

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

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26

1 **Abstract**

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

34

35 **Keywords:** Crops, climate change, GCM, APSIM, yield, phenology

36

1. Introduction

Since the 1960's, a major driver of crop yield stability in Western and Southern Australia (WSA) has been the observed decline in winter rainfall (Smith et al., 2000; Cai and Cowan, 2008; Stokes and Howden, 2010). In WSA, increasing atmospheric carbon dioxide (CO₂) 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; Sinclair, 2011; CSIRO and BoM, 2007-2012). Therefore, a major concern arises for the long-term productivity and sustainability of dry land broad acre cropping systems under future climate conditions (Stokes and Howden, 2010; Anwar et al., 2013; Challinor et al., 2014; Rodriguez et al., 2014). 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; Dogliotti et al., 2014; Challinor et al., 2014). The effects of climate change are likely to exacerbate high natural climatic variability on broadacre crop production systems in semi-arid environments in Australia (IPCC, 2007; Hayman et al., 2012). The intensive rain fed farming systems of WSA are climatically sensitive, as demonstrated by the significant fluctuations in regional crop yields in dry and wet years (Hennessy et al., 2007; ABARES, 2013). 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 (Stokes and Howden, 2010; Challinor et al., 2014). 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 (van Ittersum et al., 2003; Ludwig and Asseng, 2006; Anwar et al., 2007; Crimp et al., 2008; Basu et al., 2011; Wang et al., 2011; Potgieter et al., 2013; 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 (van Ittersum et al., 2003; Ludwig and

1 Asseng, 2006; Yang et al., 2014) can be attributed to reductions in rainfall in the projected
2 climates. The relevant research has demonstrated that the major constraints to rain fed
3 cropping include crop type, agronomy, climate, and soil type (Olesen et al., 2011; White et
4 al., 2011; Iizumi et al., 2013). Climate change constitutes the major exogenous shock to
5 which adaptation responses specific for crop type, soil type and agronomy would be
6 required. In this article, five important broad acre crops in Western and South- Eastern
7 Australia are considered. These include wheat (*Triticum aestivum* L), barley (*Hordeum*
8 *vulgare* L), lupins (*Lupinus angustifolius*), canola (*Brassica napus* L) and field peas (*Pisum*
9 *sativum*).

10

11 Impact assessments of climate change on agricultural crops often use climate scenarios
12 (Nakićenović and Swart, 2000) developed by downscaling Global Climate Model (GCM)
13 predictions to a region of interest (e.g., Ines and Hansen, 2006; Robertson et al., 2007; Betts
14 et al., 2011), and these are crucial for planning adaptation strategies (Stokes and Howden
15 2010; Anwar et al., 2013; Rodriguez et al., 2014). The resulting climate scenarios are used
16 as inputs to drive process-oriented crop simulation models for impact assessment (Tubiello
17 et al., 2002; Alexandrov et al., 2002; Reilly et al., 2003; Betts, 2005; Ozdogan, 2011;
18 Lobell, 2013). Most crop simulation models require daily climate data (de Wit and van
19 Keulen, 1987; Stockle and Nelson, 2001; Keating et al., 2003; Soussana et al., 2010).
20 However, one of the unpredictable aspects of climate change is the future amount of annual
21 rainfall and how it will be distributed during the growing seasons (Folland et al., 2001;
22 Ramirez-Villegas and Challinor, 2012). Different GCM can provide different future
23 projections for a particular region (Laurent and Cai, 2007; Zhang and Cai, 2013).
24 Moreover, GCM grid-cell estimates over the studied land surfaces may be influenced by
25 the radiative forcing of the climate system (Mearns et al., 1996; Eric and Salathe, 2003;
26 Randall et al., 2007). GCM grid-cells typically have coarse spatial resolutions of
27 hundreds of kilometre. Such estimates in combination with different emission scenarios
28 and uncertainty originating from the choice of GCMs (Nakićenović and Swart, 2000; Ines
29 and Hansen, 2006; Beniston et al., 2007), can result in over or underestimated rainfall
30 amounts that may not be applicable to future climates at regional scales (Randall et al.,
31 2007; World Bank, 2012, 2013). There is also a diversity of approaches and methods
32 available for making future climate projections, including anomalies, variable corrections,
33 climate change factors, scaling, empirical relationships, and statistical downscaling (e.g.,
34 Ines and Hansen, 2006; Randall et al., 2007; Anwar et al., 2007; Timbal et al., 2008;

1 Maraun et al., 2010; Liu and Zuo, 2012). Commonly numerical models or statistical
2 relationships are used to develop future climate projections based on historical climate
3 records. This is done in conjunction with GCM grid-cell spatial average values over the
4 land surfaces being studied (Mearns et al., 1996; IPCC, 2001; Randall et al., 2007).

5
6 When we use best-practice climate downscaling for individual Australian locations, how
7 do the climate sequences compare with the historical record in terms of distributions of key
8 variables? This paper provides the first location-level estimates of projected climate in
9 three time periods spanning from the present to 2030, 2060 and 2090. Our analysis
10 considers four important broadacre crop growing regions in Australia by applying a
11 statistically downscaled bias correction method (Liu and Zuo, 2012) involving 18 GCMs
12 under the A2 emission scenario (Nakićenović and Swart, 2000). Other objectives of this
13 study were to quantify the impact of climate scenarios (2030, 2060 and 2090) on yield and
14 phenological variations of five important broadacre crops (wheat, barley, lupin, canola,
15 field pea) grown in three different soil types and these results can be an important basis for
16 adaptations.

17 18 **2. Materials and Methods**

19 20 *2.1 Study sites and climate*

21 The effects of current climate (1961-2010) and future climate scenarios (2030, 2060 and
22 2090) on five important broadacre crops (wheat, barley, lupin, canola and field pea) in four
23 locations of Australian dryland farming systems were selected for this study (Table 1). The
24 locations of Cunderdin and Katanning in Western Australia have a Mediterranean-type
25 climate, characterised by hot, dry summers and cool, wet winters receiving average annual
26 rainfall of 359 and 477 respectively with high inter-annual rainfall variability. The
27 Hamilton location in Victoria has a temperate climate receiving average annual rainfall of
28 694 mm. Wagga Wagga in New South Wales (NSW) is considered to be a uniform
29 rainfall environment with a climate characterised by hot summers and cool winters
30 receiving average annual rainfall of 548 mm with high inter-annual and intra-annual
31 rainfall variability. In general, crop yields are closely related to plant available water
32 capacity (PAWC) (Yang et al., 2014). Therefore, at each location, three soil types typical of
33 the location with different PAWC values were considered (Table 1). To establish a climate
34 baseline, daily meteorological data (solar radiation, maximum temperature, minimum

1 temperature and rainfall) for the period 1961 – 2010 for each location are obtained from
2 SILO climate data systems (Jeffrey et al., 2001,
3 <<http://www.longpaddock.qld.gov.au/silo/ppd/index.php>>).

4

5 *2.2 Climate projections*

6

7 Climate projections were derived from GCM simulations of the SRES A2 scenario for
8 emissions of greenhouse gases and sulphate aerosols (Nakićenović and Swart, 2000). This
9 scenario has been used in numerous recent climate change impact studies (van Roosmalen
10 et al., 2009, Anandhi et al., 2011, Yang et al., 2014). It has relatively high future
11 greenhouse gas emissions relative to other commonly used scenarios. Monthly mean
12 values of solar radiation, daily maximum and daily minimum temperature and rainfall for
13 the 21st century were required for this study. This data was available for 18 different GCMs
14 from the World Climate Research Programme's (WCRP's) Coupled Model
15 Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007a). To
16 sample uncertainty in future climate changes, all 18 GCMs (Table 2 in Yang et al., (2014))
17 were used for this study. Monthly gridded data from each GCM was statistically
18 downscaled to daily site-specific data for each location using the method described by Liu
19 and Zuo, (2012). The downscaling procedure starts from interpolation of the monthly
20 gridded data to specific locations of interest using an inverse distance cubed weighting
21 method. This is followed by a bias correction between the observed and raw GCM monthly
22 data – the detailed description of bias correction is given by Liu and Zuo (2012). Daily
23 climate data are then generated for each location using a modified stochastic weather
24 generator (WGEN) (Richardson and Wright, 1984). The parameters required to driving
25 WGEN are derived from the monthly GCM data and daily historical climate data from
26 1889 to 2010, as described in Liu and Zuo, (2012). Historical climate data from 1961 and
27 2010 were used as a baseline climate to compare against the projected future climates.
28 Three periods of future climate projection were chosen for the impact assessment:
29 2020-2039, 2050-2069 and 2080-2099, referred as 2030, 2060 and 2090, respectively.

30

31 *2.3 Simulations*

32

33 Simulations of broadacre crop responses to historic and future climates with elevated
34 atmospheric CO₂ in four locations were performed using the Agricultural Production

1 Systems Simulator (APSIM) (Keating et al., 2003) version 7.5. APSIM is a framework of
 2 biophysical modules (<<http://www.apsim.info/>>) that has previously been shown to
 3 adequately simulate cropping systems at these and other locations (Yunusa et al., 2004;
 4 Bassu et al., 2011; Asseng and Pannell, 2013; Yang et al., 2014; Zeleke et al., 2014).
 5 Briefly, APSIM simulates biological and physical processes in a farming system (McCown
 6 et al., 1996) in response to climate (daily maximum and minimum temperature, rainfall and
 7 solar radiation) and management for an array of annual and perennial C3 and C4 crop
 8 plants. Biological processes include phenological development, leaf area growth, biomass
 9 and N concentration of leaves, stems and roots, grain number, grain size and final crop
 10 yield under prescribed management, as well as the changes in soil water and soil nitrogen
 11 supply during the cropping season (Robertson et al., 2002; van Ittersum et al., 2003;
 12 Ludwig and Asseng, 2006; Wessolek and Asseng, 2006). The APSIM-crop modules
 13 (wheat, barley, lupin, canola and field pea) calculate daily biomass production based on
 14 sunlight interception and radiation use efficiency (RUE). The standard RUE is 1.24 g MJ⁻¹
 15 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
 16 canola from emergence to the end of grain-filling. The radiation induced production is
 17 modified by temperature, nitrogen, vapour pressure deficit and soil water supply. Crop
 18 grain yield is a function of grain number, grain filling and carbohydrate remobilization
 19 (Robertson et al., 2002). Elevated levels of atmospheric CO₂ in the plant module of APSIM
 20 affects crop growth by influencing RUE, transpiration efficiency and critical leaf nitrogen
 21 concentration. A detailed description of the response to elevated CO₂ concentration in
 22 APSIM-Wheat is given in Reyenga et al., (1999). Yearly atmospheric CO₂ concentration
 23 for 2030, 2060 and 2090 projections required in the APSIM-simulation is calculated using
 24 the method described by Yang et al. (2014) in equation 1.

25

$$26 \quad [CO_2]_{year} = 2641 + \frac{(0.098139 \times year - 211.71)}{3.5566 \times year^{-0.37996} - 0.19123} \quad (1)$$

27 This equation sets atmospheric CO₂ concentrations approximately equal to the multi-model
 28 mean mid-range carbon cycle projections for the SRES A2 emissions scenario (Meehl et
 29 al., 2007b, fig. 10.26).

30

31

1 The crop cultivars were selected on the basis that they are commonly used by the majority
2 of growers at present - Mace for wheat, Baudin for barley, Drum for canola, Kasper for field
3 pea and Merrit for lupin. Using a common cultivar can minimise the effects of non-climate
4 parameters. Parameters used for the setup of simulations of wheat and barley (Yunusa et
5 al., 2004), lupin (Farré et al., 2004), canola (Farré et al., 2000; Robertson and Kirkegaard,
6 2005), and field pea (Chen et al., 2008) were constituted from previous studies and further
7 refined using available information about crop phenology and morphological,
8 physiological, and biophysical characteristics from sources published by R&D agencies
9 such as Farmnotes (<http://www.agric.wa.gov.au/PC_91689.html>), Grains and Other
10 crops (<<http://www.dpi.vic.gov.au/agriculture/grain-crops>>), NSW Grains Report and
11 Farm business
12 (<<http://www.dpi.nsw.gov.au/aboutus/resources/periodicals/newsletters/grains-report-nsw>
13 >) (<<http://www.dpi.nsw.gov.au/agriculture/farm-business/budgets/winter-crops>
14 >). To generate realistic crop yields for each location, the simulated yields based on historical
15 climate data were corroborated by discussions with local agronomists and published
16 district or regional benchmarks (Planfarm-Bankwest, 2011). Accordingly, the simulation
17 was setup to include initial nutrient balances, soil water and crop management to achieve a
18 realistic set of crop yields for each location.

19
20 Simulation setup in respect of crop sowing conditions and fertilizer application was
21 adopted from Yang et al., (2014). Briefly, similar to current farming practice (Heenan et al.,
22 1994; GRDC, 2005, Hunt and Kirkegaard, 2011), a standard sowing window was
23 considered from 1st April to 31st July and sowing to germination was dependent on soil
24 water status driven by autumn rains in any day between 1April and 31July. To exclude the
25 “carry-over” effects from previous seasons, soil organic carbon, C:N ratio, soil mineral N
26 and water contents were re-set on 10th January of every year. Locally well-adapted
27 broadacre crops (wheat, barley, lupin, canola and field pea) variety was sown at each
28 location when the water content in the top 20 cm soil depth was at least 1.5 and 0.7 times
29 PAWC, as described in Yang et al., (2014). To represent non-deficient soil N for optimum
30 crop growth, fertilizer nitrogen (N) was applied at 280 kg N/ha. Elevated levels of future
31 atmospheric CO₂ were considered in the modelling to account for physiological effects on
32 crops. Levels consistent with the SRES A2 emission scenario were incorporated into the
33 modelling, as described by Yang et al., (2014).

1 “Please insert Table 1 here”

3. Results

3.1 Future climate characteristics relative to baseline

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

22
23 Projected changes in mean annual rainfall are highly significant and spatially
24 heterogeneous across the four studied locations (Fig. 1C). At the four locations two patterns
25 of change in the amount of annual rainfall stand out when comparing the present to the
26 future (2030, 2060, and 2090). The first is an overall decrease in annual rainfall. At
27 Cunderdin, for example, the average rainfall projection of the 18 GCMs decreases by 9%,
28 16% and 26% in 2030, 2060 and 2090, relative to the 1961-2010 baseline, respectively
29 (Fig. 1C). Katanning and Hamilton show similar annual rainfall decreases. However, a
30 similar comparison for Wagga Wagga suggests that annual rainfall is only likely to decline
31 by 4 to 5% there. The second pattern is the progressive increase in the CV of annual rainfall
32 between the future periods for Cunderlin, Katanning and Hamilton (Fig. 1D).

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

4 “Please insert Fig.1 here”
5

6 3.2 Effects of climate change on crop phenology 7

8 In the life cycle of annual crops, the timing of phenological events is critical for crop yields.
9 Two critical events are the length of the period from sowing to flowering, known as days to
10 flowering, (*DTF*) and days to maturity (*DTM*). Across all crops in the baseline (1961 -
11 2010) period, there were no significant differences in *DTF* between the soil types (Fig 2).
12 However, as flowering depends on both day length and temperature, the predicted *DTF*
13 occurs earlier in sites where annual temperature is higher (Table 1 and Fig. 2). For instance,
14 the wheat crop in Cunderdin (higher temperature site) across all soil types, flowered 103
15 days after sowing, compared to 179 days after sowing in Hamilton (lower temperature site).
16 The climate change impacts on phenology (*DTF* and *DTM*) for each of the locations and
17 crops are presented in Figures 3 and 4. One of the most striking *features* is the significant
18 overall reduction of the flowering period and earlier maturity in the future climate (2030,
19 2060 and 2090) relative to the baseline for all of the five crops across the four locations
20 (Fig. 3 and 4). For example, there is a significant advancement in median flowering date of
21 wheat at Hamilton for 2030, 2060, and 2090 of 10, 18 and 29 days respectively. Likewise,
22 for field peas at Katanning, a similar comparison suggests the median flowering date is
23 advanced by 8, 14 and 25 days and at Cunderdin, barley matured earlier by about 5, 11, and
24 19 days. The advancement in phenological events is likely to be related to projected
25 temperature increases and, to some extent, rainfall changes (see Fig. 7).

26 “Please insert Figures 2, 3 and 4 here”
27

28 3.3 Evaluation of crop yield changes 29

30 In the baseline period, simulated annual crop grain yields vary across locations depending
31 on annual rainfall, crop and, to a much lesser extent, soil type (Fig. 5). The crop yields were
32 highest at Hamilton, with its temperate climate and comparatively higher rainfall compared
33 to other three sites. Wheat, for example, recorded its highest median grain yield (7 t/ha) at
34 Hamilton, whereas at Cunderdin and Katanning the median wheat yield were below 2.8

1 t/ha (Fig. 5). The most variable crop yield (5th to 95th percentiles) occurred in field pea
2 crop, followed by wheat and barley and Wagga Wagga was the most variable location (Fig.
3 5). The smallest yield variability across the three soil types (5th to 95th percentiles) are at
4 Cunderdin for most of the crops, followed by lupin at Hamilton. The simulated annual yield
5 of all the crops shows variation depending on the season and is similar to average farm
6 yields variation of the regions (ABARES, 2013). Figure 6 shows the percentage change in
7 total crop biomass between the base line (1961-2010) and the future climate (2030, 2060,
8 and 2090) for each crop and location. Even though there is a large variation in total crop
9 biomass across crops and locations, the overall change in median biomass values of 18
10 GCMs is negative in all future climates relative to base line, with smaller decreases
11 projected for the 2030 and 2060 compared to 2090. There is large variation in the range of
12 inter-quartile total crop biomass changes across crops and locations and inter-quartile crop
13 biomass variation is always highest in 2090 compared to 2030 and 2060 (Fig. 6). For
14 instance, the median total crop biomass values for lupin, canola and field pea crops at
15 Cunderdin are about 10% to 40% less in the future climate relative to 1961-2010. At
16 Hamilton wheat total crop biomass is projected to be 5% to 10% less in the future. Canola
17 showed the largest reduction in total crop biomass (10 to 45%) in the future relative to base
18 line (Fig. 6) at all the locations.

19
20 *“Please insert Figures 5 & 6 here”*

21 22 3.4 Crop yield relationship with future climate

23
24 Figure 8 summarizes the projected changes of crop yields between the baseline
25 (1961-2010) and the future climate (2030, 2060, and 2090) at each location. Three
26 distinct patterns of yield change are evident. First, grain yield is lower for all crops in the
27 future scenarios, across all sites, for most of the GCMs. Second, the negative impact of
28 projected climate on grain yield increases from 2030 to 2090. This is likely to be due to
29 higher temperatures and lower rainfalls in these GCMs (Fig. 1). The third pattern is the
30 increasing dispersion between the 5th and 95th percentiles of crop yields that increases
31 from 2030 to 2090, with a larger dispersion in 2090 for all the crops and locations (Fig. 8).
32 Large dispersion of crop yield values between the 5th and 95th percentiles in 2090 could
33 relate to higher uncertainty in associated with future climate change (Fig. 1, Challinor,
34 2011). In general, Cunderdin and Katanning (lower rainfall sites) showed the highest

1 yield variation between the 5th and 95th percentiles compared to Hamilton (higher
2 rainfall site). Across all crops, the negative impacts of median crop yield could range
3 from – 2 to -10% (wheat yield in 2030-2060) and -20 to - 42% in canola and field pea in
4 2030 - 2090 compared with baseline particularly in lower rainfall sites.

5
6 A descriptive statistical analysis was conducted, with a linear regression model, for
7 changes in crop yield between 18 GCMs projected future (2030, 2060 and 2090) rainfall
8 or temperature or simulated phenological events and crop yields as shown in Figures 7
9 and 9. The regression provided useful insights into the nature and strength of the
10 relationships. Across all crops and sites, there is an advancement of phenology (i.e.,
11 flowering date) which is strongly correlated ($P=0.001$, Fig. 7) with each Celsius degree
12 increase in future temperature. This advancement of phenology, increased progressively
13 from lower rainfall to higher rainfall sites (Table 1). For instance, lupin crop in Cunderdin
14 (low rainfall site), flowered and matured 6 and 5 days, respectively earlier compared to
15 Hamilton (higher rainfall site) of 14 and 9 days (Figures 3, 4 and 7). Likewise, in low
16 rainfall site (Cunderdin), flowering date advanced by 9 days in wheat crop compared to
17 20 days earlier-flowering in higher rainfall site (Hamilton). In general at all sites except
18 Hamilton (higher rainfall site), the change in grain yield significantly correlated ($P=0.001$,
19 Fig. 9) with each percentage change in the future rainfall and the impact increased
20 progressively from higher rainfall to lower rainfall sites. For example, wheat crop in
21 Hamilton (higher rainfall site), there is significant 0.50% grain yield changes for each
22 percentage change in rainfall compared to significant 0.90% grain yield changes in
23 Cunderdin (lower rainfall sites). However, the impact is non-significant in barley grain
24 yield due to comparatively higher rainfall at Hamilton than the other sites (Fig. 9). Across
25 all locations and crops, the aggregate impacts are that temperature in the future will
26 significantly reduce the flowering period and the pattern of future rainfall changes shows
27 a significantly robust relationship with grain yield.

28 *“Please insert Figs. 7, 8, and 9 here”*

30 **4. Discussion**

31 Our simulations of the 1961-2010 baseline period gave yields for five crops that were
32 highest in Hamilton, a high rainfall location, and lowest in Cunderlin, the driest location
33 (Fig. 5). This, and the approximate magnitudes of the yields for all four study locations,

1 was consistent with yields from farm and research trials conducted between 1997 and 2003
2 (GRDC, 2005; ABARES, 2012). Almost all of our simulations under 2030, 2060 and 2090
3 climate conditions show decreases in crop yields (Fig. 8) This suggests that adaptation
4 strategies (for example, agronomic management) are needed (Stokes and Howden, 2010;
5 Sacks and Kucharik, 2011). Note, however, that the magnitude of yield decreases is
6 different for different crops and locations.

7

8 Although there is a considerable range of uncertainty about the consequences of future
9 climate change for yields (Fig. 8), this analysis of the consequences of future climate
10 change on crops considers two important components simultaneously. First, the impact
11 analysis of climate change in this study compares results for five important broadacre crops
12 (wheat, barley, lupin, canola and field pea) in three different soil types across four locations
13 (Table 1) in Australia. This is in contrast to earlier studies of single crops (Anwar et al.,
14 2007; Turner et al., 2011; Asseng and Pannell, 2013; Yang et al., 2014). Second, this
15 analysis involves statistically downscaled climate projections (Liu and Zuo, 2012) from 18
16 GCMs. This contrasts with other studies that have used scaling methods for generating
17 future climate data for fewer GCMs (Luo et al., 2005; Anwar et al., 2007).

18

19 Comparison of the results from 18 GCMs (Fig. 1) demonstrates significant reduction of
20 rainfall in the range of 3 to 10 percentage by 2030, to as much as 20 percentage (average
21 across the studied locations) by 2090, with the reduction being greater at Katanning, which
22 is in line with previous projections for regions across South-Eastern Australia (Timbal and
23 Jones, 2008; Hennessy et al., 2010). Results from all 18 GCM models suggest consistent
24 increases in annual temperature (Hennessy et al., 2010) from year 2030 to 2090 (Fig. 1).
25 Consequently, future increase of atmospheric CO₂, higher temperatures and reduction in
26 rainfall will affect the rate of plant growth and development (Van Ittersum et al., 2003;
27 Ludwig and Asseng, 2006; Ludwig et al., 2009) eventually leading to decline in yields (Fig.
28 8). Wessolek and Asseng, (2006) have also reported yield decline with reduction of rainfall
29 by 20% and by every 1.5⁰C increase over average temperature.

30

31 The observed variation in year-to-year annual rainfall at the four locations is critical in
32 determining future yields in Australian rainfed broadacre crops, as demonstrated by data

1 summarised in Figure 5 and reported by Van Ittersum et al., (2003); Turner, (2004);
2 ABARES, (2011 & 2013). Interestingly, despite substantial decreases in mean rainfall, the
3 bias corrected downscaled data projected to 2030, 2060 and 2090 show broadly similar
4 coefficient of variation values compared to baseline (1961-2010) (Fig. 1, Liu and Zuo,
5 2012). The projected progressive reduction in rainfall progressively impacted future
6 broadacre crop yields (Figs. 5 and 8). For wheat, Yang et al., (2014) show similar results.
7 Across all five crops and locations, we observed significant strong associations ($P = 0.05$ to
8 $P = 0.001$) between grain yield and changes in rainfall (Fig. 9) but not at Hamilton for
9 barley due to higher annual rainfall compared to other locations. Generally, high rainfall
10 variability accompanied by projected reduction on annual rainfall will have a large
11 influence on plant available soil water content (SWC) (Turner, 2004; Tsubo et al., 2007),
12 and, in turn, impact crop yields. Wang et al., (2009) reported that in South-East Australia,
13 decreases in rainfall will reduce growing season evapotranspiration and eventually reduce
14 yields, with implications for adaptation strategies. Some examples of adaptation available
15 to growers include practices that maintain SWC, such as row spacing, reduced tillage,
16 fallows, rotations and irrigation (Stokes and Howden, 2010; Wheeler et al., 2013).

17
18 We observed significant hastening of crop phenology (Figures 2, 3 and 4) in both baseline
19 and projected future climates, which is often a reason for reduction in crop yields (Sadras
20 and Monzon, 2006; Yang et al., 2014). The duration from sowing to flowering and maturity
21 time are critical phenological stages (Sacks and Kucharik, 2011) and there is a positive
22 correlation between the length of photosynthetic activity and the time spent on grain filling
23 and eventual grain yield (Bidinger et al., 1977; Gebbing et al., 1999; Richards, 2000).
24 Results also show that the timing of flowering is negatively correlated ($P = 0.001$) with
25 changes in temperature across all five crops and locations (Fig. 7). This implies
26 environmental conditions may lead to a hastening of crop development eventually causing
27 yield decline (Asseng et al., 2004; Porter and Semenov, 2005; Ludwig and Asseng, 2010).
28 Moreover, flowering time and maturity period are important phenological traits for
29 adaptation to climate change. Indeed, researchers often manipulate these traits, so as to
30 make the pre and post-anthesis assimilation coincide with a high photothermal quotient,
31 thus enhancing grain yields (Long et al., 2006; Stokes and Howden, 2010; Lobell et al.,
32 2012). For farming systems with growing season conditions that, in the future, are expected
33 to have lower rainfall, higher temperatures and raised atmospheric CO_2 the pattern of plant

1 development will be altered as a consequence of reduced plant available soil water and
2 high-temperature stress. As the phenological responses of crops to a more hostile climate
3 will vary between species so will their yields (Drake et al., 1997; Amthor, 2000; Lobell et
4 al., 2013).

5

6 The negative impact of climate change in this study is consistent with other studies (Asseng
7 et al., 2004; Anwar et al., 2007; Lobell and Field, 2007; Turner et al., 2011). For example,
8 Asseng et al., (2004) reported that increasing average temperature by 1.7⁰C resulted in
9 earlier flowering (by 11 days) which eventually led to decline in both total biomass and
10 grain yield in wheat crop. Similarly, Lobell et al., (2013) indicated a reduction of 17 days
11 in growing season length for an increase of 2⁰C increase causing a yield decline of 13% in a
12 maize crop. Results also show that there is a large variation in yields between current and
13 future climate conditions and across locations and crops (Figures 5 and 8) and this implies
14 crop species have differing sensitivities to climatic variations (Huntingford et al., 2005).
15 For example, this study suggests field peas are more sensitive to changes in climate, than
16 cereals or canola. The ensemble median changes in field pea yield range from at least a
17 decrease of 12% in 2030 to up to a decrease of 45% in 2090. In contrast, the ensemble
18 median changes in wheat yield range from at least a decrease of 5% in 2030 to up to a
19 decrease of 30% in 2090. However, when viewed from a national perspective the
20 disproportionately larger impact of climate change on the yield of field peas is likely to be
21 less economically significant than the impact on cereals. This is due to the volume of field
22 pea production only being ~1% of the combined volume of wheat, barley and canola in the
23 last five years (ABARES, 2013).

24

25 Change in climate results in a different response in the growth and development each crop
26 species due to interspecies variation in temperature requirement for achieving certain
27 phenological stages (Fuhrer, 2003; Craufurd and Wheeler, 2009; Mitter et al., 2013).
28 Future climatic conditions (Fig. 1) with warmer temperatures and reduced rainfall will
29 induce large enough shifts to offset future crop yields that mediate through disruption of
30 phenological synchrony (Wheeler et al., 2000). Additionally, analyses of climate-yield
31 relationships (Fig. 9) suggest that in all locations rainfall is the primary climate change
32 threat to future crop yield, while increasing temperature is secondary (Turner, 2004;
33 Sinclair, 2011). This emphasises the importance and urgency of the requirement of the

1 grain industry to find or gain access to genetic and agronomic innovations that can address
2 the negative impact of the adverse changes in the climate of the growing seasons which
3 crucially determine broadacre crop yields. Findings reported here may be important in
4 informing adaptation strategies, such as maintaining or increasing soil water reserves so as
5 to ensure adequate water availability to sustain profitable crop yields (Sinclair, 2011).

6
7 Annual broadacre grain yields vary according to influence of agroclimatic and edaphic
8 conditions as well as genetic attributes and crop management (Ramankutty et al., 2008;
9 Monfreda et al., 2008). Furthermore, at any particular location productivity and
10 profitability of a crop is determined by not only changes in prices and cost of production
11 but also the changes in climate such as seasonal distribution of rainfall and temperature
12 (Gornall et al., 2010). Quantifying the potential impacts of future climate change on the
13 yield of major field crops for a specified location provides useful insights that can inform
14 policy formulation, provide direction and help for prioritizing research, reforming crop
15 management practises, and thus sustain agricultural production and reduce vulnerability in
16 the future (Roudier et al., 2011; Challinor et al., 2014).

17 18 **5. Conclusion**

19 A methodology involves output of 18 Global Climate Models projecting locally by bias
20 corrected statistical downscaling to predict the possible effects of climate change on
21 broadacre crop yields (wheat, barley, lupin, canola, field pea) in Western and
22 South-Eastern Australia. Projected annual rainfall can decrease by 9%, 16% and 26% in
23 2030, 2060 and 2090 respectively, and rainfall amount is critical in determining crop yields
24 but, equally, higher future temperatures can reduce crop productivity primarily due to
25 advanced crop phenology. Our study shows that, for a wheat crop at Hamilton (higher
26 rainfall site), there is a significant advancement in median flowering date for 2030, 2060,
27 and 2090 of 10, 18, and 29 days respectively with a significant 0.50% grain yield changes
28 for each percentage change in rainfall compared to significant 0.90% grain yield changes in
29 Cunderdin (lower rainfall sites). Field peas are more sensitive to changes in climate, 12% to
30 45% declines in yield between current and future climates, than cereals or canola. Overall,
31 the impact of climate change on broadacre crops will be negative (3 to 20% yield loss) in
32 the short term (2030), but increasingly detrimental with time (potential yield losses
33 reaching 42% for some crops by 2090). Given this impact of declining projected rainfall
34 and higher temperatures in the future, it is important that policies and adaptation strategies

1 are aimed at dealing these climatic shifts. Depending on crop species, climate impact
2 assessment suggest adaptation strategies that covers advances in agronomy, soil moisture
3 conservation, seasonal climate forecast and breeding to combat the negative consequences
4 of predicted climate change at these locations.

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Tables and figures

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.

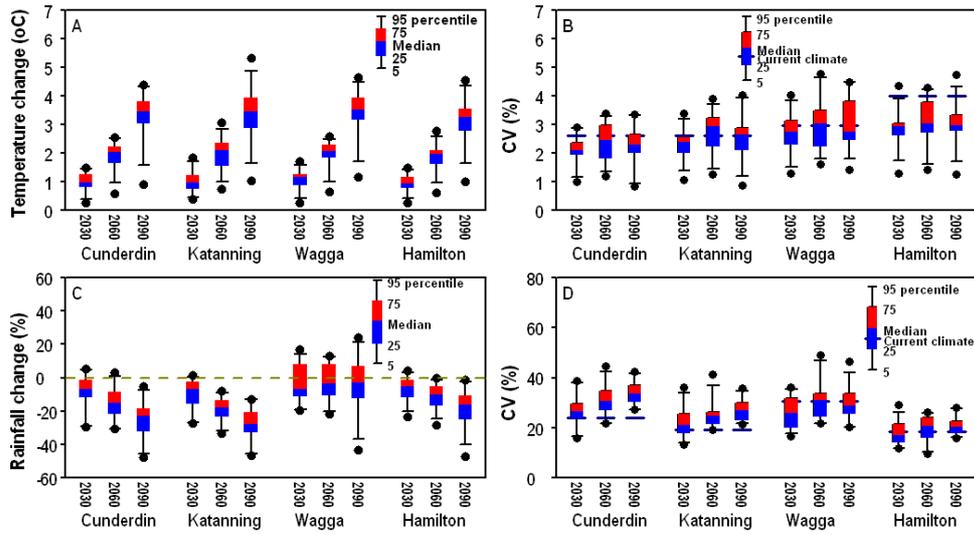
Site	Latitude, Longitude	Soil type (S)	Soil depth (cm)	PAWC (mm)	Climate	Average annual temperature (°C)	Average annual precipitation (mm)
Cunderdin, Western Australia	-31.65, 117.23	(S1) Acid loamy sand (Tenosol)	250	78	Mediterranean	18.3	361
		(S2) High clay (Kandosol)	250	135			
		(S3) Deep sandy 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			

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Fig. 1

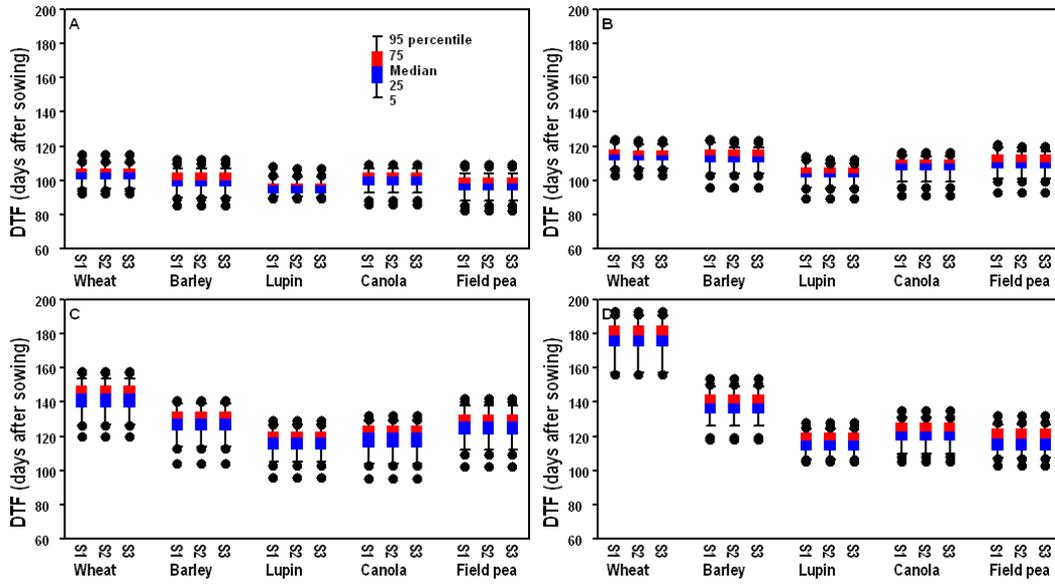


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Figure 1: Box-plots of 18 GCM projected temperature and rainfall changes (A and C) with coefficient of variation (CV) (B and D) in three periods (2030, 2060, and 2090) at four Australian sites. The CV of current (1961 – 2010) temperature and rainfall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

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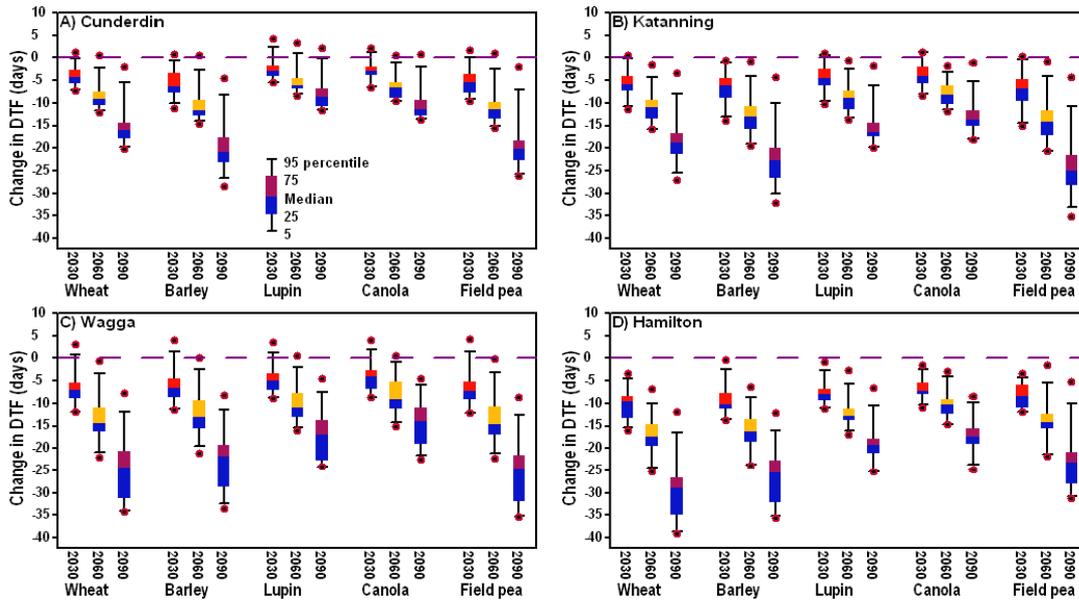
Fig 2



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Figure 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).

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 6 Figure 3: Box-plots of 18 GCMs projected changes days to flowering (DTF) of five crops in three
 7 periods (2030, 2060 and 2090) at four Australian sites.
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Fig. 4

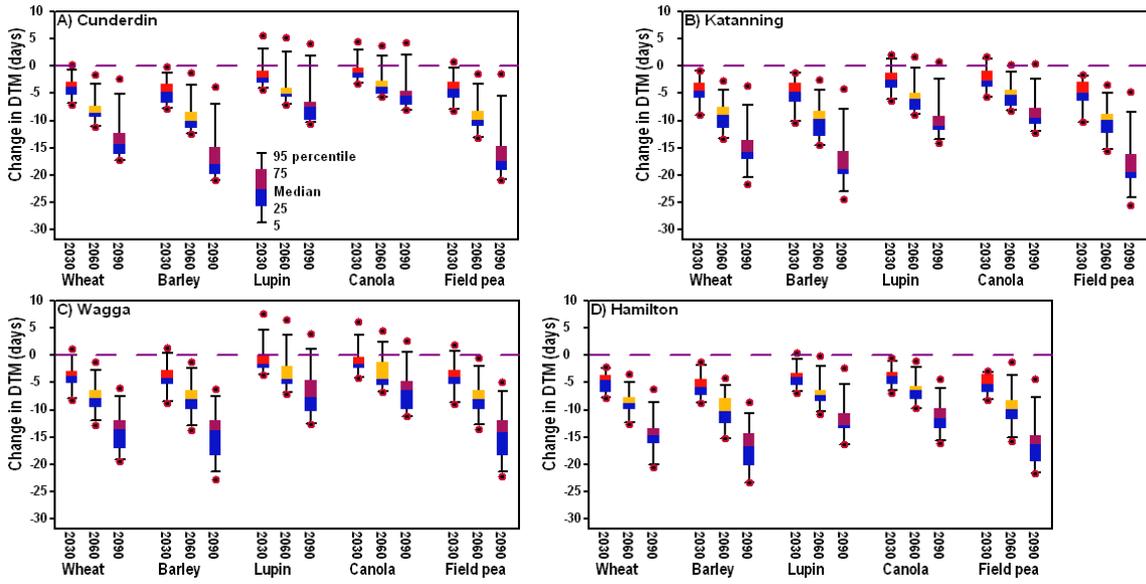
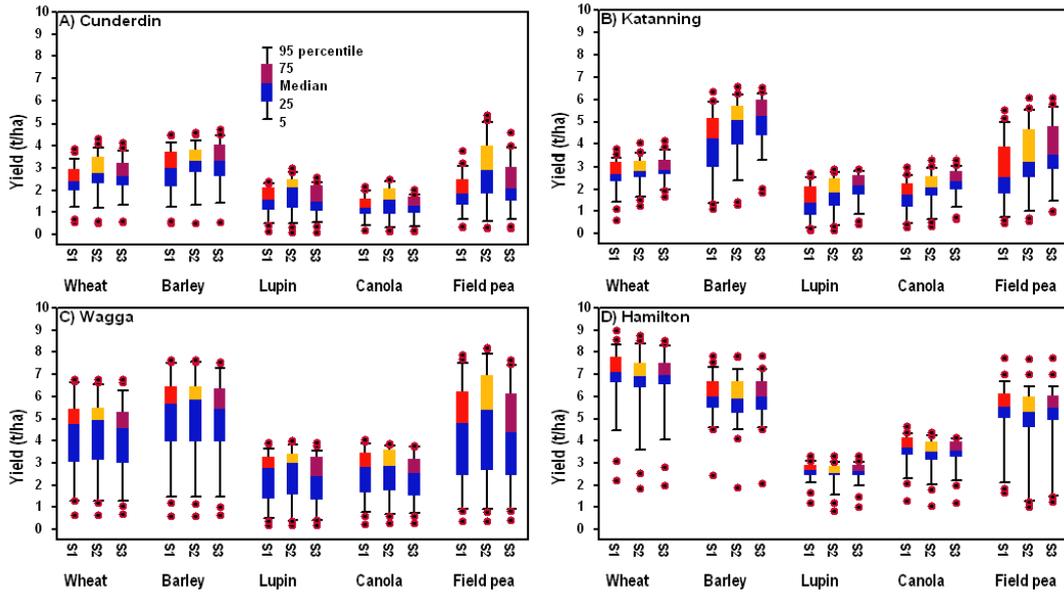


Figure 4: Box-plot of 18 GCMs projected changes in days to mature (DTM) of five crops in three periods (2030, 2060, and 2090) at four Australian sites.

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Fig. 5



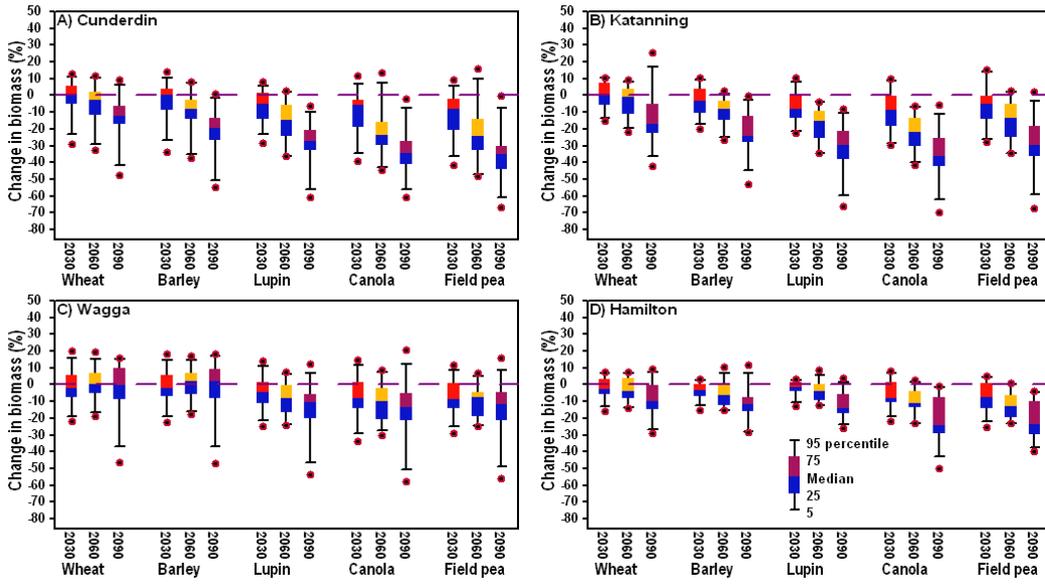
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Figure 5: Box-plot of simulated five winter crop yields in baseline period (1961-2010) on three local soils at four Australian sites.

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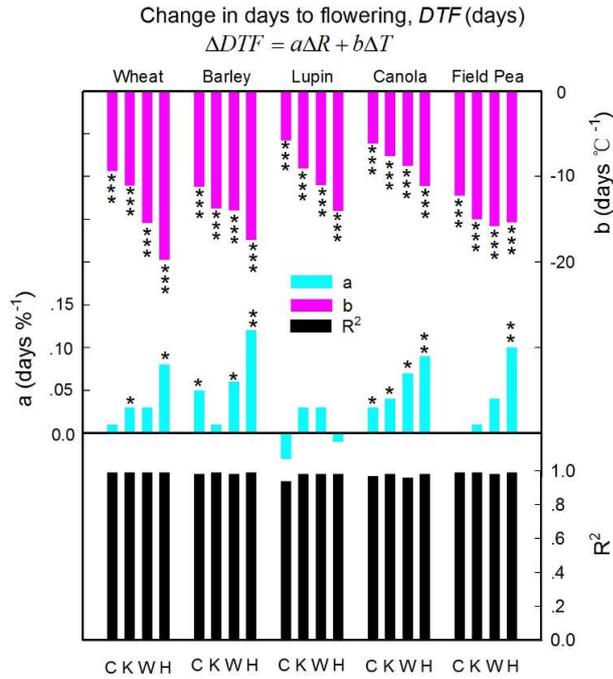


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7 **Figure 6:** Box-plot of 18 GCMs projected changes in biomass of five crops in three periods (2030,
8 2060, and 2090) at four Australian sites.

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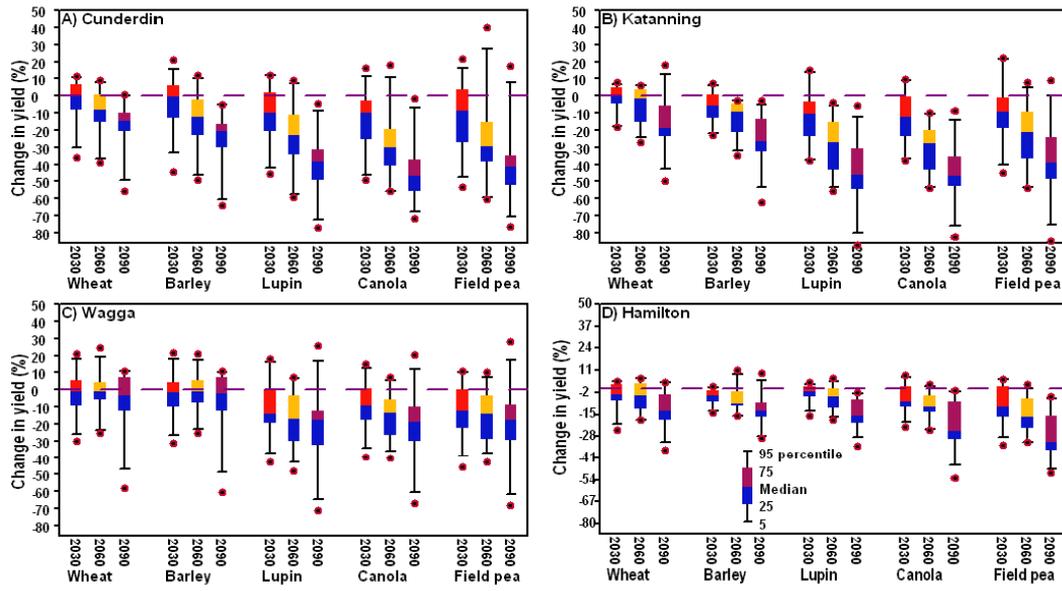
1 Fig. 7
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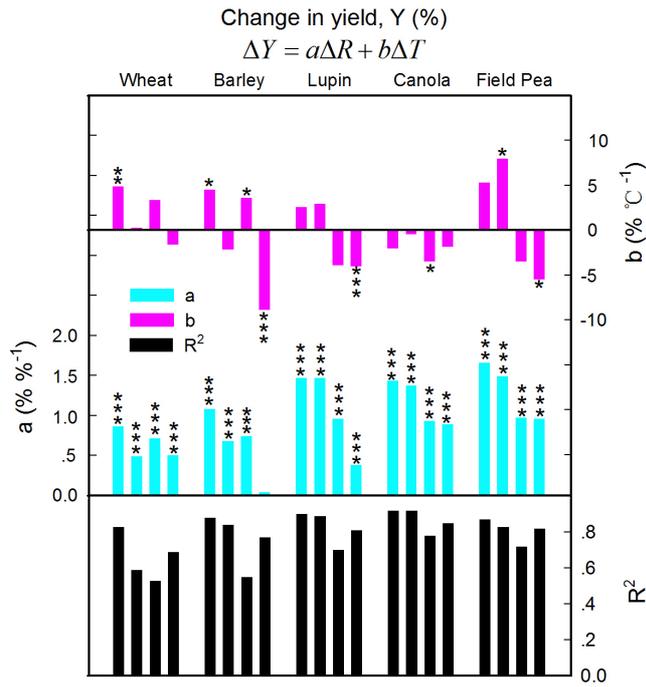
Figure 7: Regression analysis of the impact rates of climate change on days to flowering (DTF) in wheat, barley, lupin and field pea at Cunderdin, Katanning, Wagga and Hamilton as abbreviated to be C, K, W and H, respectively. The change rates (ΔDTF) as functions of the change in rainfall (ΔR) and temperature (ΔT) are shown in the respective figure. The bars with *, ** and *** indicate the significant level at $P=0.05$, $P=0.01$ and $P=0.001$, respectively, otherwise, the coefficients are not significant difference from zero at $P>0.05$.

1 Fig. 8
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5 **Figure 8:** Box-plot of 18 GCMs projected changes in crop yield of five crops in three
6 periods (2030, 2060, and 2090) at four Australian sites.
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1 Fig. 9
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 6 **Figure 9:** Regression analysis of the impact rates of climate change on grain yield (Y) in wheat, barley,
 7 lupin and field pea at Cunderdin, Katanning, Wagga and Hamilton as abbreviated to be C, K, W and H,
 8 respectively. The change rates (ΔY) as functions of the change in rainfall (ΔR) and temperature (ΔT)
 9 are shown in the respective figure. The bars with *, ** and *** indicate the significant level at $P=0.05$,
 10 $P=0.01$ and $P=0.001$, respectively, otherwise, the coefficients are not significant difference from zero
 11 at $P>0.05$.
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