Agricultural Systems 132 (2015) 133–144

Contents lists available at ScienceDirect

Agricultural Systems

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

Climate change impacts on phenology and yields of five broadacre crops at four climatologically distinct locations in Australia

Muhuddin Rajin Anwar [a,b,*], De Li Liu [a,b], Robert Farquharson [c], Ian Macadam [d], Amir Abadi [e], John Finlayson [a,b], Bin Wang [a,b,f], Thiagarajah Ramilan [g]

[a] NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, PMB, Wagga Wagga, NSW 2650, Australia
[b] Graham Centre for Agricultural Innovation (An alliance between NSW Department of Primary Industries and Charles Sturt University), Wagga Wagga, NSW 2650, Australia
[c] Melbourne School of Land & Environment and Future Farm Industries Cooperative Research Centre, University of Melbourne, Australia
[d] Climate Change Research Centre and ARC Centre of Excellence for Climate System Science, University of New South Wales, Sydney, NSW 2052, Australia
[e] Department of Parks and Wildlife Western Australia, Department of Agriculture and Food Western Australia and Future Farm Industries Cooperative Research Centre, Perth, WA, Australia
[f] Plant Biology and Climate Change Cluster, University of Technology Sydney, PO Box 123, Broadway, NSW 2007, Australia
[g] International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India

ARTICLE INFO

Article history:
Received 2 June 2014
Received in revised form 27 September 2014
Accepted 30 September 2014

Keywords:
Crops
Climate change
GCM
APSIM
Yield
Phenology

ABSTRACT

Shifts in rainfall and rising temperatures due to climate change pose a formidable challenge to the sustainability of broadacre crop yields in Western and South-Eastern Australia. Output from18 Global Climate Models (GCMs) for the Special Report on Emission Scenarios (SRES) A2 scenario was statistically downscaled to four contrasting locations. For the first time in these regions, bias corrected statistically downscaled climate data were employed to drive the Agricultural Production Systems Simulator (APSIM) crop model that integrates the effects of soil, crop phenotype, and management options for a quantitative comparison of crop yields and phenology under an historical and a plausible projected climate. The dynamic APSIM simulation model explore the implications of climate change across multiple locations and multiple time periods (1961–2010, 2030, 2060 and 2090) for multiple key crops (wheat, barley, lupin, canola, field pea) grown in three different types of soil. On average, the ensemble of downscaled GCM projections show a decrease in rainfall in the future at the four locations considered, with increased variability at two locations. At all locations and for five crops, future changes in both crop biomass and grain yield are strongly associated with changes in rainfall ($P = 0.05$ to $P = 0.001$). The overall rainfall amount is critical in determining yields but, equally, higher future temperatures can contribute to reducing crop productivity primarily due to advanced crop phenology. For example, for wheat cropping at Hamilton (a higher rainfall site), there is a significant advancement in median flowering date for 2030, 2060, and 2090 of 10, 18, and 29 days respectively with a significant 0.50% grain yield changes for each percentage change in rainfall compared to significant 0.90% grain yield changes in Cunderdin (a lower rainfall site). At all sites except Hamilton, the change in crop grain yield is significantly correlated ($P = 0.001$) with the percentage change in the future rainfall and the impact increased progressively from higher rainfall to lower rainfall sites. However, the magnitude of the change in crop phenology and yield were not significantly different between soil types. These results help to define regions of concern and their relative importance in the coming years. In this future climate the negative consequences for crop yields and advancement of phenology relative to baseline are not uniform across crops and locations. Of the crops studied – wheat, barley, lupin, canola and field pea – field pea is the most sensitive to the projected future climate changes, and the ensemble median changes in field pea yield range from a decrease of 12% to a decrease of 45%, depending on location. These results highlight the importance of research and policy to support strategies for adapting to climate change, such as advances in agronomy, soil moisture conservation, seasonal climate forecasting and breeding new crop varieties.

---

[*] Corresponding author. Tel.: +61 2 69381993; fax: +61 2 69381809.
E-mail address: muhuddin.anwar@dpi.nsw.gov.au (M.R. Anwar).

http://dx.doi.org/10.1016/j.agsy.2014.09.010
0308-521X/

1. Introduction

Since the 1960s, a major driver of crop yield stability in Western and Southern Australia (WSA) has been the observed decline in winter rainfall (Cai and Cowan, 2008; Smith et al., 2000; Stokes and Howden, 2010). In WSA, increasing atmospheric carbon dioxide (CO_2) concentrations are projected to be accompanied by increases in mean temperature of 0.6 to 1.5 °C by 2030 and 2.2 to 2.5 °C by 2070 and decreases in annual mean rainfall by –2.5 to –10% by 2030 and 2070 (Cai and Cowan, 2008; CSIRO and BoM, 2007; CSIRO and BoM, 2010; CSIRO and BoM, 2012; Sinclair, 2011). Therefore, a major concern arises for the long-term productivity and sustainability of dry land broadacre cropping systems under future climate conditions (Anwar et al., 2013; Challinor et al., 2014; Rodríguez et al., 2014; Stokes and Howden, 2010). A strong scientific evidence base is needed to help farmers choose resilient strategies and to guide research and development (R&D) investments in the presence of climate change (Anwar et al., 2013; Challinor et al., 2014; Dogliotti et al., 2014). The effects of climate change are likely to exacerbate high natural climatic variability on broadacre crop production systems in semiarid environments in Australia (Hayman et al., 2012; IPCC, 2007). The intensive rainfed farming systems of WSA are climatically sensitive, as demonstrated by the significant fluctuations in regional crop yields in dry and wet years (ABARES, 2013; Hennessy et al., 2007). Such yield variation could be amplified by projected climate changes (Lobell and Field, 2007; Stokes and Howden, 2010). However, changes in rainfall and temperature are different for different locations and time horizons and may have different effects on crop yields depending on crop and soil types (Challinor et al., 2014; Stokes and Howden, 2010). Regional assessments of vulnerability and the consequent management responses must therefore take into account the effects of climate changes for different locations and time horizons on a range of crops growing in a range of different soil.

Numerous studies have assessed the effects of climate change on crop productivity in rainfed cropping systems in Australia at various scales (Anwar et al., 2007; Bassu et al., 2011; Crimp et al., 2008; Ludwig and Asseng, 2006; Potgieter et al., 2013; van Ittersum et al., 2003; Wang et al., 2011; Yang et al., 2014). In these studies, wheat was the most commonly assessed crop, though there are other important broadacre crops in the domain of rainfed cropping system that dictates food crop productivity (ABARES, 2013). Analyses suggest that considerable decreases in wheat yield (Ludwig and Asseng, 2006; van Ittersum et al., 2003; Yang et al., 2014) can be attributed to reductions in rainfall in the projected climates. The relevant research has demonstrated that the major constraints to rainfed cropping include crop type, agronomy, climate, and soil type (Iizumi et al., 2013; Olesen et al., 2011; White et al., 2011). Climate change constitutes the major exogenous shock to which adaptation responses specific for crop type, soil type and agronomy would be required. In this article, five important broadacre crops in Western and South-Eastern Australia are considered. These include wheat (*Triticum aestivum* L), barley (*Hordeum vulgare* L), lupins (*Lupinus angustifolius*), canola (*Brassica napus* L) and field peas (*Pisum sativum*).

Impact assessments of climate change on agricultural crops often use climate scenarios (Nakićenović and Swart, 2000) developed by downscaling Global Climate Model (GCM) predictions to a region of interest (e.g., Betts et al., 2011; Ines and Hansen, 2006; Robertson et al., 2007), and these are crucial for planning adaptation strategies (Anwar et al., 2013; Rodríguez et al., 2014; Stokes and Howden, 2010). The resulting climate scenarios are used as inputs to drive process-oriented crop simulation models for impact assessment (Alexandrov et al., 2002; Betts, 2005; Lobell, 2013; Ozdogan, 2011; Reilly et al., 2003; Tubiello et al., 2002). Most crop simulation models require daily climate data (de Wit and van Keulen, 1987; Keating et al., 2003; Soussana et al., 2010; Stockle and Nelson, 2001). However, one of the unpredictable aspects of climate change is the future amount of annual rainfall and how it will be distributed during the growing seasons (Folland et al., 2001; Ramirez-Villegas and Challinor, 2012). Different GCM can provide different future projections for a particular region (Laurent and Cai, 2007; Zhang and Cai, 2013). Moreover, GCM grid-cell estimates over the studied land surfaces may be influenced by the radiative forcing of the climate system (Eric and Salathe, 2003; Mearns et al., 1996; Randall et al., 2007). GCM grid-cells typically have coarse spatial resolutions of hundreds of kilometres. Such estimates, in combination with different emission scenarios and uncertainty originating from the choice of GCMs (Beniston et al., 2007; Ines and Hansen, 2006; Nakićenović and Swart, 2000), can result in over- or underestimated rainfall amounts that may not be applicable to future climates at regional scales (Randall et al., 2007; World Bank, 2012, 2013). There is also a diversity of approaches and methods available for making future climate projections, including anomalies, variable corrections, climate change factors, scaling, empirical relationships, and statistical downscaling (e.g., Anwar et al., 2007; Ines and Hansen, 2006; Liu and Zuo, 2012; Maraun et al., 2010; Randall et al., 2007; Timbal et al., 2008). Commonly numerical models or statistical relationships are used to develop future climate projections based on historical climate records. This is done in conjunction with GCM grid-cell spatial average values over the land surfaces being studied (IPCC, 2001; Mearns et al., 1996; Randall et al., 2007).

When we use best-practice climate downscaling for individual Australian locations, how do the climate sequences compare with the historical record in terms of distributions of key variables? This paper provides the first location-level estimates of projected climate in three time periods spanning from the present to 2030, 2060 and 2090. Our analysis considers four important broadacre crop growing regions in Australia by applying a statistically downscaled bias correction method (Liu and Zuo, 2012) involving 18 GCMs under the A2 emission scenario (Nakićenović and Swart, 2000). Other objectives of this study were to quantify the impact of climate scenarios (2030, 2060 and 2090) on yield and phenological variations of five important broadacre crops (wheat, barley, lupin, canola, field pea) grown in three different soil types and these results can be an important basis for adaptations.

2. Materials and methods

2.1. Study sites and climate

The effects of current climate (1961–2010) and future climate scenarios (2030, 2060 and 2090) on five important broadacre crops (wheat, barley, lupin, canola and field pea) in four locations of Australian dryland farming systems were selected for this study (Table 1). The locations of Cunderdin and Katanning in Western Australia have a Mediterranean-type climate, characterised by hot, dry summers and cool, wet winters receiving average annual rainfall of 359 and 477 respectively with high inter-annual rainfall variability. The Hamilton location in Victoria has a temperate climate receiving average annual rainfall of 694 mm. Wagga Wagga in New South Wales (NSW) is considered to be a uniform rainfall environment with a climate characterised by hot summers and cool winters receiving average annual rainfall of 548 mm with high inter-annual and intra-annual rainfall variability. In general, crop yields are closely related to plant available water capacity (PAWC) (Yang et al., 2014). Therefore, at each location, three soil types typical of the location with different PAWC values were considered (Table 1). To establish a climate baseline, daily meteorological data (solar radiation, maximum temperature, minimum temperature and rainfall) for the period 1961–2010 for each location are obtained from SILO climate data systems (Jeffrey et al., 2001, <http://www.longpaddock.qld.gov.au/silo/ppd/index.php>).

Table 1
Location of meteorological stations including soil type (Isbell, 2002), soil depth, plant available water capacity (PAWC), climate zone, average annual temperature and precipitation (1900–2012) of the study area.

Site	Latitude, Longitude	Soil type (S)	Soil depth (cm)	PAWC (mm)	Climate	Average annual temperature (°C)	Average annual precipitation (mm)
Cunderdin, Western Australia	–31.65, 117.23	(S1) Acid loamy sand (Tenosol)	250	78	Mediterranean	18.3	361
		(S2) High clay (Kandosol)	250	135			
		(S3) Deep sandy duplexes (Sodosol)	210	74			
Katanning, Western Australia	–33.69, 117.56	(S1) Acid shallow duplex (Kurosol)	240	59	Mediterranean	15.7	475
		(S2) Sandy duplexes (Sodosols)	250	82			
		(S3) Deep sand (Tenosol)	200	123			
Wagga Wagga, New South Wales	–35.13, 147.31	(S1) Red Chromosol	180	161	Mediterranean	15.8	571
		(S2) Grey Vertosol	150	251			
		(S3) Red Kandosal	160	158			
Hamilton, Victoria	–37.83, 142.06	(S1) Brown Kurosol	150	151	Temperate	13.0	676
		(S2) Black Vertosol	150	138			
		(S3) Brown Sodosol	180	163			

2.2. Climate projections

Climate projections were derived from GCM simulations of the SRES A2 scenario for emissions of greenhouse gases and sulphate aerosols (Nakićenović and Swart, 2000). This scenario has been used in numerous recent climate change impact studies (Anandhi et al., 2011; van Roosmalen et al., 2009; Yang et al., 2014). It has relatively high future greenhouse gas emissions relative to other commonly used scenarios. Monthly mean values of solar radiation, daily maximum and daily minimum temperature and rainfall for the 21st century were required for this study. These data were available for 18 different GCMs from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007a). To sample uncertainty in future climate changes, all 18 GCMs (table 2 in Yang et al., 2014) were used for this study. Monthly gridded data from each GCM was statistically downscaled to daily site-specific data for each location using the method described by Liu and Zuo (2012). The downscaling procedure starts from interpolation of the monthly gridded data to specific locations of interest using an inverse distance cubed weighting method. This is followed by a bias correction between the observed and raw GCM monthly data – the detailed description of bias correction is given by Liu and Zuo (2012). Daily climate data are then generated for each location using a modified stochastic weather generator (WGEN) (Richardson and Wright, 1984). The parameters required to driving WGEN are derived from the monthly GCM data and daily historical climate data from 1889 to 2010, as described in Liu and Zuo (2012). Historical climate data from 1961 and 2010 were used as a baseline climate to compare against the projected future climates. Three periods of future climate projection were chosen for the impact assessment: 2020–2039, 2050–2069 and 2080–2099, referred as 2030, 2060 and 2090, respectively.

2.3. Simulations

Simulations of broadacre crop responses to historic and future climates with elevated atmospheric CO_2 in four locations were performed using the Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003) version 7.5. APSIM is a framework of biophysical modules (<http://www.apsim.info/>) that has previously been shown to adequately simulate cropping systems at these and other locations (Asseng and Pannell, 2013; Bassu et al., 2011; Yang et al., 2014; Yunusa et al., 2004; Zeleke et al., 2014). Briefly, APSIM simulates biological and physical processes in a farming system (McCown et al., 1996) in response to climate (daily maximum and minimum temperature, rainfall and solar radiation) and management for an array of annual and perennial C3 and C4 crop plants. Biological processes include phenological development, leaf area growth, biomass and N concentration of leaves, stems and roots, grain number, grain size and final crop yield under prescribed management, as well as the changes in soil water and soil nitrogen supply during the cropping season (Ludwig and Asseng, 2006; Robertson et al., 2002; van Ittersum et al., 2003; Wessolek and Asseng, 2006). The APSIM-crop modules (wheat, barley, lupin, canola and field pea) calculate daily biomass production based on sunlight interception and radiation use efficiency (RUE). The standard RUE is 1.24 g MJ^{-1} for wheat and Barley, 1.10 g MJ^{-1} for field pea, 0.80 g MJ^{-1} for lupin and 1.35 g MJ^{-1} for canola from emergence to the end of grain-filling. The radiation induced production is modified by temperature, nitrogen, vapour pressure deficit and soil water supply. Crop grain yield is a function of grain number, grain filling and carbohydrate remobilisation (Robertson et al., 2002). 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. A detailed description of the response to elevated CO_2 concentration in APSIM-Wheat is given in Reyenga et al. (1999). Yearly atmospheric CO_2 concentration for 2030, 2060 and 2090 projections required in the APSIM-simulation is calculated using the method described by Yang et al. (2014) in equation 1.

$$[CO_2]_{year} = 2641 + \frac{(0.098139 \times year - 211.71)}{3.5566 \times year^{-0.37996} - 0.19123} \qquad (1)$$

This equation sets atmospheric CO_2 concentrations approximately equal to the multi-model mean mid-range carbon cycle projections for the SRES A2 emissions scenario (Meehl et al., 2007b, fig. 10.26).

The crop cultivars were selected on the basis that they are commonly used by the majority of growers at present – Mace for wheat, Baudin for barley, Drum for canola, Kaspa for field pea and Merrit for lupin. Using a common cultivar can minimise the effects of non-climate parameters. Parameters used for the setup of simulations of wheat and barley (Yunusa et al., 2004), lupin (Farré et al., 2004), canola (Farré et al., 2000; Robertson and Kirkegaard, 2005), and field pea (Chen et al., 2008) were constituted from previous studies and further refined using available information about crop phenology and morphological, physiological, and biophysical characteristics from sources published by R&D agencies such as Farmnotes (<http://www.agric.wa.gov.au/PC_91689.html>), Grains and Other crops (<http://www.dpi.vic.gov.au/agriculture/grain-crops>), NSW Grains Report (<http://www.dpi.nsw.gov.au/aboutus/resources/periodicals/newsletters/grains-report-nsw>) and Farm business (<http://www.dpi.nsw.gov.au/agriculture/farm-business/budgets/winter-crops>). To generate realistic crop yields for each location, the simulated yields based on historical climate data were corroborated by discussions with local agronomists and published district or regional benchmarks (Planfarm-Bankwest, 2011). Accordingly, the simulation was set up to include initial nutrient balances, soil water and crop management to achieve a realistic set of crop yields for each location.

Simulation setup in respect of crop sowing conditions and fertiliser application was adopted from Yang et al. (2014). Briefly, similar to current farming practice (GRDC, 2005; Heenan et al., 1994; Hunt and Kirkegaard, 2011), a standard sowing window was considered from 1st April to 31st July and sowing to germination was dependent on soil water status driven by autumn rains in any day between 1 April and 31 July. To exclude the "carry-over" effects from previous seasons, soil organic carbon, C:N ratio, soil mineral N and water contents were re-set on 10th January of every year. Locally well-adapted broadacre crops (wheat, barley, lupin, canola and field pea) variety was sown at each location when the water content in the top 20 cm soil depth was at least 1.5 and 0.7 times PAWC, as described in Yang et al. (2014). To represent non-deficient soil N for optimum crop growth, fertiliser nitrogen (N) was applied at 280 kg N/ha. Elevated levels of future atmospheric CO_2 were considered in the modelling to account for physiological effects on crops. Levels consistent with the SRES A2 emission scenario were incorporated into the modelling, as described by Yang et al. (2014).

3. Results

3.1. Future climate characteristics relative to baseline

For the baseline period 1961–2010, the mean annual temperatures for Cunderdin, Katanning, Wagga Wagga and Hamilton are 18 °C, 16 °C, 16 °C, and 13 °C respectively. Fig. 1A shows changes in mean annual temperatures projection by all 18 GCMs, relative to the baseline (1961–2010) in the four locations. Projected annual temperatures increase progressively by 2030, 2060 and 2090. Relative to baseline, averaged across all 18 GCMs, the projected increases in annual temperature are +1.02 °C, +2.04 °C and +3.51 °C for 2030, 2060 and 2090 respectively in Cunderdin, with similar changes for Katanning, Wagga Wagga and Hamilton. These increases are consistent with the projections for the whole of Australia presented by Hennessy et al. (2010), which indicated relatively modest changes for the study regions relative to warming further inland, which exceeded 1 °C by 2030 and around 3.4 °C by 2070. Fig. 1B shows that the coefficient of variation (CV) for annual temperatures is similar between the three future periods for all four locations. However, future CV values are generally less than for the baseline at Cunderlin and Hamilton, which suggests that all GCMs consistently projected a reduced temperature variation in these two sites.

Projected changes in mean annual rainfall are highly significant and spatially heterogeneous across the four studied locations (Fig. 1C). At the four locations two patterns of change in the amount of annual rainfall stand out when comparing the present to the future (2030, 2060, and 2090). The first is an overall decrease in annual rainfall. At Cunderdin, for example, the average rainfall projection of the 18 GCMs decreases by 9%, 16% and 26% in 2030, 2060 and 2090, relative to the 1961–2010 baseline, respectively (Fig. 1C). Katanning and Hamilton show similar annual rainfall decreases. However, a similar comparison for Wagga Wagga suggests that annual rainfall is only likely to decline by 4 to 5% there. The second pattern is the progressive increase in the CV of annual rainfall between the future periods for Cunderlin, Katanning and Hamilton (Fig. 1D).

Solar radiation is an important climate variable controlling photosynthesis and evaporation but solar radiation projections did not show significant future changes relative to baseline (data not shown).

3.2. Effects of climate change on crop phenology

In the life cycle of annual crops, the timing of phenological events is critical for crop yields. Two critical events are the length of the

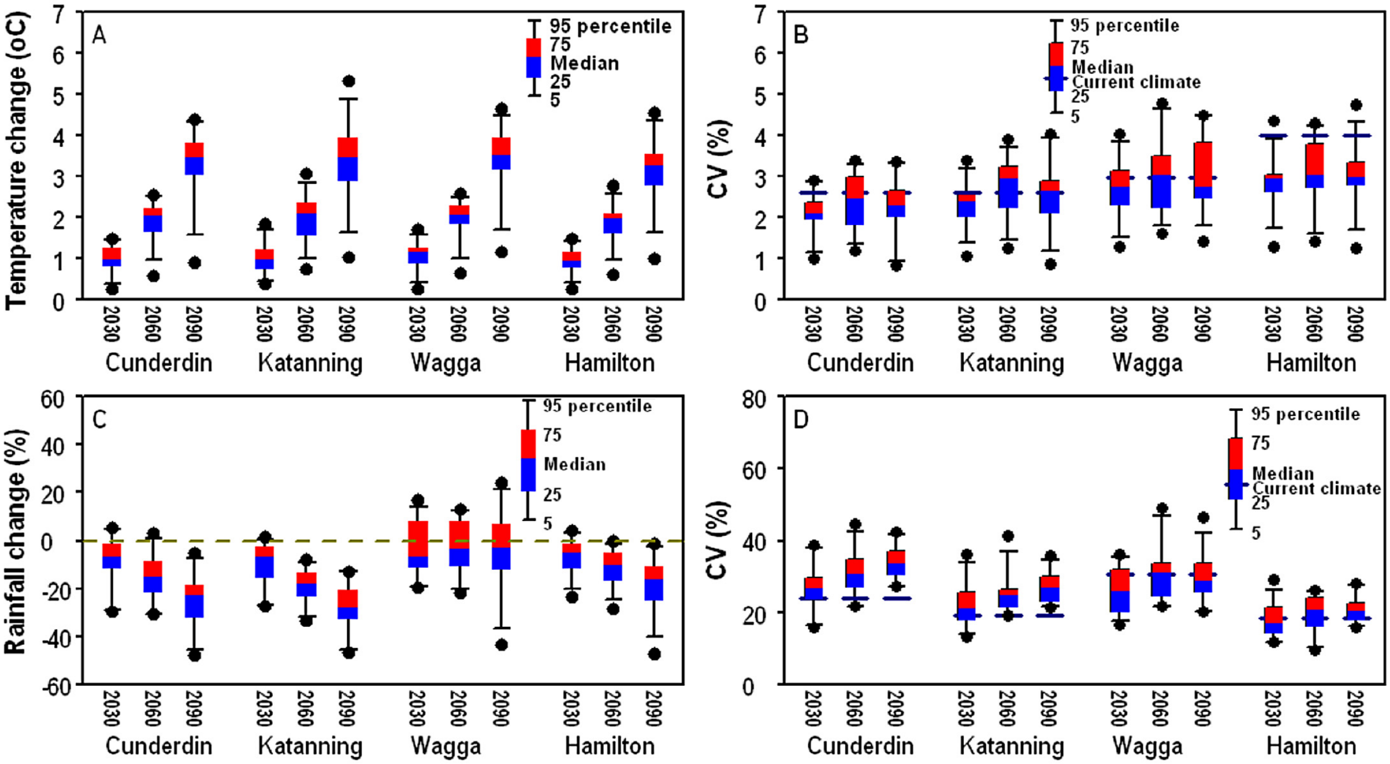

Fig. 1. Box-plots of 18 GCMs' projected temperature and rainfall changes (A and C) with coefficient of variation (CV) (B and D) in three periods (2030, 2060, and 2090) at four Australian sites. The CV of current (1961–2010) temperature and rainfall are indicated by black horizontal line on the box-plots (B and D).

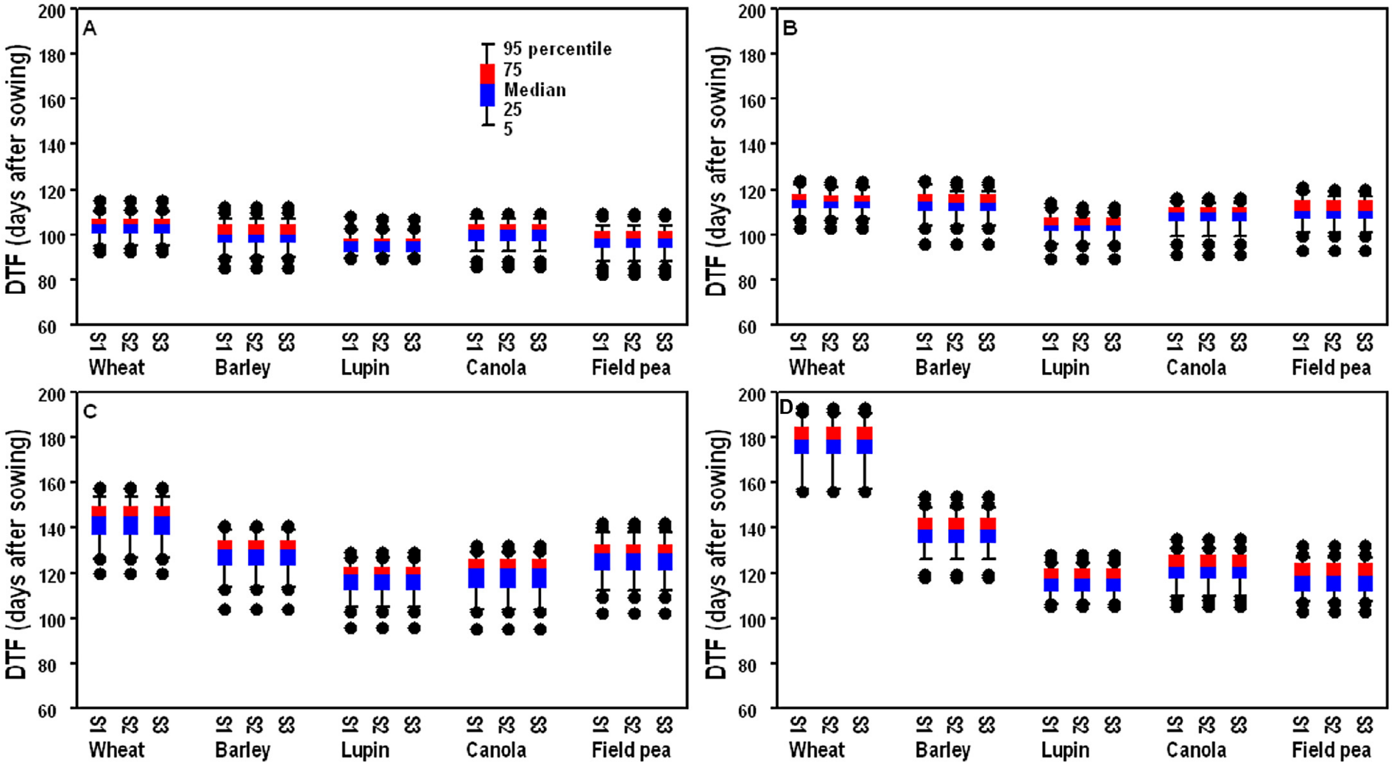

Fig. 2. Box-plots of simulated days to flowering (DTF) for the 1961–2010 period. Data for five crops and three soil types (S1, S2 and S3) are shown for Cunderdin (A), Katanning (B), Wagga Wagga (C) and Hamilton (D).

period from sowing to flowering, known as days to flowering, (*DTF*) and days to maturity (*DTM*). Across all crops in the baseline (1961–2010) period, there were no significant differences in *DTF* between the soil types (Fig. 2). However, as flowering depends on both day length and temperature, the predicted *DTF* occurs earlier in sites where annual temperature is higher (Table 1 and Fig. 2). For instance, the wheat crop in Cunderdin (higher temperature site) across all soil types flowered 103 days after sowing, compared to 179 days after sowing in Hamilton (lower temperature site). The climate change impacts on phenology (*DTF* and *DTM*) for each of the locations and crops are presented in Figs. 3 and 4. One of the most striking *features* is the significant overall reduction of the flowering period and earlier maturity in the future climate (2030, 2060 and 2090) relative to the baseline for all of the five crops across the four locations (Figs. 3 and 4). For example, there is a significant advancement in median flowering date of wheat at Hamilton for 2030, 2060, and 2090 of 10, 18 and 29 days respectively. Likewise, for field peas at Katanning, a similar comparison suggests the median flowering date is advanced by 8, 14 and 25 days and at Cunderdin, barley matured earlier by about 5, 11, and 19 days. The advancement in phenological events is likely to be related to projected temperature increases and, to some extent, rainfall changes (see Fig. 5).

3.3. Evaluation of crop yield changes

In the baseline period, simulated annual crop grain yields vary across locations depending on annual rainfall, crop and, to a much lesser extent, soil type (Fig. 6). The crop yields were highest at Hamilton, with its temperate climate and comparatively higher rainfall compared to other three sites. Wheat, for example, recorded its highest median grain yield (7 t/ha) at Hamilton, whereas at Cunderdin and Katanning the median wheat yield were below 2.8 t/ha (Fig. 6). The most variable crop yield (5th to 95th percentiles) occurred in field pea crop, followed by wheat and barley, and Wagga Wagga was the most variable location (Fig. 6). The smallest yield variability across the three soil types (5th to 95th percentiles) are at Cunderdin for most of the crops, followed by lupin at Hamilton. The simulated annual yield of all the crops shows variation depending on the season and is similar to average farm yields variation of the regions (ABARES, 2013). Fig. 7 shows the percentage change in total crop biomass between the baseline (1961–2010) and the future climate (2030, 2060, and 2090) for each crop and location. Even though there is a large variation in total crop biomass across crops and locations, the overall change in median biomass values of 18 GCMs is negative in all future climates relative to baseline, with smaller decreases projected for the 2030 and 2060 compared to 2090. There is large variation in the range of inter-quartile total crop biomass changes across crops and locations and inter-quartile crop biomass variation is always highest in 2090 compared to 2030 and 2060 (Fig. 7). For instance, the median total crop biomass values for lupin, canola and field pea crops at Cunderdin are about 10% to 40% less in the future climate relative to 1961–2010. At Hamilton wheat total crop biomass is projected to be 5% to 10% less in the future. Canola showed the largest reduction in total crop biomass (10 to 45%) in the future relative to baseline (Fig. 7) at all the locations.

3.4. Crop yield relationship with future climate

Fig. 8 summarises the projected changes of crop yields between the baseline (1961–2010) and the future climate (2030, 2060, and 2090) at each location. Three distinct patterns of yield change are evident. First, grain yield is lower for all crops in the future scenarios, across all sites, for most of the GCMs. Second, the negative impact of projected climate on grain yield increases from 2030 to 2090. This is likely to be due to higher temperatures and lower

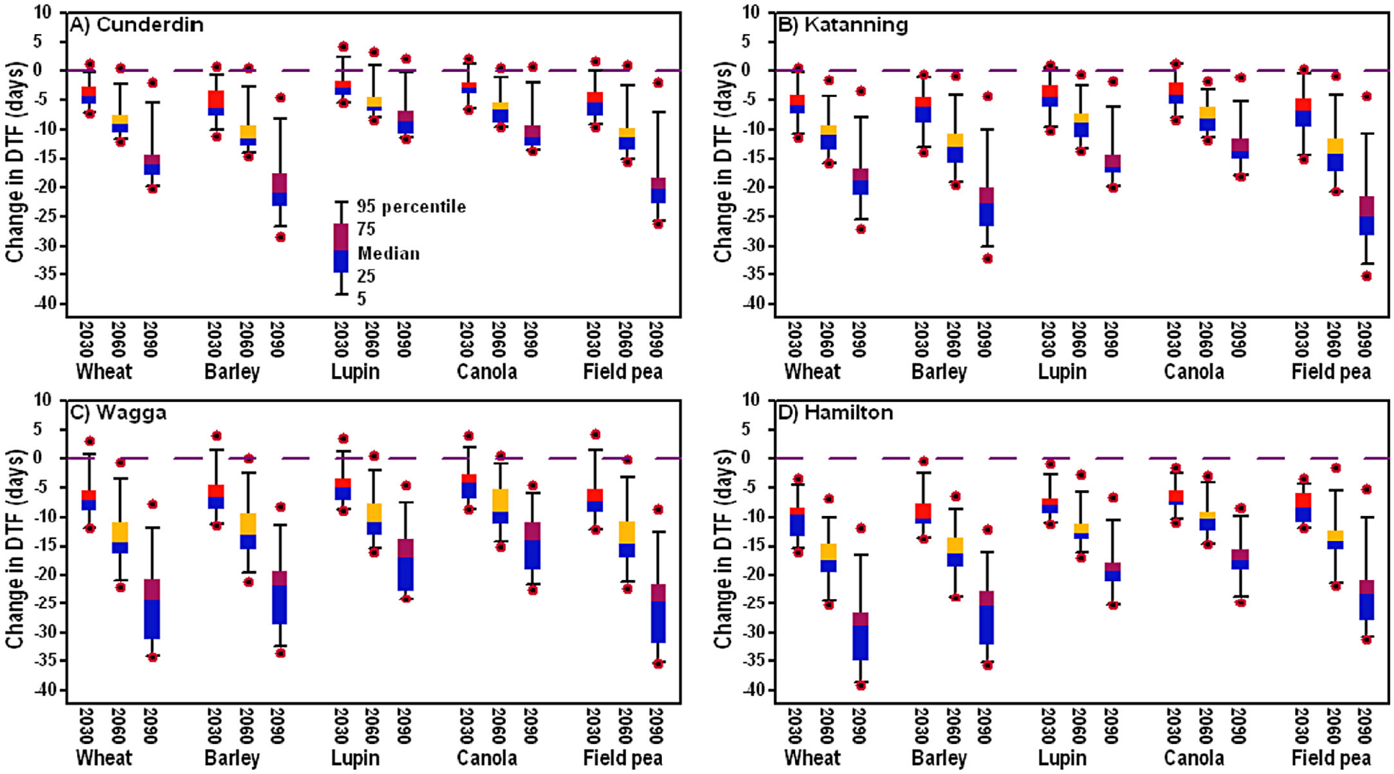

Fig. 3. Box-plots of 18 GCMs' projected changes days to flowering (DTF) of five crops in three periods (2030, 2060 and 2090) at four Australian sites.

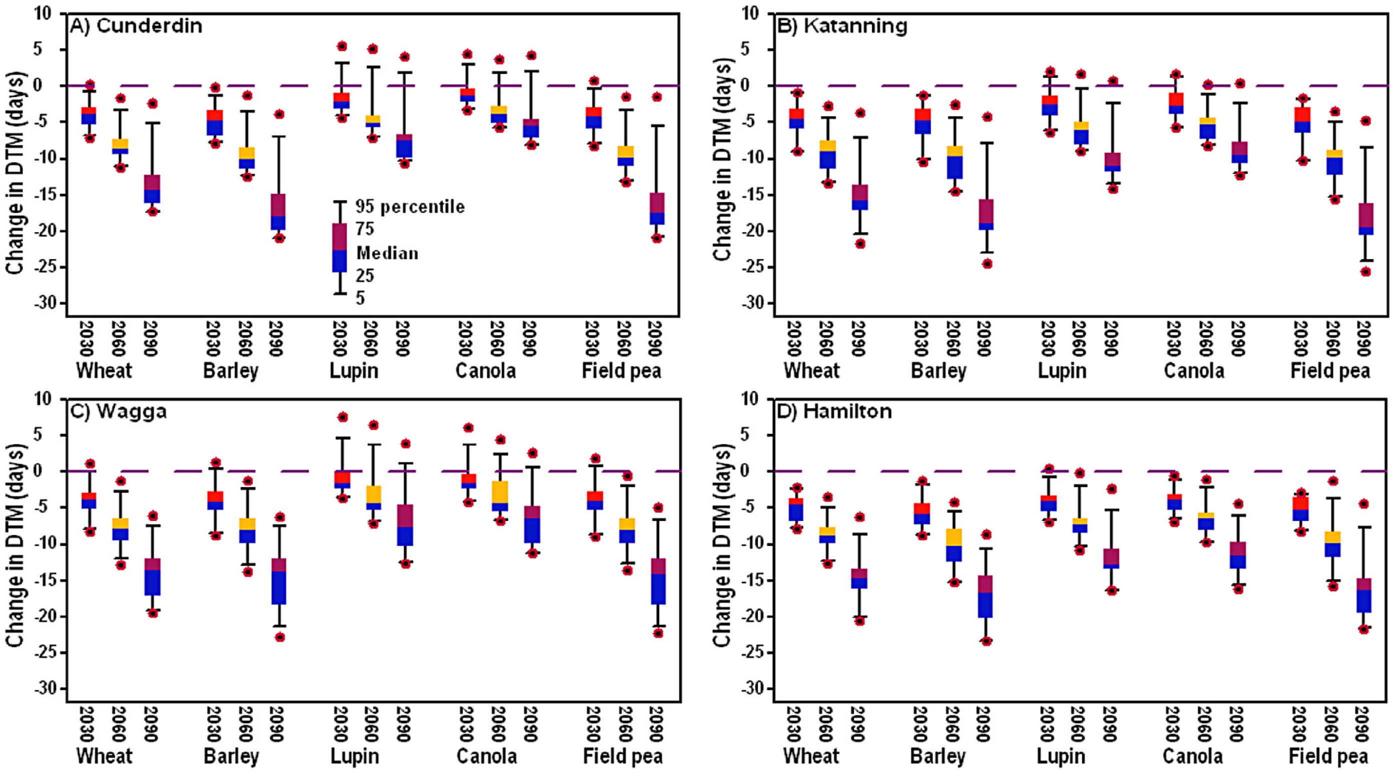

Fig. 4. Box-plot of 18 GCMs' projected changes in days to mature (DTM) of five crops in three periods (2030, 2060, and 2090) at four Australian sites.

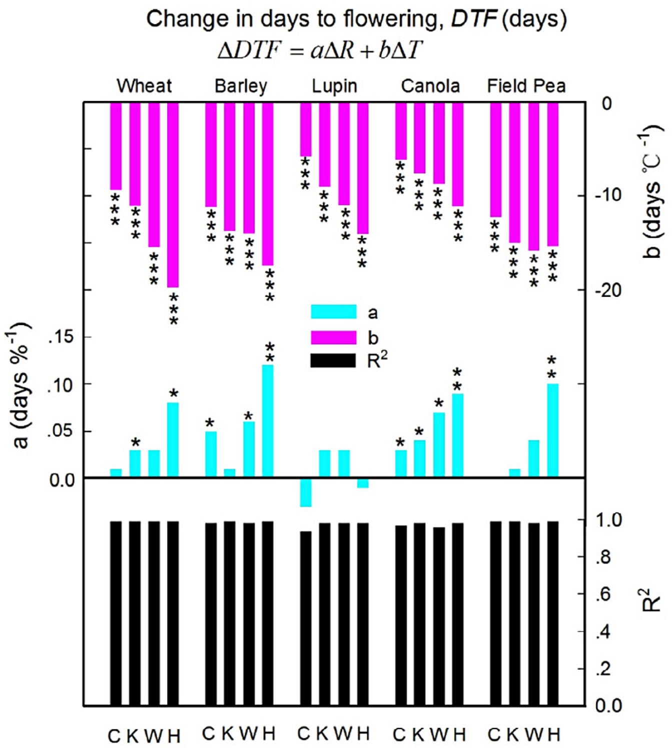

Fig. 5. Regression analysis of the impact rates of climate change on days to flowering (*DTF*) in wheat, barley, lupin and field pea at Cunderdin, Katanning, Wagga and Hamilton as abbreviated to be C, K, W and H, respectively. The change rates (ΔDTF) as functions of the change in rainfall (ΔR) and temperature (ΔT) are shown in the respective figure. The bars with *, ** and *** indicate the significant levels at $P = 0.05$, $P = 0.01$ and $P = 0.001$, respectively; otherwise, the coefficients are not significantly different from zero at $P > 0.05$.

rainfalls in these GCMs (Fig. 1). The third pattern is the increasing dispersion between the 5th and 95th percentiles of crop yields that increases from 2030 to 2090, with a larger dispersion in 2090 for all the crops and locations (Fig. 8). Large dispersion of crop yield values between the 5th and 95th percentiles in 2090 could relate to higher uncertainty associated with future climate change (Fig. 1, Challinor, 2011). In general, Cunderdin and Katanning (lower rainfall sites) showed the highest yield variation between the 5th and 95th percentiles compared to Hamilton (higher rainfall site). Across all crops, the negative impacts of median crop yield could range from −2 to −10% (wheat yield in 2030–2060) and −20 to −42% in canola and field pea in 2030–2090 compared with baseline, particularly in lower rainfall sites.

A descriptive statistical analysis was conducted, with a linear regression model, for changes in crop yield between 18 GCMs' projected future (2030, 2060 and 2090) rainfall or temperature or simulated phenological events and crop yields as shown in Figs. 5 and 9. The regression provided useful insights into the nature and strength of the relationships. Across all crops and sites, there is an advancement of phenology (i.e., flowering date) which is strongly correlated ($P = 0.001$, Fig. 5) with each Celsius degree increase in future temperature. This advancement of phenology increased progressively from lower rainfall to higher rainfall sites (Table 1). For instance, lupin crop in Cunderdin (low rainfall site) flowered and matured 6 and 5 days, respectively earlier compared to Hamilton (higher rainfall site) of 14 and 9 days (Figs. 3, 4, 5). Likewise, in low rainfall site (Cunderdin), flowering date advanced by 9 days in wheat crop compared to 20 days earlier-flowering in higher rainfall site (Hamilton). In general at all sites except Hamilton (higher rainfall site), the change in grain yield significantly correlated ($P = 0.001$, Fig. 9) with each percentage change in the future rainfall and the impact increased progressively from higher rainfall to lower rainfall sites. For example, for wheat crop in Hamilton (higher rainfall

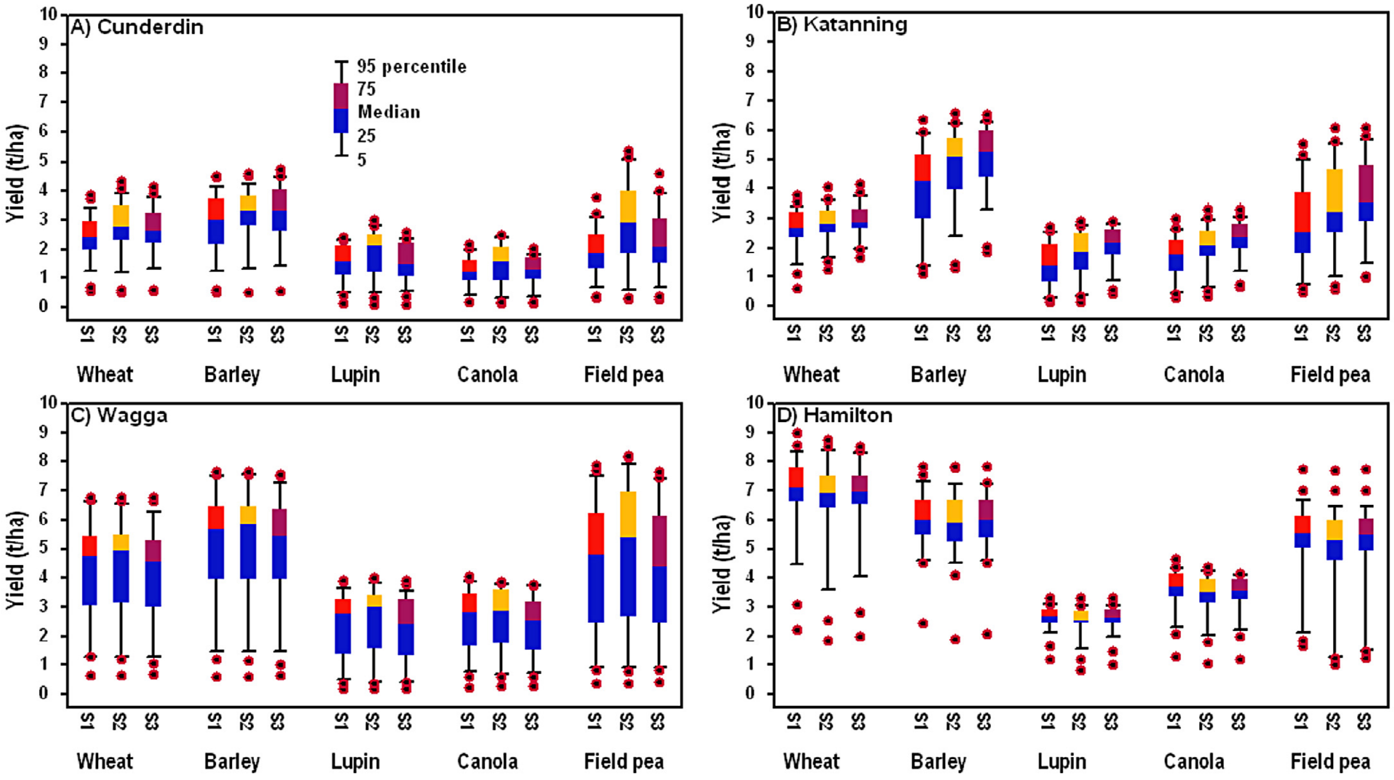

Fig. 6. Box-plot of simulated five winter crop yields in baseline period (1961–2010) on three local soils at four Australian sites.

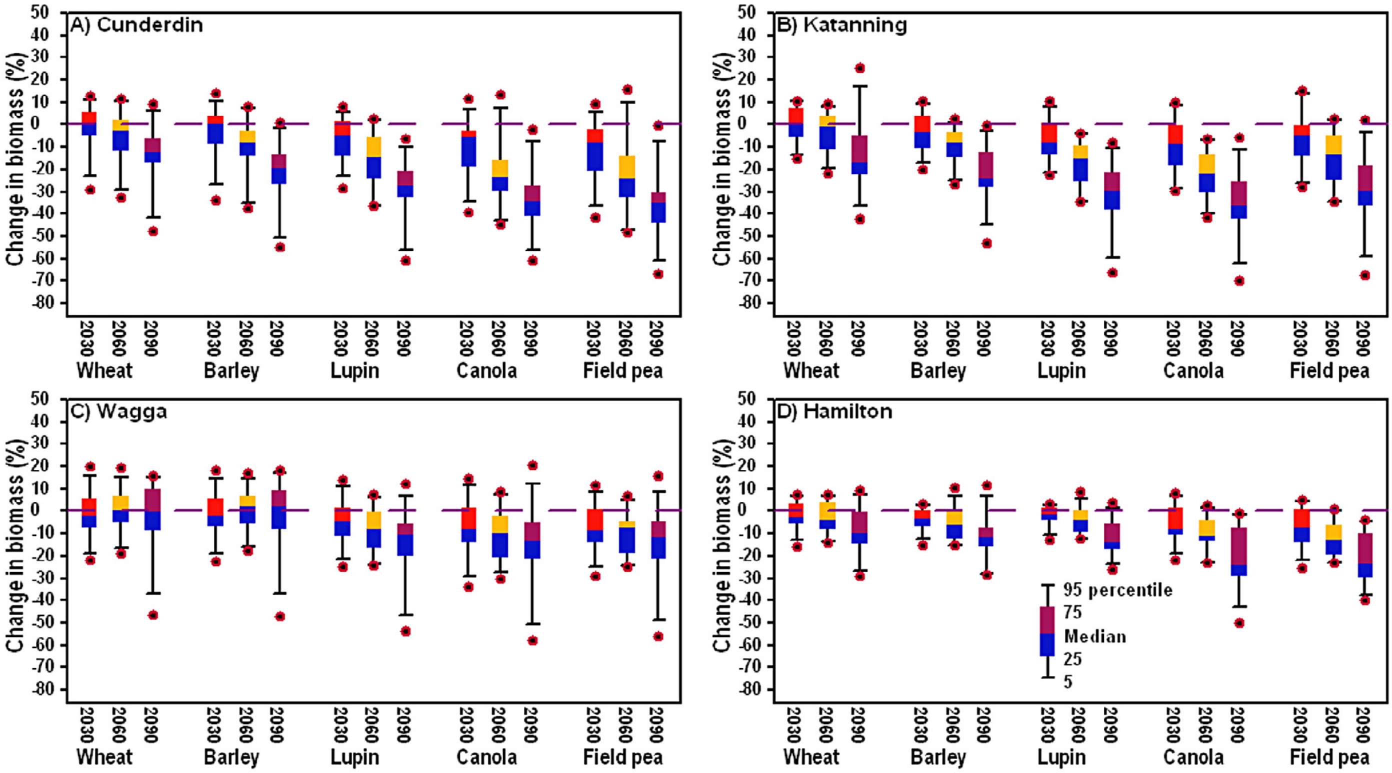

Fig. 7. Box-plot of 18 GCMs' projected changes in biomass of five crops in three periods (2030, 2060, and 2090) at four Australian sites.

site), there is significant 0.50% grain yield changes for each percentage change in rainfall compared to significant 0.90% grain yield changes in Cunderdin (lower rainfall sites). However, the impact is non-significant in barley grain yield due to comparatively higher rainfall at Hamilton than the other sites (Fig. 9). Across all locations and crops, the aggregate impacts are that temperature in the future will significantly reduce the flowering period and the pattern of future rainfall changes shows a significantly robust relationship with grain yield.

4. Discussion

Our simulations of the 1961–2010 baseline period gave yields for five crops that were highest in Hamilton, a high rainfall location, and lowest in Cunderlin, the driest location (Fig. 6). This, and the approximate magnitudes of the yields for all four study locations, was consistent with yields from farm and research trials conducted between 1997 and 2003 (ABARES, 2012; GRDC, 2005). Almost all of our simulations under 2030, 2060 and 2090 climate conditions show decreases in crop yields (Fig. 8) This suggests that adaptation strategies (for example, agronomic management) are needed (Sacks and Kucharik, 2011; Stokes and Howden, 2010). Note, however, that the magnitude of yield decreases is different for different crops and locations.

Although there is a considerable range of uncertainty about the consequences of future climate change for yields (Fig. 8), this analysis of the consequences of future climate change on crops considers two important components simultaneously. First, the impact analysis of climate change in this study compares results for five important broadacre crops (wheat, barley, lupin, canola and field pea) in three different soil types across four locations (Table 1) in Australia. This is in contrast to earlier studies of single crops (Anwar et al., 2007; Asseng and Pannell, 2013; Turner et al., 2011; Yang et al., 2014). Second, this analysis involves statistically downscaled climate projections (Liu and Zuo, 2012) from 18 GCMs. This contrasts with other studies that have used scaling methods for generating future climate data for fewer GCMs (Anwar et al., 2007; Luo et al., 2005).

Comparison of the results from 18 GCMs (Fig. 1) demonstrates significant reduction of rainfall in the range of 3 to 10 percentage by 2030, to as much as 20 percentage (average across the studied locations) by 2090, with the reduction being greater at Katanning, which is in line with previous projections for regions across South-Eastern Australia (Hennessy et al., 2010; Timbal and Jones, 2008). Results from all 18 GCM models suggest consistent increases in annual temperature (Hennessy et al., 2010) from year 2030 to 2090 (Fig. 1). Consequently, future increase of atmospheric CO_2, higher temperatures and reduction in rainfall will affect the rate of plant growth and development (Ludwig and Asseng, 2006; Ludwig et al., 2009; van Ittersum et al., 2003) eventually leading to decline in yields (Fig. 8). Wessolek and Asseng (2006) have also reported yield decline with reduction of rainfall by 20% and by every 1.5 °C increase over average temperature.

The observed variation in year-to-year annual rainfall at the four locations is critical in determining future yields in Australian rainfed broadacre crops, as demonstrated by data summarised in Fig. 6 and reported by van Ittersum et al. (2003); Turner (2004); ABARES (2011, 2013). Interestingly, despite substantial decreases in mean rainfall, the bias corrected downscaled data projected to 2030, 2060 and 2090 show broadly similar coefficient of variation values compared to baseline (1961–2010) (Fig. 1, Liu and Zuo, 2012). The projected progressive reduction in rainfall progressively impacted future broadacre crop yields (Figs. 6 and 8). For wheat, Yang et al. (2014) show similar results. Across all five crops and locations, we observed significantly strong associations ($P = 0.05$ to $P = 0.001$) between grain yield and changes in rainfall (Fig. 9) but not at Hamilton for barley due to higher annual rainfall compared to other

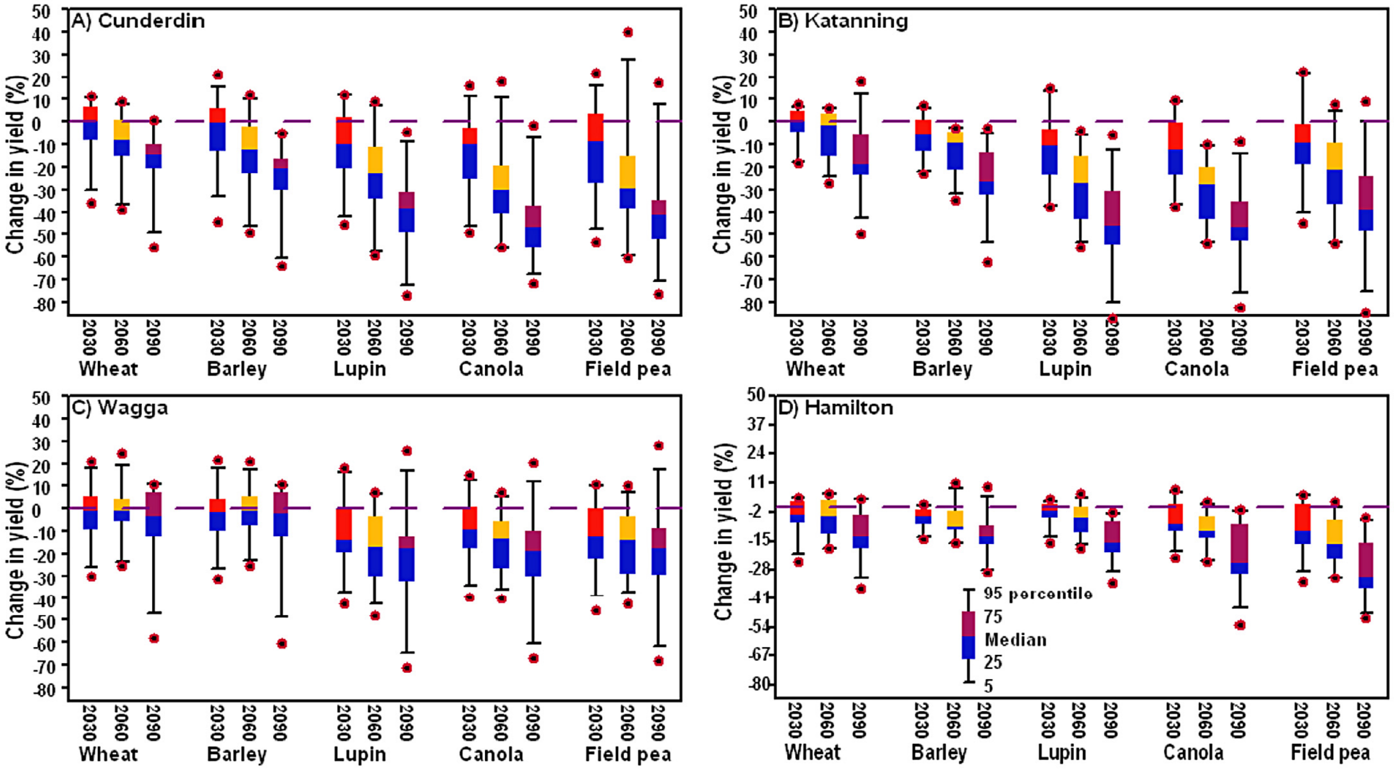

Fig. 8. Box-plot of 18 GCMs' projected changes in crop yield of five crops in three periods (2030, 2060, and 2090) at four Australian sites.

locations. Generally, high rainfall variability accompanied by projected reduction on annual rainfall will have a large influence on plant available soil water content (SWC) (Tsubo et al., 2007; Turner, 2004), and, in turn, impact crop yields. Wang et al. (2009) reported that in South-East Australia, decreases in rainfall will reduce growing season evapotranspiration and eventually reduce yields, with implications for adaptation strategies. Some examples of adaptation available to growers include practices that maintain SWC, such as row spacing, reduced tillage, fallows, rotations and irrigation (Stokes and Howden, 2010; Wheeler et al., 2013).

We observed significant hastening of crop phenology (Figs. 2–4) in both baseline and projected future climates, which is often a reason for reduction in crop yields (Sadras and Monzon, 2006; Yang et al., 2014). The duration from sowing to flowering and maturity time are critical phenological stages (Sacks and Kucharik, 2011) and there is a positive correlation between the length of photosynthetic activity and the time spent on grain filling and eventual grain yield (Bidinger et al., 1977; Gebbing et al., 1999). Results also show that the timing of flowering is negatively correlated ($P = 0.001$) with changes in temperature across all five crops and locations (Fig. 5). This implies environmental conditions may lead to a hastening of crop development eventually causing yield decline (Asseng et al., 2004; Ludwig and Asseng, 2010; Porter and Semenov, 2005). Moreover, flowering time and maturity period are important phenological traits for adaptation to climate change. Indeed, researchers often manipulate these traits, so as to make the pre and post-anthesis assimilation coincide with a high photothermal quotient, thus enhancing grain yields (Lobell et al., 2012; Long et al., 2006; Stokes and Howden, 2010). For farming systems with growing season conditions that, in the future, are expected to have lower rainfall, higher temperatures and raised atmospheric CO_2, the pattern of plant development will be altered as a consequence of reduced plant available soil water and high-temperature stress. As the phenological responses of crops to a more hostile climate will vary between

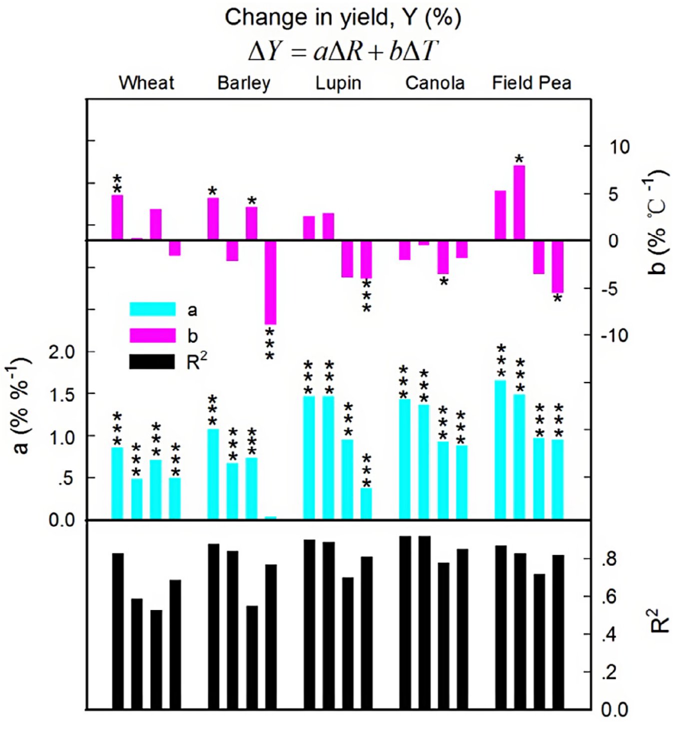

Fig. 9. Regression analysis of the impact rates of climate change on grain yield (Y) in wheat, barley, lupin and field pea at Cunderdin, Katanning, Wagga and Hamilton as abbreviated to be C, K, W and H, respectively. The change rates (ΔY) as functions of the change in rainfall (ΔR) and temperature (ΔT) are shown in the respective figure. The bars with *, ** and *** indicate the significant levels at $P = 0.05$, $P = 0.01$ and $P = 0.001$, respectively; otherwise, the coefficients are not significantly different from zero at $P > 0.05$.

species so will their yields (Amthor, 2000; Drake et al., 1997; Lobell et al., 2013).

The negative impact of climate change in this study is consistent with other studies (Anwar et al., 2007; Asseng et al., 2004; Lobell and Field, 2007; Turner et al., 2011). For example, Asseng et al. (2004) reported that increasing average temperature by 1.7 °C resulted in earlier flowering (by 11 days) which eventually led to decline in both total biomass and grain yield in wheat crop. Similarly, Lobell et al. (2013) indicated a reduction of 17 days in growing season length for an increase of 2 °C increase causing a yield decline of 13% in a maize crop. Results also show that there is a large variation in yields between current and future climate conditions and across locations and crops (Figs. 6 and 8) and this implies crop species have differing sensitivities to climatic variations (Huntingford et al., 2005). For example, this study suggests field peas are more sensitive to changes in climate, than cereals or canola. The ensemble median changes in field pea yield range from at least a decrease of 12% in 2030 to up to a decrease of 45% in 2090. In contrast, the ensemble median changes in wheat yield range from at least a decrease of 5% in 2030 to up to a decrease of 30% in 2090. However, when viewed from a national perspective, the disproportionally larger impact of climate change on the yield of field peas is likely to be less economically significant than the impact on cereals. This is due to the volume of field pea production only being ~1% of the combined volume of wheat, barley and canola in the last five years (ABARES, 2013).

Change in climate results in a different response in the growth and development of each crop species due to interspecies variation in temperature requirement for achieving certain phenological stages (Craufurd and Wheeler, 2009; Fuhrer, 2003; Mitter et al., 2013). Future climatic conditions (Fig. 1) with warmer temperatures and reduced rainfall will induce large enough shifts to offset future crop yields that mediate through disruption of phenological synchrony (Wheeler et al., 2000). Additionally, analyses of climate–yield relationships (Fig. 9) suggest that in all locations rainfall is the primary climate change threat to future crop yield, while increasing temperature is secondary (Sinclair, 2011; Turner, 2004). This emphasises the importance and urgency of the requirement of the grain industry to find or gain access to genetic and agronomic innovations that can address the negative impact of the adverse changes in the climate of the growing seasons which crucially determine broadacre crop yields. Findings reported here may be important in informing adaptation strategies, such as maintaining or increasing soil water reserves so as to ensure adequate water availability to sustain profitable crop yields (Sinclair, 2011).

Annual broadacre grain yields vary according to influence of agroclimatic and edaphic conditions as well as genetic attributes and crop management (Monfreda et al., 2008; Ramankutty et al., 2008). Furthermore, at any particular location, productivity and profitability of a crop is determined by not only changes in prices and cost of production but also the changes in climate such as seasonal distribution of rainfall and temperature (Gornall et al., 2010). Quantifying the potential impacts of future climate change on the yield of major field crops for a specified location provides useful insights that can inform policy formulation, provide direction and help for prioritising research, reform crop management practices, and thus sustain agricultural production and reduce vulnerability in the future (Challinor et al., 2014; Roudier et al., 2011).

5. Conclusion

Our methodology involves output of 18 Global Climate Models projecting locally by bias corrected statistical downscaling to predict the possible effects of climate change on broadacre crop yields (wheat, barley, lupin, canola, field pea) in Western and South-Eastern Australia. Projected annual rainfall can decrease by 9%, 16% and 26% in 2030, 2060 and 2090 respectively, and rainfall amount is critical in determining crop yields but, equally, higher future temperatures can reduce crop productivity primarily due to advanced crop phenology. Our study shows that, for a wheat crop at Hamilton (higher rainfall site), there is a significant advancement in median flowering date for 2030, 2060, and 2090 of 10, 18, and 29 days respectively with a significant 0.50% grain yield changes for each percentage change in rainfall compared to significant 0.90% grain yield changes in Cunderdin (lower rainfall sites). Field peas are more sensitive to changes in climate, 12% to 45% declines in yield between current and future climates, than cereals or canola. Overall, the impact of climate change on broadacre crops will be negative (3 to 20% yield loss) in the short term (2030), but increasingly detrimental with time (potential yield losses reaching 42% for some crops by 2090). Given this impact of declining projected rainfall and higher temperatures in the future, it is important that policies and adaptation strategies are aimed at dealing with these climatic shifts. Depending on crop species, climate impact assessment suggest adaptation strategies that covers advances in agronomy, soil moisture conservation, seasonal climate forecast and breeding to combat the negative consequences of predicted climate change at these locations.

Acknowledgments

The authors acknowledge financial support provided by the Australian Government (Department of Climate Change and Energy Efficiency), the National Climate Change Adaptation Research Facility, NSW Department of Primary Industry and the ARC Centre of Excellence for Climate System Science (grant CE110001028). We 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 CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

References

ABARES, 2011. The impact of recent flood events on commodities. ABARES Special Report, Canberra. <http://www.daff.gov.au/abares/Pages/Default.aspx>.
ABARES, 2012. Agricultural commodity statistics 2012. Australian Bureau of Agricultural and Resource Economics and Sciences, December, Canberra. <http://www.daff.gov.au/abares/Pages/Default.aspx>.
ABARES, 2013. Australian crop report. Australian Bureau of Agricultural and Resource Economics and Sciences, Department of Agriculture, Fisheries and Forestry, Canberra, June, No. 166. <http://daff.gov.au/abares/publications>.
Alexandrov, V., Eitzinger, J., Cajic, V., Oberforster, M., 2002. Potential impact of climate change on selected agricultural crops in north-eastern Austria. Glob. Chang. Biol. 8, 372–389.
Amthor, J.S., 2000. The Mccree-de Wit-Penning de Vries-Thornley respiration paradigms: 30 years later. Ann. Bot. 86, 1–20.
Anandhi, A., Frei, A., Pierson, D.C., Schneiderman, E.M., Zion, M.S., Lounsbury, D., et al., 2011. Examination of change factor methodologies for climate change impact assessment. Water Resour. Res. 47, W03501. doi:10.1029/2010WR009104.
Anwar, M.R., O'Leary, G., McNeil, D., Hossain, H., Nelson, R., 2007. Climate change impact on wheat crop yield and adaptation options in Southeastern Australia. Field Crop. Res. 104, 139–147.
Anwar, M.R., Liu, D.L., Macadam, I., Kelly, G., 2013. Adapting agriculture to climate change: a review. Theor. Appl. Climatol. (113), 225–245. doi:10.1007/s00704-012-0780-1.
Asseng, S., Pannell, D.J., 2013. Adapting dryland agriculture to climate change: farming implications and research and development needs in Western Australia. Clim. Change 118, 167–181. doi:10.1007/s10584-012-0623-1.
Asseng, S., Jamieson, P.D., Kimball, B., Pinter, P., Sayre, K., Bowden, J.W., et al., 2004. Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO2. Field Crop. Res. 85, 85–102.
Bassu, S., Asseng, S., Richards, R., 2011. Yield benefits of triticale traits for wheat under current and future climates. Field Crop. Res. 124, 14–24.
Beniston, M., Stephenson, D.B., Christensen, O.B., Ferro, C.A.T., Frei, C., Goyette, S., et al., 2007. Future extreme events in European climate-an exploration of regional climate model projections. Clim. Change 81, 71–95. doi:10.1007/s10584-006-9226-z.
Betts, R.A., 2005. Integrated approaches to climate-crop modelling: needs and challenges. Philos. Trans. R. Soc. B 360, 2049–2065. doi:10.1098/rstb.2005.1739.

Betts, R.A., Collins, M., Hemming, D.L., Jones, C.D., Lowe, J.A., Sanderson, M.G., 2011. When could global warming reach 4°C? Philos. Trans. R. Soc. A 369, 67–84. doi:10.1098/rsta.2010.0292.

Bidinger, F., Musgrave, R.B., Fischer, R.A., 1977. Contribution of stored pre-anthesis assimilate to grain yield in wheat and barley. Nature 270, 431–433. doi:10.1038/270431a0.

Cai, W., Cowan, T., 2008. Dynamics of late autumn rainfall reduction over southeastern Australia. Geophys. Res. Lett. 35 (L09708), 1–5. doi:10.1029/2008GL033727.

Challinor, A., 2011. Agriculture: forecasting food. Nat. Clim. Chang. 1, 103–104. doi:10.1038/nclimate1098.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Chang. 4, 287–291. doi:10.1038/nclimate2153.

Chen, W., Robertson, M., Lingling, L., Bellotti, W., French, R., Bell, R., 2008. Simulation of field pea growth and yield in diverse environments. In: Proceedings of 14th Australian Agronomy Conference. <http://www.regional.org.au/au/asa/2008/poster/agronomy-landscape/5824_wenchen.htm>.

Craufurd, P.Q., Wheeler, T.R., 2009. Climate change and the flowering time of annual crops. J. Exp. Bot. 60, 2529–2539. doi:10.1093/jxb/erp196.

Crimp, S., Howden, M., Power, B., Wang, E., De Voil, P., 2008. Global Climate Change Impacts on Australia's Wheat Crops, Report Prepared for the Garnaut Climate Change Review. CSIRO, Canberra.

CSIRO and BoM, 2007. Climate change in Australia. In: Pearce, K.B., Holper, P.N., Hopkins, M., Bouma, W.J., Whetton, P.H., Hensessy, K.J., et al. (Eds.), Technical Report, 2007. CSIRO. 148pp.

CSIRO and BoM, 2010. State of the Climate – 2010. <http://www.csiro.au/resources/State-of-the-Climate>.

CSIRO and BoM, 2012. State of the Climate – 2012. <http://www.csiro.au/resources/State-of-the-Climate>.

de Wit, C.T., van Keulen, H., 1987. Modelling production of field crops and its requirements. Geoderma 40, 253–265.

Dogliotti, S., García, M.C., Peluffo, S., Dieste, J.P., Pedemonte, A.J., Bacigalupe, G.F., et al., 2014. Co-innovation of family farm systems: a systems approach to sustainable agriculture. Agric. Syst. 126, 75–85.

Drake, B.G., Gonzàlez-Meler, M.A., Long, S.P., 1997. More efficient plants: a consequence of rising atmospheric CO2? Annu. Rev. Plant Physiol. Plant Mol. Biol. 48, 609–639.

Eric, P., Salathe, J.R., 2003. Comparison of various precipitation downscaling methods for the simulation of streamflow in a rainshadow river basin. Int. J. Climatol. 23, 887–901.

Farré, I., Robertson, M.J., Walton, G.H., Asseng, S., 2000. Simulating response of canola to sowing date in Western Australia. In: Proceedings of the 10th Australian Agronomy Conference. <http://www.regional.org.au/au/asa/2001/6/d/farrel.htm>.

Farré, I., Robertson, M.J., Asseng, S., French, R.J., Dracup, M., 2004. Simulating lupin development, growth, and yield in a Mediterranean environment. Aust. J. Agric. Res. 55, 863–877. http://dx.doi.org/10.1071/AR04027.

Folland, C.K., Karl, T.R., Christy, J.R., Clarke, R.A., Gruza, G.V., Jouzel, J., et al., 2001. Observed climate variability and change. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., et al. (Eds.), Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 881pp.

Fuhrer, J., 2003. Agroecosystem responses to combinations of elevated CO2, ozone, and global climate change. Agric. Ecosyst. Environ. 97, 1–20. doi:10.1016/S0167-8809(03)00125-7.

Gebbing, T., Schnyder, H., Kuhbauch, W., 1999. The utilization of pre-anthesis reserves in grain filling of wheat: assessment by steady-state 13CO2/12CO2 labelling. Plant Cell Environ. 22, 851–858.

Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K., et al., 2010. Implications of climate change for agricultural productivity in the early twenty-first century. Philos. Trans. R. Soc. B 365, 2973–2989. doi:10.1098/rstb.2010.0158.

GRDC, 2005. Field Pea: Western NSW Planting Guide. Pulse Australia, Grain Research & Development Corporation. <http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/157507/field-pea-western-NSW-planting-guide.pdf>.

Hayman, P., Rickards, L., Eckard, R., Lemerle, D., 2012. Climate change through the farming systems lens: challenges and opportunities for farming in Australia. Crop Pasture Sci. 63, 203–214.

Heenan, D.P., Taylor, A.C., Cullis, B.R., Lill, W.J., 1994. Long term effect of rotation, tillage and stubble management on wheat production in southern NSW. Aust. J. Agric. Res. 45, 93–117.

Hennessy, K., Fitzharris, B., Bates, B.C., Harvey, N., Howden, S.M., Hughes, L., et al. 2007. Australia and New Zealand. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 507–540.

Hennessy, K.J., Whetton, P.H., Preston, B., 2010. Climate projections. In: Stokes, C., Howden, M. (Eds.), Adapting Agriculture to Climate Change: Preparing Australian Agriculture, Forestry and Fisheries for the Future. CSIRO, Collingwood, Victoria, Australia, pp. 13–20.

Hunt, J.R., Kirkegaard, J.A., 2011. Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. Crop Pasture Sci. 62, 915–929.

Huntingford, C., Lambert, F.H., Gash, J.H.C., Taylor, C.M., Challinor, A.J., 2005. Aspects of climate change prediction relevant to crop productivity. Philos. Trans. R. Soc. B 360, 1999–2009. doi:10.1098/rstb.2005.1748.

Iizumi, T., Sakuma, H., Yokozawa, M., Luo, J., Challinor, A.J., Brown, M.E., et al., 2013. Prediction of seasonal climate-induced variations in global food production. Nat. Clim. Chang. 3, 904–908. doi:10.1038/nclimate1945.

Ines, A.V.M., Hansen, J.W., 2006. Bias correction of daily GCM rainfall for crop simulation studies. Agric. For. Meteorol. 138, 44–53.

IPCC, 2001. Summary for policymakers. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Van Der Linden, P.J., Xioaosu, D. (Eds.), Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. 944 pp.

IPCC, 2007. Climate change 2007: impacts, adaptation and vulnerability. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK. 976pp.

Isbell, R.F., 2002. The Australian Soil Classification, Revised Edition. CSIRO Publishing, Melbourne.

Jeffrey, S.J., Carter, J.O., Moodie, K.M., Beswick, A.R., 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environ. Model. Softw. 16, 309–330.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., et al., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288.

Laurent, R., Cai, X., 2007. A maximum entropy method for combining AOGCMs for regional intra-year climate change assessment. Clim. Chang. 82, 411–435.

Liu, D.L., Zuo, H., 2012. Statistical downscaling of daily climate variables for climate change impact assessment over New South Wales, Australia. Clim. Change 115, 629–666. doi:10.1007/s10584-012-0464-y.

Lobell, D.B., 2013. Errors in climate datasets and their effects on statistical crop models. Agric. For. Meteorol. 170, 58–66.

Lobell, D.B., Field, C.B., 2007. Global scale climate-crop yield relationships and the impacts of recent warming. Environ. Res. Lett. 2, 014002. doi:10.1088/1748-9326/2/1/014002.

Lobell, D.B., Sibley, A., Ortiz-Monasterio, J.I., 2012. Extreme heat effects on wheat senescence in India. Nat. Clim. Chang. 2, 186–189. doi:10.1038/NCLIMATE1356.

Lobell, D.B., Hammer, G.L., McLean, G., Messina, C., Roberts, M.J., Schlenker, W., 2013. The critical role of extreme heat for maize production in the United States. Nat. Clim. Chang. 3, 497–501. doi:10.1038/nclimate1832.

Long, S.P., Zhu, X.-G., Naidu, S.L., Ort, D.R., 2006. Can improvement in photosynthesis increase crop yields? Plant Cell Environ. 29, 315–330. doi:10.1111/j.1365-3040.2005.01493.x.

Ludwig, F., Asseng, S., 2006. Climate change impacts on wheat production in a Mediterranean environment in Western Australia. Agric. Syst. 90, 159–179.

Ludwig, F., Asseng, S., 2010. Potential benefits of early vigor and changes in phenology in wheat to adapt to warmer and drier climates. Agric. Syst. 103, 127–136.

Ludwig, F., Milroy, S.P., Asseng, S., 2009. Impacts of recent climate change on wheat production systems in Western Australia. Clim. Change 92, 492–517.

Luo, Q.Y., Bellotti, W., Williams, M., Bryan, B., 2005. Potential impact of climate change on wheat yield in South Australia. Agric. For. Meteorol. 132, 273–285.

Maraun, D., Wetterhall, F., Ireson, A.M., Chandler, R.E., Kendon, E.J., Widmann, M., et al., 2010. Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user. Rev. Geophys. 48, RG3003. doi:10.1029/2009RG000314.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., Freebairn, D.M., 1996. APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. Agric. Syst. 50, 255–271.

Mearns, L.O., Rosenzweig, C., Goldberg, R., 1996. The effects of changes in daily and interannual climatic variability on CERES-Wheat: a sensitivity study. Clim. Change 32, 257–292.

Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., et al., 2007a. The WCRP CMIP3 multi-model dataset: a new era in climate change research. Bull. Am. Meteorol. Soc. 88, 1383–1394.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., et al., 2007b. Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., et al. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. <http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter10.pdf>.

Mitter, H., Sinabell, F., Schmid, E., 2013. Assessing climate change and policy impacts on protein crop production in Austria. In: Proceedings of the Impacts World 2013, International Conference on Climate Change Effects. <http://www.climate-impacts-2013.org/files/wism_mitter.pdf>.

Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem. Cycles 22, GB1022. doi:10.1029/2007 GB002947.

Nakićenović, N., Swart, R. (Eds.), 2000. Special Report on Emissions Scenarios. Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., et al., 2011. Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34, 96–112.

Ozdogan, M., 2011. Modeling the impacts of climate change on wheat yields in Northwestern Turkey. Agric. Ecosyst. Environ. 141, 1–12.

Planfarm-Bankwest, 2011. 2011 Planfarm Bankwest Benchmarks Survey. <http://www.bankwest.com.au/media-center/media-releases/2011-planfarm-bankwest-benchmarks-survey-1292483721448>.

Porter, J.R., Semenov, M.A., 2005. Crop responses to climatic variation. Philos. Trans. R. Soc. B 360, 2021–2035.

Potgieter, A., Meinke, H., Doherty, A., Sadras, V.O., Hammer, G., Crimp, S., et al., 2013. Spatial impact of projected changes in rainfall and temperature on wheat yields in Australia. Clim. Change 117, 163–179. doi:10.1007/s10584-012-0543-0.

Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochem. Cycles 22, GB1003. doi:10.1029/2007 GB002952.

Ramirez-Villegas, J., Challinor, A., 2012. Assessing relevant climate data for agricultural applications. Agric. For. Meteorol. 161, 26–45.

Randall, D.A., Wood, R.A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., et al., 2007. Climate models and their evaluation. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., et al. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge UK, pp. pp589–pp662.

Reilly, J., Tubiello, F., McCarl, B., Abler, D., Darwin, R., Fuglie, K., et al., 2003. U.S. agriculture and climate change: new results. Clim. Change 57, 43–69. doi:10.1023/A:1022103315424.

Reyenga, P.J., Howden, S.M., Meinke, H., McKeon, G.M., 1999. Modelling global change impacts on wheat cropping in south-east Queensland, Australia. Environ. Model. Softw. 14, 297–306.

Richardson, C.W., Wright, D.A., 1984. WGEN: A Model for Generating Daily Weather Variables. U. S. Department of Agriculture, Agricultural Research Service, ARS-8. 83pp. <ftp://ftp.biosfera.dea.ufv.br/users/francisca/Franciz/papers/Richardson%20&%20Wright.pdf>.

Robertson, A.W., Ines, A.V.M., Hansen, J.W., 2007. Downscaling of seasonal precipitation for crop simulation. J. Appl. Meteor. Climatol. 46, 677–693. http://dx.doi.org/10.1175/JAM2495.1.

Robertson, M.J., Kirkegaard, J.A., 2005. Water-use efficiency of dryland canola in an equi-seasonal rainfall environment. Aust. J. Agric. Res. 56, 1373–1386. http://dx.doi.org/10.1071/AR05030.

Robertson, M.J., Carberry, P.S., Huth, N.I., Turpin, J.E., Probert, M.E., Poulton, P.L., et al., 2002. Simulation of growth and development of diverse legume species in APSIM. Aust. J. Agric. Res. 53, 429–446.

Rodríguez, D., Cox, H., deVoil, P., 2014. A participatory whole farm modelling approach to understand impacts and increase preparedness to climate change in Australia. Agric. Syst. 126, 49–60.

Roudier, P., Sultan, B., Quirion, P., Berg, A., 2011. The impact of future climate change on West African crop yields: what does the recent literature say? Global Environ. Chang. 21, 1073–1083.

Sacks, W.J., Kucharik, C.J., 2011. Trends in crop management and phenology in the U.S. corn belt, and impacts on yields, evapotranspiration, and energy balance. Agric. For. Meteorol. 151, 882–894. doi:10.1016/j.agrformet.2011.02.010.

Sadras, V.O., Monzon, J.P., 2006. Modelled wheat phenology captures rising temperature trends: shortened time to flowering and maturity in Australia and Argentina. Field Crop. Res. 99, 136–146.

Sinclair, T.R., 2011. Precipitation: the thousand-pound gorilla in crop response to climate change. In: Hillel, D., Rosenzweig, C. (Eds.), Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation. Imperial College Press, pp. 179–190.

Smith, I.N., McIntosh, P., Ansell, T.J., Reason, C.J.C., McInnes, K., 2000. Southwest Western Australian winter rainfall and its association with Indian Ocean climate variability. Int. J. Climatol. 20, 1913–1930. doi:10.1002/1097-0088(200012).

Soussana, J.F., Graux, A.-I., Tubiello, F.N., 2010. Improving the use of modelling for projections of climate change impacts on crops and pastures. J. Exp. Bot. 61, 2217–2228. doi:10.1093/jxb/erq100.

Stockle, C.O., Nelson, R., 2001. Cropping System Simulation Model User's Manual. Biological Systems Engineering Department. Washington State University. <http://www.bsyse.wsu.edu/cropsyst/>.

Stokes, C., Howden, M. (Eds.), 2010. Adapting Agriculture to Climate Change: Preparing Australian Agriculture, Forestry and Fisheries for the Future. CSIRO Publication, Collingwood VIC, Australia. 286pp.

Timbal, B., Jones, D., 2008. Future projections of winter rainfall in southeast Australia using a statistical downscaling technique. Clim. Change 86, 165–187.

Timbal, B., Hope, P., Charles, S., 2008. Evaluating the consistency between statistically downscaled and global dynamical model climate change projections. J. Climate 21, 6052–6059.

Tsubo, M., Fukai, S., Tuong, T.P., Ouk, M., 2007. A water balance model for rainfed lowland rice fields emphasising lateral water movement within a toposequence. Ecol. Model. 204, 503–515. doi:10.1016/j.ecolmodel.2007.02.001.

Tubiello, F.N., Rosenzweig, C., Goldberg, R.A., Jagtap, S., Jones, J.W., 2002. Effects of climate change on US crop production: simulation results using two different GCM scenarios. Part I: wheat, potato, maize, and citrus. Clim. Res. 20, 259–270.

Turner, N.C., 2004. Agronomic options for improving rainfall-use efficiency of crops in dryland farming systems. J. Exp. Bot. 55, 2413–2425.

Turner, N.C., Molyneux, N., Yang, S., Xiong, Y.C., Siddique, K.H.M., 2011. Climate change in south-west Australia and north-west China: challenges and opportunities for crop production. Crop Pasture Sci. 62, 445–456.

van Ittersum, M.K., Howden, S.M., Asseng, S., 2003. Sensitivity of productivity and deep drainage of wheat cropping systems in a Mediterranean environment to changes in CO2 temperature and precipitation. Agric. Ecosyst. Environ. 97, 255–273.

van Roosmalen, L., Sonnenborg, T.O., Jensen, K.H., 2009. Impact of climate and land use change on the hydrology of a large-scale agricultural catchment. Water Resour. Res. 45, 25 W00A15. doi:10.1029/2007WR006760.

Wang, E., Cresswell, H., Xu, J., Jiang, Q., 2009. Capacity of soils to buffer impact of climate variability and value of seasonal forecasts. Agric. For. Meteorol. 149, 38–50.

Wang, J., Wang, E., Liu, D.L., 2011. Modelling the impacts of climate change on wheat yield and field water balance over the Murray–Darling Basin in Australia. Theor. Appl. Climatol. 104, 285–300. doi:10.1007/s00704-010-0343-2.

Wessolek, G., Asseng, S., 2006. Trade-off between wheat yield and drainage under current and climate change conditions in northeast Germany. Eur. J. Agron. 24, 333–342.

Wheeler, S., Zuo, A., Bjornlund, H., 2013. Farmers' climate change beliefs and adaptation strategies for a water scarce future in Australia. Global Environ. Chang. 23, 537–547.

Wheeler, T.R., Craufurd, P.Q., Ellis, R.H., Porter, J.R., Prasad, P.V.V., 2000. Temperature variability and the yield of annual crops. Agric. Ecosyst. Environ. 82, 159–167.

White, J.W., Hoogenboom, G., Kimball, B.A., Wall, G.W., 2011. Methodologies for simulating impacts of climate change on crop production. Field Crop. Res. 124, 357–368.

World Bank, 2012. Turn down the heat: why a 4°C warmer world must be avoided. 1818 H Street NW Washington, DC 20433. <www.worldbank.org>.

World Bank, 2013. Turn down the heat: climate extremes, regional impacts, and the case for resilience. 1818 H Street NW Washington, DC 20433. <www.worldbank.org>.

Yang, Y., Liu, D.L., Anwar, M.R., Zuo, H., Yang, Y., 2014. Impact of future climate change on wheat production in relation to plant-available water capacity in a semiarid environment. Theor. Appl. Climatol. 115, 391–410. doi:10.1007/s00704-013-0895-z.

Yunusa, I.A.M., Bellotti, W.D., Moore, A.D., Probert, M.E., Baldock, J.A., Miyan, S.M., 2004. An exploratory evaluation of APSIM to simulate growth and yield processes for winter cereals in rotation systems in South Australia. Aust. J. Exp. Agric. 44, 787–800. http://dx.doi.org/10.1071/EA03121.

Zeleke, K.T., Anwar, M., Liu, D.L., 2014. Managing crop stubble during fallow period for soil water conservation: field experiment and modelling. Environ. Earth Sci. doi:10.1007/s12665-014-3235-4.

Zhang, X., Cai, X., 2013. Climate change impacts on global agricultural water deficit. Geophys. Res. Lett. 40, 1111–1117. doi:10.1002/grl.50279.