily climate data for 2061–2090 were also derived for each site from simulations of 28 different CMIP5 GCMs (Wang et al., 2015b) of two different Representative Concentration Pathways (RCPs) (Van Vuuren et al., 2011) (RCP4.5 and RCP8.5) using a statistical downscaling method. Briefly, monthly GCM output data (solar radiation, rainfall, daily maximum and minimum temperature) from 28 GCMs were firstly downscaled to the observed sites using an inverse distance-weighted interpolation method. Biases were then corrected using a transfer function derived from interpolated GCM data and observed data for the sites. Daily climate data for each site for 1900–2100 were generated by a modified stochastic weather generator (WGEN) (Richardson & Wright, 1984) with parameters derived from the bias-corrected monthly data. The detailed description of this method can be found in Liu and Zuo (2012). This method has been widely applied in recent climate change impact studies in Australia (Guo et al., 2016; Liu et al., 2016; Wang et al., 2015b).

Soils vary widely in their soil water retention characteristics, ranging from shallow sandy soil, with minimal capacity to retain water, to deep clay soils, with great capacity to retain water (Table 2). Each study site has at least one soil type that is representative of the area. These 12 soils were selected from the APSOIL database according to PAWC ranging from 72 to 293 mm, step by approximately 20 mm (Liu et al., 2014). These soils provide a potential maximum rooting depth of the wheat crop, which ranges from 120 to 180 cm. Although some of the soils may not be found at all the six study sites, it was assumed that the spatial variation of the soils at any one site can give a range of PAWC and therefore that the range represented by the soils in Table 2 is reasonable (Wang et al., 2009a). Soil hydraulic parameters are shown in Fig. 2.

2.2. Wheat simulations

APSIM (Agricultural Production System sIMulator) version 7.7 (www.apsim.info) (Holzworth et al., 2014) was used to evaluate the effect of future climate change on wheat yields at the six sites. The APSIM model has been well-tested for many modern wheat cultivars and is able to sufficiently simulate the behaviour of crops exposed to a wide range of conditions including those in the Australian wheat belt (Asseng et al., 1998; Keating et al., 2003; Ludwig and Asseng, 2006). It has been widely used in studies of the effects of climate change on wheat productivity and water use in Australia (Chenu et al., 2013; Lobell et al., 2015; Yang et al., 2016). The model is an appropriate tool for determining potential yield (Y_p) which is defined as the yield of an adapted crop cultivar grown under favourable conditions without growth limitations from water, nutrients, pests, disease or other non-climatic factors (Evans, 1996). Y_p is a benchmark for systems in semi-arid climates with insufficient water supplies to avoid water stress. In this case, automatic irrigation (full irrigation) in APSIM was set to eliminate water stress. The definition of water-limited crop yield (Y_w) is similar to Y_p, but crop growth is limited by water supply. Water-limited yield is equivalent to water-limited potential yield for rain-fed crops.

The Liu and Zuo (2012) downscaling procedure used in this study is somewhat effective at correcting the biases in the monthly GCM. However, the bias correction approach used in the downscaling procedure is largely limited to correcting stationary biases in the GCM output and cannot fully account for biases that are non-stationary during the training period. Therefore, the downscaled daily data for a period that might be different from the training period and may have residual biases in some cases. In order to minimise the impact of these on crop model outputs, Yang et al. (2016) applied a simple additional bias correction called secondary bias correction to the outputs of model simulations forced with the downscaled data. In this study, crop simulation outputs Y_w and Y_p were also corrected by a secondary bias-correction procedure according to Yang et al. (2016) in order to minimise the impact of biophysical biases in the downscaling procedure on outputs of crop model simulations.

Elevated levels of atmospheric CO_2 in the plant module of APSIM affects crop growth by influencing RUE, transpiration efficiency and critical leaf nitrogen concentration. However, APSIM has no facility to ingest time-varying values of CO_2 concentration. Therefore, a function was added to APSIM whereby yearly atmospheric CO_2 concentrations were calculated using empirical functions of calendar year during 1900–2100 (Liu et al., 2014). For RCP4.5 scenario, the atmospheric CO_2 concentration was calculated by:

Table 2
The 12 soils used in this study including soil type, soil depth, plant available water capacity (PAWC).

No.	Mainly distributed region	Soil type	Soil depth (cm)	PAWC (mm)
S1	Riverina	Loam (Caldwell-Womboota 2 No616-YP)	150	72
S2	Upper Western	Sandy Clay over Clay (Wirracanna site 8 No561-YP)	120	86
S3	Upper Western	Clay (Wirracanna site 6 No563-YP)	120	111
S4	North West Slopes and Plains	Grey Vertosol (Walgett No1016)	180	131
S5	North West Slopes and Plains	Grey Vertosol (Pilliga No1014)	180	155
S6	Riverina	Sandy Loam over Clay (Rand No211)	150	170
S7	Central West Slopes and Plains	Grey Vertosol (Forbes No546-YP)	150	188
S8	Central West Slopes and Plains	Clay over Sandy Clay (Eugowra No196)	180	209
S9	North West Slopes and Plains	Grey Vertosol-Light Brigalow (Tulloona No102)	150	239
S10	Riverina	Grey Vertosol (Urana No541-YP)	150	251
S11	North West Slopes and Plains	Grey Vertosol-Heavy Brigalow (Tulloona No101)	150	266
S12	Riverina	Wunnamurra Clay (Jerilderie No542)	180	293

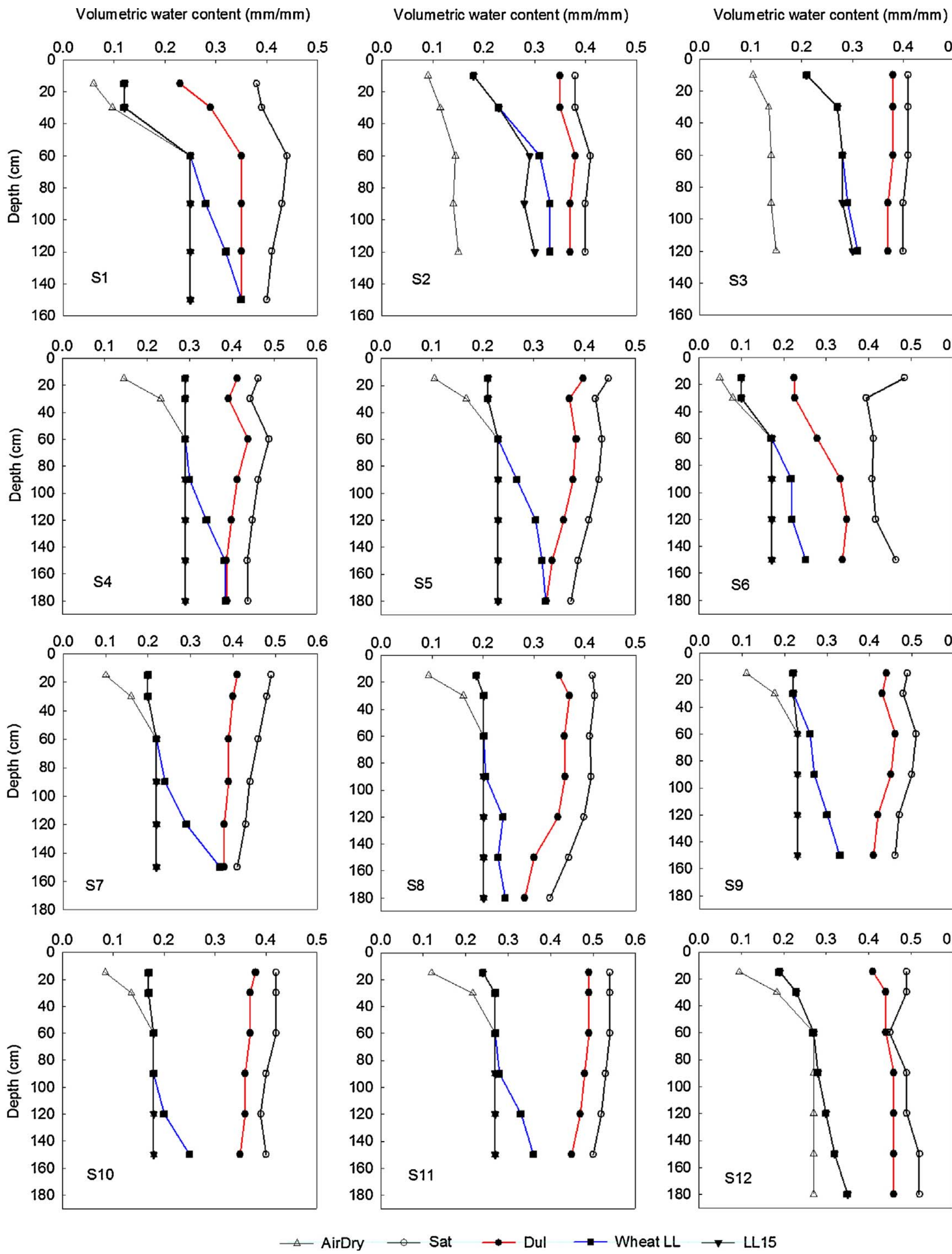

Fig. 2. APSIM soil parameters used to define plant available water capacity (PAWC) and values of soil water reset for 12 soil types (S1–S12) used in this study. Sat is the saturated water content. DUL represents the drained upper limit of soil water. Wheat LL stands for crop lower limit. LL15 is the 15Bar lower limit of soil water.

$$[CO_2]_{year} = 650.18 + \frac{0.000075326*y - 0.16276}{0.00022299 - \frac{727.97}{y^2}} - 0.00018747*(y - 2045)^3 \quad (1)$$

For RCP8.5, it was fitted by:

$$[CO_2]_{year} = 1034.3 + \frac{267.78 - 1.6188*y}{4.0143 + \frac{53.342}{y^{5.2822}}} + 21.746*\left(\frac{y - 2010}{100}\right)^3 + 100.65*\left(\frac{y - 1911}{100}\right)^3 \quad (2)$$

These equations set atmospheric CO_2 concentrations approximately equal to the multi-model mean mid-range carbon cycle projections for RCP4.5 (520 ppm) and RCP8.5 (720 ppm) during study period 2061–2090 (Van Vuuren et al., 2011).

The difference in volumetric water content between drained upper limit (DUL) and wheat lower limit (wheat LL) is calculated as plant available water capacity (PAWC), which represents the 'bucket' size for water stored by the soil that is available for use by a crop (Asseng et al., 2001; Yang et al., 2014). DUL is defined as the amount of water that a soil can hold after drainage has been significantly slowed and wheat LL refers to the lowest water content at which a wheat crop can extract water. In general, wheat yield are closely related to PAWC in rain-fed conditions (Oliver et al., 2006; Wang et al., 2009a). With rainfall and surface evaporation being equal, a soil with a low PAWC provides less water to a crop than a soil with a high PAWC. This study focuses on the effect of PAWC on the impact of climate change on wheat yields simulated by APSIM. Other soil parameters, such as soil pH, were set to the same value between the 12 soil types considered.

In our simulations, the wheat sowing window was set from 1 April to 31 July (Zhao et al., 2013). Wheat was sown every year when cumulative rainfall in ten consecutive days exceeded 25 mm, or when the end of sowing window was reached (Wang et al., 2009b). Two wheat cultivars, Waagan and Bolac, were widely sown in NSW wheat belt (Matthews et al., 2014). To optimally use the available resources (light, temperature, water and nutrients), Bolac was selected for sowing date between April 1 and May 20 (early start to season) and Waagan between May 21 to July 31 (late start to season). Sowing density was 120 plants m^{-2}, at a depth of 3 cm. Summer rainfall is important in northern NSW wheat belt. However, to exclude the "carry-over" effects from previous seasons, simulations were reset on 1 January of every year, with soil organic carbon (OC) reset to 1.2% and soil profile mineral N reset to 35 kg ha^{-1} nitrate-N and 15 kg ha^{-1} ammonium-N in the top of soil, rapidly declining with depth, with wheat stubble reset to 1000 kg ha^{-1} and a soil C:N ration of 12, soil water reset to wheat crop lower limit (Fig. 2) (Asseng et al., 2000; Oliver et al., 2010b). Each year, 100 kg ha^{-1} N fertiliser was applied at sowing date and another 50 and 100 kg ha^{-1} N fertiliser were added at the juvenile and initial flowering stage, respectively (Wang et al., 2009b). The high level of N application used was to avoid any nitrogen stress of the crop so that simulated wheat yield was a reflection of climate change rather than fertiliser management in the APSIM model.

2.3. Heat and drought stress indices

In this study, heat stress around flowering date (P_{HSF}) was defined as probability of the daily maximum temperature exceeding 30 °C from 100 °Cd before flowering to 100 °Cd after flowering. We mainly focused on extreme temperature during the short period surrounding anthesis in which grain set is particularly sensitive to heat stress. Drought stress index (*DSI*) (Semenov, 2009; Vanuytrecht et al., 2014) was defined as:

$$DSI = \frac{Y_p - Y_w}{Y_p} * 100\% \tag{3}$$

where Y_w and Y_p are water-limited and potential grain yields. The greater the DSI, the higher the water stress because DSI measures the percentage of the yield reduction from the potential yield due to water stress.

3. Results

3.1. Projected changes in growing season temperature and rainfall

Fig. 3 shows changes in growing season (April–November) temperature and rainfall by 2061–2090, relative to 1961–1990, based on the downscaled data for the 28 GCMs for RCP4.5 and RCP8.5. The data for all GCM simulations show warming for all six sites. The increases in temperature are greatest for the high-concentration scenario (RCP8.5) than for the low-concentration scenario (RCP4.5). Although the eastern sites (MP, MU and WW) have lower mean temperatures (Table 1), the simulated temperature increases are more for these sites than for the western sites (WA, LA and BA) (Fig. 3a). The largest warming occurs in MU, with ensemble-mean warmings of 2.3 °C for RCP4.5 and 3.8 °C for RCP8.5. In contrast, the lowest increase is found in BA, with ensemble-mean warmings of 1.9 °C for RCP4.5 and 3.2 °C for RCP8.5.

The changes in growing season rainfall show large variations between GCMs, which indicates large uncertainty. Some GCMs project increasing rainfall but most GCMs indicate a decrease. Changes in rainfall are more pronounced for RCP8.5 than for RCP4.5. Overall, projected rainfall at northern sites (WA and MP) declines more than that at other four sites. The greatest ensemble-mean decreases in rainfall occur in MP, 7.1% for RCP4.5 and 9.4% for RCP8.5, while the smallest decreases are for MU, 3.2% and 4.5% for RCP4.5 and RCP8.5, respectively.

3.2. Change in days to flowering and probability of heat stress around flowering

Results indicate that the future climate changes could have a large impact on wheat flowering. Fig. 4a shows change in days to flowering for 2061–2090 relative to 1961–1990 under RCP4.5 and RCP8.5. The length of period from sowing to flowering is clearly shortened under future climate scenarios for all six sites mainly due to increasing temperature, although sowing earlier can also result in flowering earlier due to the variable sowing rule. For RCP4.5, the ensemble-mean days to flowering averaged across the six sites is shortened by 15.8 days. For RCP8.5, the equivalent value is 23.8 days. The largest shift in days to flowering is found in MU with an ensemble mean of 19.8 and 32.0 days for RCP4.5 and RCP8.5, respectively. The smallest change in vegetative period occurs in WA, where days are shortened by 12.0 and 17.7 days for RCP4.5 and RCP8.5, respectively. Fig. 5a shows days to flowering are negatively related to growing season mean temperature. It is shortened by approximately 5.2–8.4 days for each 1 °C rise in growing season mean temperature, which depends on locations. Change days to flowering in cool sites (MU and WW) are more sensitive to temperature change than in warm sites (WA and MP).

Fig. 4b shows changes in the probability of heat stress (the number of days with daily maximum temperature exceeding 30 °C within 200 °Cd of flowering). Although increases in temperature accelerate wheat development, bringing forward flowering date, the risk of heat stress around anthesis is still severe in the future. Overall, heat stress probability increases more under RCP8.5 than under RCP4.5 for all six locations. Heat stress increases most at the two northern sites (WA and MP) for RCP8.5 due to higher temperature and less shift in days to flowering than the other sites. In contrast, the smallest increase is found at the cool MU and WW sites, which can be partly attributed to larger

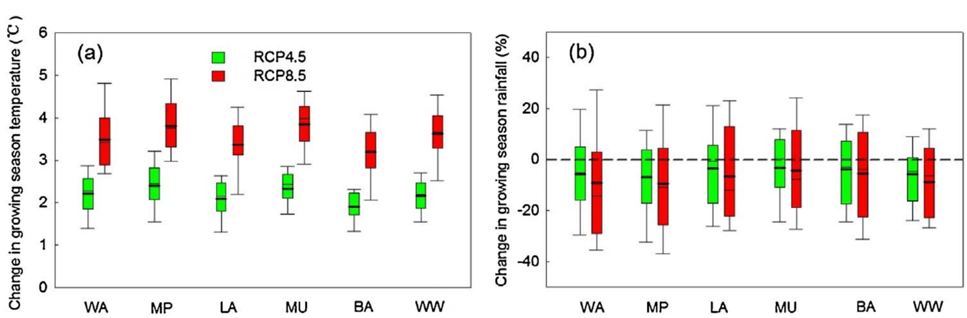

Fig. 3. Projected changes in wheat growing season (April–November) (a) mean temperature and (b) rainfall in 2061–2090 relative to the baseline (1961–1990) under RCP4.5 and RCP8.5 using 28 GCMs for six sites in the NSW wheat belt. Box boundaries indicate the 25th and 75th percentiles; the black thin and thick lines within the box mark the median and mean, respectively; whiskers below and above the box indicate the 10th and 90th percentiles.

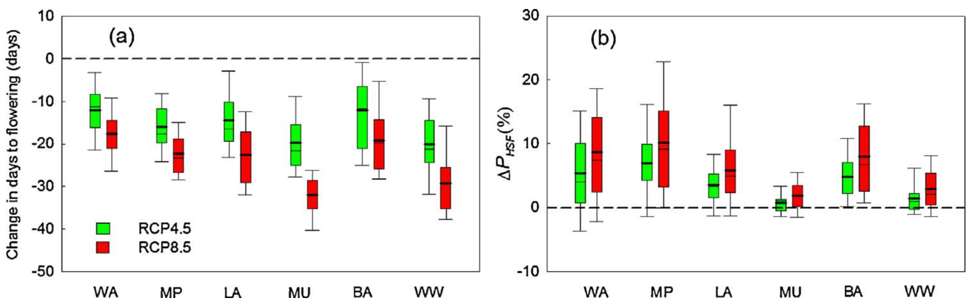

Fig. 4. Simulated change in days to flowering and probability of the occurrence of heat stress with daily maximum temperature exceeding 30 °C around flowering (± 100 °C days) (ΔP_{HSF}) in 2061–2090 relative to baseline (1961–1990) under RCP4.5 and RCP8.5 using 28 GCMs for six sites in the NSW wheat belt. Box boundaries indicate the 25th and 75th percentiles; the black thin and thick lines within the box mark the median and mean, respectively; whiskers below and above the box indicate the 10th and 90th percentiles.

advances in flowering date. Fig. 5b shows the relationships between simulated ΔP_{HSF} and growing season maximum temperature ($\Delta T_{\max}$). ΔP_{HSF} is positively correlated to $\Delta T_{\max}$ across the six sites. The response of ΔP_{HSF} to $\Delta T_{\max}$ varies among locations. In the three western sites, on average, ΔP_{HSF} increases by 3.5% for each 1 °C increase in maximum temperature, which is higher than that in the three eastern sites (on average, 2.2% °C^{-1}). It is noteworthy that the largest response is found in the warm site MP (3.0% °C^{-1}) while the smallest response is in the cool site MU (0.5% °C^{-1}).

3.3. Changes in potential yield (Y_p)

Potential yields are simulated under full irrigation conditions and thereby only affected by changing temperature, solar radiation and atmospheric CO_2 concentration. Y_p shows small variations between the 28 GCMs for each soil type (Fig. 6). Soil conditions play an important role in determining yield. However, the yield response stagnates at high PAWC values (greater than about 210 mm). Ensemble-mean Y_p based on the 28 GCMs increases by 2.7–6.0% for RCP4.5 and 2.5–5.8% for RCP8.5 for four sites (WA, LA, BA and WW). There is no large overall difference in potential yield change between two RCPs. However, Y_p decreases by 2.0% in MP and by 0.8% in MU under the high-concentration RCP8.5 scenario, which can be attributed to greater warming accelerating phenological development, resulting in less time to grow over the course of the growing season.

3.4. Changes in water limited yield (Y_w)

In addition to temperature, radiation and CO_2 concentration, Y_w is also limited by water supply, and hence by rainfall and soil properties. Increasing yield with increasing PAWC occurs when the crops need to use water stored deep in the profile. A high PAWC can provide a buffer to crops, reducing the sensitivity to the temporal distribution of rainfall. The response of Y_w to PAWC differs due to the amount of growing season rainfall. Similar to Y_p, a curvilinear response to yield can be seen in Y_w. At wet sites (e.g. MU), soils with higher PAWC have a greater water reserve to meet crop water demand. By contrast, at dry sites (e.g. BA) there is no significant relationship between yield and PAWC as wheat mostly grows from current low rainfall. Water storage in soils with higher PAWC is not fully utilized due to incomplete profile wetting by limited growing season rainfall. In addition, most rain-fed crops suffer at least short-term water deficit at some point during the growing season, and thus the climate impacts are more variable for Y_w compared to Y_p. There are large variations in Y_w between the 28 GCMs for each soil type (Fig. 6). Simulation results show that water limited yield is substantially affected by growing season rainfall (Fig. 7) and this large variation is likely due to the large variation in rainfall changes between the GCMs. The highest Y_w occurs for the wet sites MU and WW (Fig. 6d and f) while lowest Y_w is found in dry site BA (Fig. 6e). There is an overall strong positive relationship between yield change and growing season rainfall (R^2 = 0.48) (Fig. 7). This suggests that growing season rainfall is the most important yield determining factor at these six study sites. Moreover, the western dry sites have larger response to growing season rainfall than that of eastern wet sites. However, increasing PAWC results in low response of Y_w to rainfall except dry site BA (Fig. 8). In other words, soils with higher PAWC are less affected by growing season rainfall compared with soils with lower PAWC.

The ensemble-mean Y_w value is higher for RCP8.5 than for RCP4.5 in the warm and dry sites (Fig. 6a and e), which indicates that higher atmospheric CO_2 concentrations can offset the increasing negative effects of decreased rainfall during growing season and shortened growth period in rain-fed conditions. There is an interaction between higher temperature, rainfall and elevated CO_2. Rising CO_2 concentration is expected to decrease plant water stress due to improved transpiration efficiency. Overall, Y_w changes depend on location and scenario. For example, simulated Y_w increases for the warm site WA, ensemble-mean changes of 3.6% and 15.2% for RCP4.5 and RCP8.5, respectively (Fig. 6a). Similarly, for the dry site BA, Y_w increases by 0.5% for RCP4.5 and 14.7% for RCP8.5 (Fig. 6e). Earlier flowering due to higher temperatures moves the grain filling period to a cooler wetter part of the season which can increase grain yield avoiding severe summer drought. However, Y_w decreases in MU and WW because warmer growing season temperatures reduce the length of the growth period so less nutrition and radiation are received, which results in lower biomass production.

3.5. Changes in relative yield loss (DSI)

Simulated results also indicate that PAWC has a significant impact

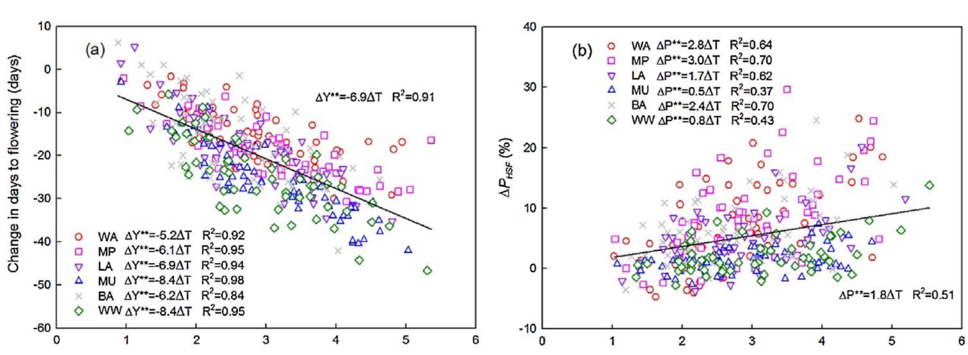

Fig. 5. Relationships between simulated change in days to flowering and growing season (April–November) change in mean temperature (ΔT_{mean}) (a), heat stress around flowering date (ΔP_{HSF}) and change in growing season maximum temperature ($\Delta T_{\max}$) (b) across six sites in the NSW wheat belt. The effect of a change in temperature was fitted using linear regression. ** indicates the significant level of $P < 0.01$.

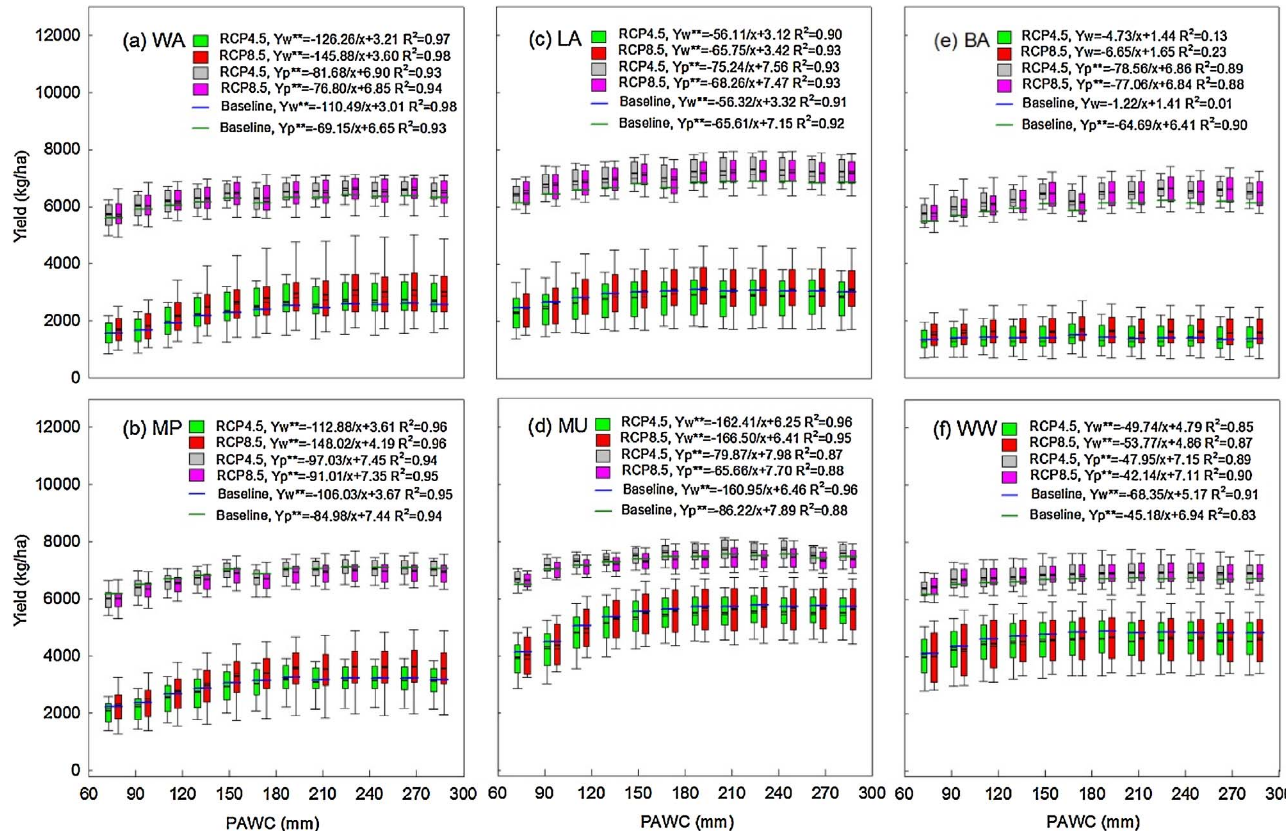

Fig. 6. Simulated potential (Y_p) and water-limited (Y_w) wheat yield for the baseline (1961–1990) and for 2061–2090 using 28 GCMs under RCP4.5 and RCP8.5 across plant available water capacities (PAWC) for six sites (a–f) in the NSW wheat belt. Box boundaries indicate the 25th and 75th percentiles; the black thin and thick lines within the box mark the median and mean, respectively; whiskers below and above the box indicate the 10th and 90th percentiles. Regression coefficients of the relationship between wheat yield (Y_p and Y_w) and plant available water capacity (PAWC, x) for baseline and two RCPs for six sites in the NSW wheat belt, as descripted by $Y = a/x + b$. The fitted coefficients a and b are the order of magnitude of 10^3. ** indicates the significant level of $P < 0.01$ for the regression model.

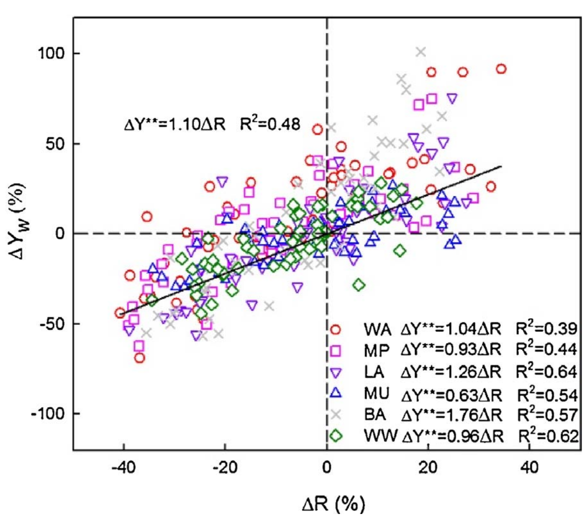

Fig. 7. Relationships between simulated change in water limited yield (ΔY_w) and growing season rainfall (ΔR) for six sites in the NSW wheat belt. The effect of a change in rainfall was fitted using linear regression. ** indicates the significant level of $P < 0.01$.

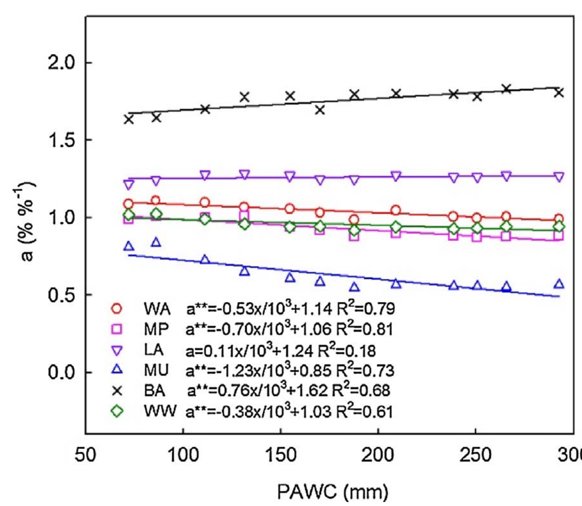

Fig. 8. Impact of plant available water capacities (PAWC) on the regression slope a ($\Delta Y_w = a\Delta R$) between change in water-limited yield (ΔY_w) and change in growing season rainfall (ΔR) for six sites in the NSW wheat belt. The slope a is% yield change per% rainfall change. ** indicates the significant level of $P < 0.01$.

on the relative yield loss. However, the response of DSI to PAWC depends on location and soil type. For the dry site BA, where water stress is relatively severe, DSI is high for all 12 soils (about 75%, Fig. 9e) and there is no relationship between DSI and PAWC. In contrast, a lower DSI is found at the wetter sites MU and WW (Fig. 9d and f), which significantly decreases with increasing PAWC and stagnates at a higher PAWC. As a result, increase in soil PAWC tends to reduce water stress at high rainfall sites. Fig. 10 shows ΔDSI under RCP4.5 and RCP8.5 averaged across the 12 soils. For RCP4.5, simulated ΔDSI increases with a mean value of 5.4%, 4.1% and 6.0% in LA, MU and WW, respectively. However, for RCP8.5, ΔDSI is expected to decline or stay about the same across all six sites, except WW. Despite a decrease in rainfall during the growing season, relative yield losses from water stress are predicted to be smaller in the future than at present. Wheat can benefit

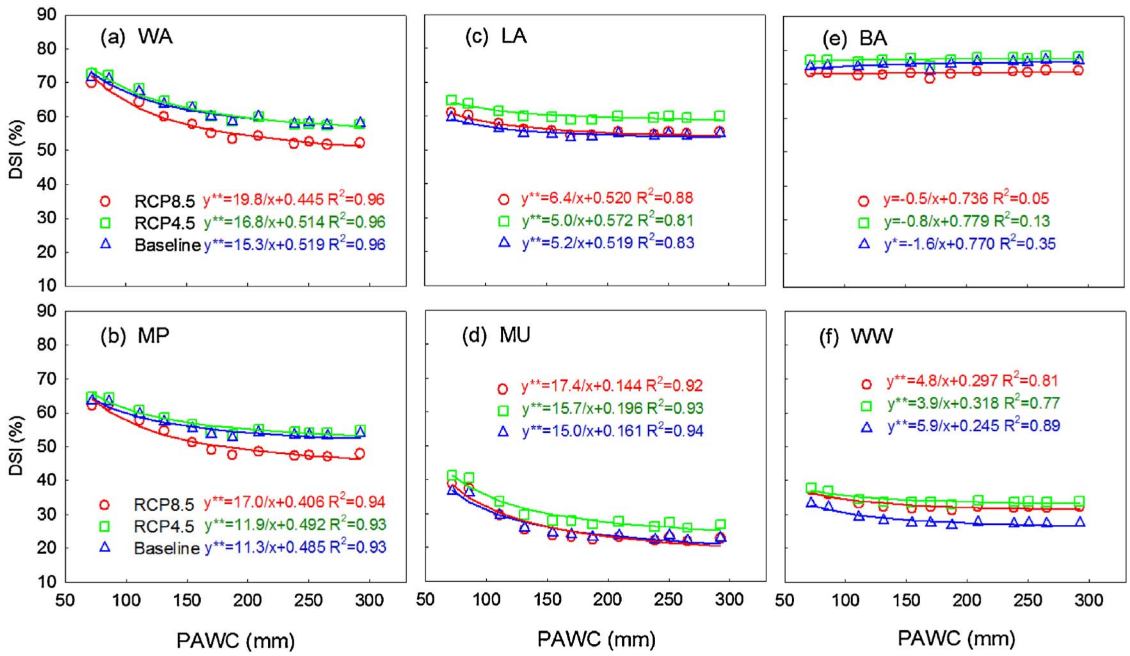

Fig. 9. Impact of plant available water capacities (PAWC) on drought stress index (DSI) for six sites in the NSW wheat belt. The effect of a change in PAWC was fitted by equation $DSI = a/x + b$. * and ** indicate the significant level of $P < 0.05$ and $P < 0.01$, respectively. A high DSI value indicates a high water stress.

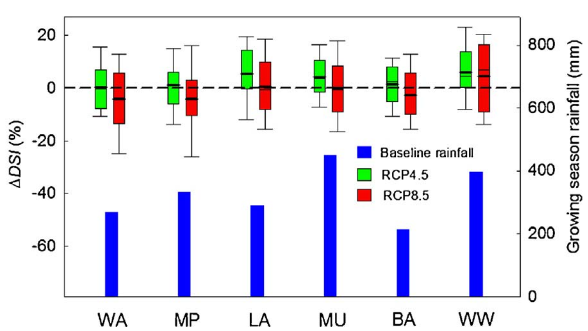

Fig. 10. Change in drought stress index (DSI) in 2061–2090 relative to baseline (1961–1990) under RCP4.5 and RCP8.5 using 28 GCMs averaged across 12 soils for six sites in the NSW wheat belt. Box boundaries indicate the 25th and 75th percentiles; the black thin and thick lines within the box mark the median and mean, respectively; whiskers below and above the box indicate the 10th and 90th percentiles.

from higher CO_2 concentration in the atmosphere arising from high emission RCP8.5 in 2061–2090.

4. Discussion

Previous studies have constructed climate scenarios by linearly manipulated historical weather records with regional average GCM-simulated climate changes (Asseng et al., 2013; Potgieter et al., 2013; Wang et al., 2009b). In this approach, the future variability of the climate is kept consistent with the variability of the historical weather records (Ludwig and Asseng, 2010). Namely, the variability for the historical climate (still very large in a Mediterranean climate) and future climate scenarios is kept the same. In this study, we used statistical downscaled data derived from the latest CMIP5 GCMs to generate future climate scenarios in which climate variability was allowed to change. This was important as the focus of the study was on stresses to wheat crops resulting from climate extremes.

The analysis considered data derived from 28 different GCMs for six sites in eastern Australia. The use of many GCMs was important to capture the uncertainty in future projections that arises from uncertainties in model structure and parameterization (Lobell et al., 2015). Multi-model mean climate changes from our method are consistent with recently developed climate change projections for Australia. Under RCP4.5, the multi-model mean growing season mean temperature increased by 2.2 °C averaged across locations for the period 2061–2090 relative to 1961–1990. The equivalent value for RCP8.5 was 3.6 °C. CSIRO and BoM (2015) projected annual mean temperature increases of 1.9 °C for RCP4.5 and 3.9 °C for RCP8.5 in eastern Australia for the time period 2080–2099. Wheat growing season rainfall decreased by 4.9% for RCP4.5 and 7.4% for RCP8.5 averaged across locations. These changes are also in line with the findings of CSIRO and BoM (2015), which stated that climate models projected a decrease in spring and winter rainfall in the late 21st century.

The results indicated that simulated potential yield increased for both RCPs in most study sites. However, the difference in potential yields between the RCPs were small due to interactions such as higher temperatures offsetting greater CO_2-induced yield gains for RCP8.5 (Araya et al., 2015; Balkovič et al., 2014). The effects of climate change on water limited yield depended on location. Rain-fed yield increased at warm and dry sites, which can be attributed to earlier flowering moving the grain filling period to a cooler wetter part of the season and thus increasing grain yield in case of terminal drought (Moriondo et al., 2011; Sadras and Monzon, 2006). In contrast, yields decreased at wet and cool sites because warmer temperatures accelerated phenological development, resulting in less intercepted nutrition and radiation and consequently lower biomass production over the course of the growing season. However, there were interacting effects of temperature, rainfall and CO_2 concentration on wheat yields (Ludwig and Asseng, 2006), which were not exhaustively explored in this study but reported in Wang et al. (2017) with a spatial context across the entire NSW wheat area.

Our simulation results showed that, despite flowering date occurring earlier, the probability of heat stress around flowering still increased by 2061–2090 for both RCPs. This is likely to cause more frequent wheat failure across this region. Additionally, higher temperatures reduce the length of the growing season, which results in lower biomass production (Asseng et al., 2011; Stratonovitch and Semenov, 2015). It might be beneficial to develop cultivars with higher thermal requirements and later maturity that are capable of coping with an increased heat stress around flowering.

PAWC is a key determinant of crop productivity (Asseng et al., 2001; Wang et al., 2009a; Yang et al., 2014) and crops grown in a soil with high PAWC have a better chance of surviving in drought conditions than with a low PAWC (Yang et al., 2014). High PAWC can provide a large buffer that moderates the impact of within-season variability in rainfall on yield (Wang et al., 2009a). High PAWC soils were less responsive to reductions in rainfall due to climate change. Our results showed that at wetter sites, soils with high PAWC had larger simulated water limited yields. Wheat yields increased with increasing PAWC and then the yield response stagnated at a high PAWC. However, PAWC had little impact on the yield range at a dry site like BA due to water limitation. The results presented here are partly consistent with findings of Wang et al. (2009a).

Our simulation results showed DSI was higher at a dry site and PAWC also had little effect on DSI due to lack of rainfall reaching deeper soil layers. In contrast, wetter sites had low DSI, which decreased with increasing PAWC when water stored in the soil profile was available. The main limitation imposed by climate change for wheat cropping system in the NSW wheat belt is rainfall. Despite growing season rainfall decreasing under climate change for the six sites, relative yield losses for the period of 2061–2090 compared to baseline were predicted to be small, especially for high atmospheric greenhouse gas concentrations (RCP8.5). This is consistent with results from Semenov and Shewry (2011) in Europe, who demonstrated that drought would not increase vulnerability of wheat. They suggested that climate warming could result in earlier wheat flowering and maturity dates, which shift the grain filling period to a cooler and wetter part of the season, where soil water deficit still stayed at the same level, and allows the crop to avoid severe summer drought. In many Mediterranean and winter-dominant rainfall environments, grain yields are often limited by terminal drought in which case early flowering can be an advantage. Although flowering earlier with increasing temperature allowed the crop to escape increasing terminal drought (Semenov and Shewry, 2011), higher atmospheric CO_2 concentrations under RCP8.5 compared to RCP4.5 can also offset the increased negative effects of decreased rainfall and shortened growth period. Therefore, a successful adaptation strategy in a drying region could be to develop an early flowering cultivar, but only up to a point where shortened growing season does not limit yields, to mitigate the impacts of water stress.

Nevertheless, drought is the most significant environmental stress in agriculture worldwide and improving yields in water-limited environments is a major goal of agronomy and plant breeding (Oliver et al., 2010a; Soussana et al., 2010). The future impacts of drought on yield will depend on soil types and the spatial and temporal patterns of climate change. An emerging threat for wheat production in eastern Australia may result from an increase in frequency and magnitude of heat stress around flowering with potentially significant yield losses for heat sensitive wheat cultivars commonly grown in the northern parts of the NSW wheat belt. However, it is important to realize that the present study assumed no adaptive management strategies were put into practice in response to climate change and this is clearly an unrealistic assumption. However, the study did provide a clear picture of the adverse effects of climate change on wheat yield given no adaptive management strategies. In reality, farmers would likely gradually adapt to climate change. Indeed, even under current climate conditions, farmers often avoid sowing wheat crops in drought years with late starts to the growing season or only sow in some areas with sufficient stored soil water (Gomez-Macpherson and Richards, 1995; Wang et al., 2015a).

Changing the sowing window could be an ‘escape’ strategy for avoiding adverse impacts of heat and water stress on yield. As the risk of frost strongly decreases when mean temperature increases (Wang et al., 2015b; Zheng et al., 2012), it might be viable to expand the sowing window to take advantage of some earlier planting opportunities. Moreover, the reduction in rainfall under future climate scenarios in eastern Australia has mainly occurred during the winter and spring months but not during autumn (CSIRO and BoM, 2015), so farmers could benefit from the relatively wet autumns by sowing earlier. Another strategy is developing different cultivars that are better adapted to future climates. Having limited time and resources, crop scientists and breeders must select the most appropriate traits for crop improvement and should, therefore, focus on the development of wheat cultivars with higher thermal requirements (longer growing season), which are resistant to high temperature around flowering. Additionally improved water use efficiency through, for example, more efficient root systems and morphology in soils may provide some protection against excessive drought in the future.

5. Conclusion

We conclude that despite accelerated phenological development and earlier flowering date in a warming climate across six sites in NSW, the probability of heat stress around flowering still increased by about 3.8% for RCP4.5 and 6.2% for RCP8.5. The risk of heat stress around flowering was especially high for warm sites under RCP8.5. Simulated potential yield across six sites increased in average by about 2.5% regardless of the emission scenario. However, simulated water limited yield tended to decline at wetter and cooler locations (MU and WW) under future climate while increased at warmer and drier locations (WA and BA). Soils with high PAWC provided a larger buffer to store water from variable rainfall and to supply it to crops during dry periods and therefore were less affected by rainfall decreases compared to soils with low PAWC. Although projected growing season rainfall decreased, relative yield loss due to water stress was expected to decline or stay the same as a result of increased CO_2 concentration and, to some extent, earlier flowering allowing wheat to avoid severe summer drought. Therefore, to maintain or increase yield potential and respond to climate change, increasing tolerance to heat stress and improving crop management to reduce impacts of water stress on lower plant available water holding soils should be priorities for the genetic improvement of wheat in eastern Australia.

Acknowledgements

The first author acknowledges that the Chinese Scholarship Council provided the scholarship and the NSW Department of Industry provided office facilities for conducting this work. We also acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP5 multi-model dataset. Support of this dataset is provided by the Office of Science, US Department of Energy. We are very grateful to two reviewers for their very thorough and helpful comments which greatly improved our manuscript.

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