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Earlier crop flowering caused by global warming alleviated by irrigation

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Abstract

Enabling crop flowering within an optimal calendar window minimises long-term risk of abiotic stress exposure, improving prospects for attaining potential yield. Here, we define the optimal flowering period (OFP) as the calendar time in which long-term risk of frost, water and heat stress are collectively minimised. Using the internationally-renowned farming systems model Agricultural Systems Production Systems sIMulator, we characterised combined effects of climate change and extreme climatic events on the OFPs of barley, durum wheat, canola, chickpeas, fababean and maize from 1910 to 2021. We generate response surfaces for irrigated and dryland conditions using a range of representative sowing times for early and late maturity genotypes. Global warming truncated crop lifecycles, shifting forward flowering of winter crops by 2–43 d in dryland environments, and by −6–19 d in environments with irrigation. Alleviation of water stress by irrigation delayed OFPs by 3–25 d or 11–30 d for early and late maturity winter crops, respectively, raising average yields of irrigated crops by 44%. Even so, irrigation was unable to completely negate the long-term yield penalty caused by the climate crisis; peak yields respectively declined by 24% and 13% for rainfed and irrigated crops over the 111 years simulation duration. We conclude with two important insights: (a) use of irrigation broadens OFPs, providing greater sowing time flexibility and likelihood of realising potential yields compared with dryland conditions and (b), the most preferable maturity durations for irrigated winter and summer crops to maximise potential yields are early-sown long-season (late) and later-sown short-season (early) maturity types, respectively.

1. Introduction

Australian irrigated grain crops account for AU$464 million/year from about 12% (∼300 000 ha) of total irrigated land area (∼2.5 million hectares) (ABS 2019). Irrigated grain crops are predominantly located in the Murray–Darling Basin and to a lesser extent in QLD, southeast South Australia, north-central Victoria and the Midlands of Tasmania. Yields of irrigated crops depend heavily on available water supply and irrigation water prices, both of which

are subject to extreme seasonal volatility (Harrison *et al* 2017). As well, crop exposure to abiotic stresses such as frost or heat stress during sensitive periods of crop phenological development cause severe yield penalties or even complete devastation (Harrison *et al* 2012a, 2012b, Langworthy *et al* 2018, Ibrahim *et al* 2019, Liu *et al* 2020). For determinate grain crops, anthesis represents a highly vulnerable stage to abiotic stress and loss of grain yield (Sadras and McDonald 2012, Harrison *et al* 2012a, Hu *et al* 2019). It is thus crucial that sowing dates and genotypic maturity

durations are tactfully selected such that flowering occurs during the long-term optimum flowering period, or optimal flowering period (OFP) (Harrison *et al* 2011, Ibrahim *et al* 2018, Liu *et al* 2020, 2021).

In any given environment, OFPs may be defined as the calendar window within which the risks of exposure to frost, heat, drought, waterlogging etc are minimised. Realisation of OFPs implies that long-term potential yield will be maximised, as flowering is positioned to minimise likelihood of coincidence with key abiotic stresses, notwithstanding the fact that climatic conditions within any given year may not favour potential yield, even if the OFP is reached (Donatelli *et al* 2017, Christie *et al* 2018, 2020). For grain crops with an annual life cycle and determinate flowering, the sensitive window that predetermines floret production, grain number and yield is between stem elongation and shortly after anthesis (Sadras and McDonald 2012). Crop management—through selection of crop type, genotype, maturity duration and sowing date—allows growers to minimise abiotic stress through tactical management of flowering time. Sowing time field trials at Wagga Wagga in Australia show that wheat yields were maximised (5.2 t ha^{-1}) when flowering occurred between late September and early October, with sowing conducted between 16 April and 7 May (Koetz *et al* 2016). Results from a dryland field experiment at Loxton (South Australia) suggested that long-maturity grain crop varieties were best suited to an early sowing time (19 April), while the later sowing (22 May) was best suited to short-maturity varieties (Ferrante *et al* 2019) to avoid terminal water deficit (Christie *et al* 2018). However, the studies of Koetz *et al* (2016) and Ferrante *et al* (2019) were conducted under dryland conditions in which terminal water deficits were common. In contrast, it could be posited that appropriately timed irrigation will alleviate drought stress, increase growing season duration and delay OFP. Despite the logic of this hypothesis, there appears to be few studies that specifically examine how irrigation impacts on OFPs.

Because seasonal and climatic extremes in Australia are commonplace (Bell *et al* 2013, Pembleton *et al* 2016, Chang-Fung-Martel *et al* 2017), modelling approaches are needed to facilitate insight into crop or pasture behaviour under highly variable climatic conditions over the long term (Harrison *et al* 2014a, 2014b, Alcock *et al* 2015). Recent studies have invoked the Agricultural Systems Production Systems sIMulator (APSIM) to determine the OFPs of dryland wheat, barley or canola (Flohr *et al* 2017, Luo *et al* 2018, Lilley *et al* 2019, Chen *et al* 2020, Liu *et al* 2020, 2021). Similar modelling studies have shown that early sowing improved wheat yields by up to 0.54 t ha^{-1} (Hunt *et al* 2019).

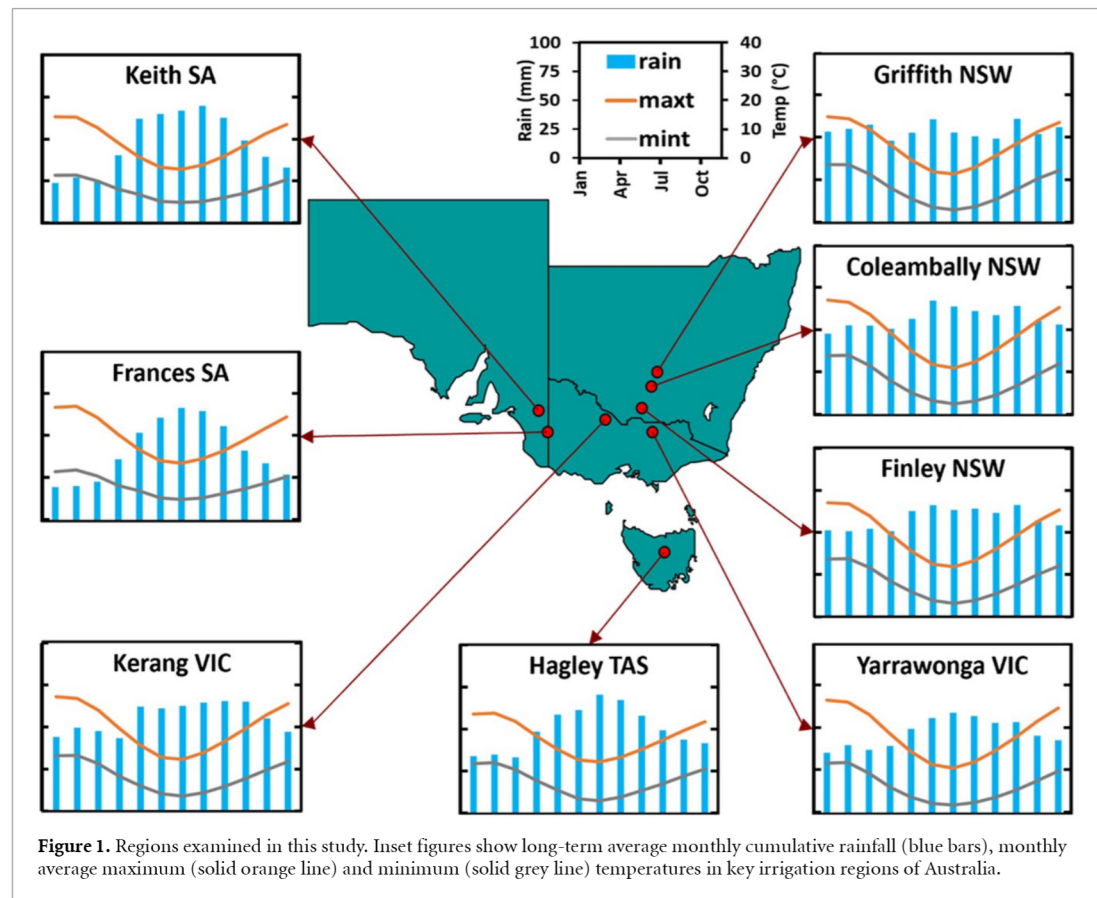In addition to short-term seasonal variability is the long-term shifts in annual flowering time observed under climate change (Craufurd and Wheeler 2009, Harrison *et al* 2014c, Ibrahim *et al* 2018). *Ceteris paribus* global warming hastens crop development, advances maturity and shifts forward flowering time. Flohr *et al* (2018) showed that a 10 d shift in planting time of wheat from 20 May to 10 May resulted in an additional 2.3 Mt yr^{-1} to the Australian national harvest. These seemingly subtle changes associated with management and climatic variability can lead to large changes in profitability (Ho *et al* 2014, Harrison *et al* 2017), underscoring the importance of enumerating genotype × management × environment combinations over the long term (Hunt *et al* 2019, Ibrahim *et al* 2019). While historical global warming has advanced flowering times, the extent to which the climate has changed OFP—or the interplay between the OFP and effects caused by irrigation—to date remains unquantified. The objectives of this study were to (a) identify the OFPs and optimal sowing times of early and late genotypes for spring barley, durum wheat, canola, chickpeas, fababean and summer maize grown under irrigated and dryland conditions, and (b) to determine the long-term historical change in OFPs associated with climate change across the grain cropping regions of Australia.

2. Materials and methods

A range of representative sites were selected to model long and short maturity groups, covering a breadth of sowing window × flowering time combinations for each crop type (figure 1, table 3). We applied rainfed and irrigation treatments with non-limiting nitrogen (N) fertilisation to ensure that *in silico* crop growth and flowering times were not confounded by nitrogen stress.

2.1. Historical and future climate data

Simulations were conducted using 111 years of climatic data (1910–2020) for eight locations (figure 1, table 1). Climatic data on a daily time-step were obtained from the SILO (Scientific Information for Land Owners) Patched Point Dataset (Jeffrey *et al* 2001). To elicit effects caused by existential climate change, we examined how crop performance was influenced by global warming under current climates (2000–20) relative historical climates (1910–30). Changes in annual average rainfall and maximum and minimum temperature between current and historical climates were computed following the approach outlined by Harrison *et al* (2016a). Averaged across locations, mean annual rainfall for the current period decreased by −14% relative to historical period, while mean annual minimum and maximum temperature of current climates were 15% greater than corresponding historical annual temperatures. Further details are shown in table S5 (available online at stacks.iop.org/ERL/17/044032/mmedia).

Figure 1. Regions examined in this study. Inset figures show long-term average monthly cumulative rainfall (blue bars), monthly average maximum (solid orange line) and minimum (solid grey line) temperatures in key irrigation regions of Australia.

Table 1. Locations and long-term climatic characteristics of study sites (SILO; Jeffrey *et al* (2001)).

Region	Met. Station	SILO station No.	Latitude (°S)	Longitude (°E)	Rainfall (mm)	Minimum temp (°C)	Maximum temp (°C)
Griffith NSW	Hillston Airport	75 032	−33.4915	145.5248	373	11	24.4
Kerang VIC	Kerang	80 023	−35.7236	143.9196	377	9.4	22.9
Finley NSW	Tocumwal Airport	74 106	−35.8170	145.6004	453	9.6	23.0
Keith SA	Keith	25 507	−36.0980	140.3556	457	9.2	22.3
Coleambally NSW	Wagga Wagga AMO	72 150	−35.1583	147.4575	559	9.1	22.2
Yarrawonga VIC	Rutherglen Research	82 039	−36.1048	146.5094	583	7.3	21.8
Frances SA	Coonawarra	26 091	−37.2906	140.8254	615	8.1	20.5
Hagley TAS	Launceston (TI Tree Bend)	91 237	−41.4194	147.1219	733	7.4	18.6

2.2. Simulation of optimal flowering dates in the G × E × M

The Agricultural Production Systems SIMulator (APSIM v7.10, (Keating *et al* 2003, Holzworth *et al* 2014)) was used to simulate irrigated and rainfed genotypes (G) of fababean (Turpin *et al* 2003), durum wheat (Wang *et al* 2003, Brown *et al* 2014), spring barley (Manschadi *et al* 2006), canola (Robertson *et al* 1999) and maize. These crops were chosen as part of participatory discussions with industry groups distributed across the Murray–Darling Basin, South Australia, Victoria and Tasmania. For each site, simulated sowing was conducted at weekly intervals from 1 March to 5 July for winter crops and from 15 September to 19 January for maize (being a summer crop in Australia); soil characteristics shown in table 2 were obtained from APSoil (Dalgliesh *et al* 2012). Crops simulated comprised slow developing (late maturity) and fast developing (early maturity) spring genotypes. Details of genotypic parameters

Table 2. Soil details of sites simulated.

No.	Region	APSoil No.	Soil type
1.	Griffith NSW	697	Sandy duplex
2.	Kerang VIC	1092	Sandy clay loam
3.	Finley NSW	184	Sandy clay loam over light clay
4.	Keith SA	345	Sand over dispersive brown clay
5.	Coleambally NSW	174	Brown chromosol
6.	Yarrawonga VIC	206	Sandy loam over clay loam
7.	Frances SA	SE069	Sandy loam over brown clay
8.	Hagley TAS	658	Loam

Table 3. Crop planting densities and genotypes.

Crop type	Plants/m^2	Genotypes	References
Fababeans	30	Warda (early), ILB1814 (late)	Zeleke (2019), Manning *et al* (2020), GRDC (2020)
Chickpeas	50	Amethyst (early), Cpi56566 (mid-late)	Dreccer *et al* (2018), Chauhan *et al* (2019), GRDC (2020)
Durum	200	Wollaroi (early), Bellaroi (late)	Jones (2017), Dreccer *et al* (2018), GRDC (2020)
Barley	150	Keel (early), Franklin (late)	Porker *et al* (2017), Dreccer *et al* (2018), GRDC (2020)
Canola	30	Monty (early), Dunkeld (late)	Dreccer *et al* (2018), Lilley *et al* (2019), GRDC (2020)
Maize	9	Pioneer_39G12 (early), Pioneer_3237 (late)	Peake *et al* (2008), Pembleton *et al* (2016)

and other simulation settings are included in table 3. Nitrogen stresses in the model were removed (see above). Irrigation was simulated such that soil water stress was negated for irrigated crops, thus facilitating insight into how optimal irrigation impacted on OFPs when contrasted with rainfed crops that experienced water-deficit.

To examine the shift in flowering time associated with the cumulative evolution of water stress over the crop lifetime, we also simulated rainfed crops. These received 15 mm at sowing to ensure emergence (as above) but otherwise did not receive any irrigation.

Table 4. Temperature thresholds for frost and heat stress during sensitive Zadoks growth stages with corresponding yield penalties (after Bell *et al* (2015)).

Temperature	Stress level	Zadoks sensitive stage	Daily yield penalty (%)
−2 °C–0 °C	Mild	60–69	10
−4 °C to −2 °C	Moderate	60–75	20
⩽−4 °C	Severe	60–79	90
32 °C–34 °C	Mild	60–79	10
34 °C–36 °C	Moderate	60–79	20
>36 °C	Severe	60–79	30

2.3. Optimal flowering periods (OFPs)

For many domesticated plants, phenology is driven by cumulative temperature exposure over their life-cycle. In APSIM, phenology is driven by thermal time in degree days from three-hourly air temperatures interpolated using daily maximum and minimum temperatures. Daily thermal times are accumulated into a thermal sum that is used to determine the duration of each phase; the duration of each phase can be inhibited by either water or nitrogen stresses, potentially resulting in delayed phenology when plants are exposed to enduring stress (www.apsim.info/documentation/model-documentation/crop-module-documentation/plant/).

OFPs were calculated using biological frost and heat thresholds (table 4) defined by Bell *et al* (2015) and Flohr *et al* (2017), implemented in APSIM following (Liu *et al* 2020). For each location, 28 consecutive sowing dates were simulated, each run using 111 years of climatic data detailed above. Flowering dates corresponding to ⩾5% peak mean yield were used to compute OFP dates for each location and genotype. Sowing dates corresponding to OFPs were defined as optimal sowing periods.

To illustrate how dry matter accumulation was influenced by stress related to water deficit, excessive heat or frost, we report stress indices for many of the results shown below. In APSIM, stress indices are calculated as dimensionless factors that reduce the extent to which maximum daily potential growth can occur: a stress index of 1.0 indicates that the plant is exposed to zero stress, allowing maximum potential growth to be realised; a stress index of zero indicates that the plant is exposed to maximum possible stress such that daily growth ceases altogether. In APSIM, daily temperature is used to compute heat and frost thresholds, whereas daily water stress indices are computed as a function of water supply and demand.

Table 5. Optimal sowing and flowering periods for early and late maturity genotypes of durum wheat for dryland and irrigated sites across the Australian cropping zone.

| Region | Genotypes | Regime | Optimal range of flowering period | | Maximum yield (kg ha^{-1}) | Optimal range of sowing dates | |
			Start	End		Earliest	Latest
Griffith	Early	Dryland	7 September	21 September	2571	3 May	17 May
		Irrigated	26 September	11 October	6227	24 May	21 June
	Late	Dryland	30 August	16 September	2774	19 April	3 May
		Irrigated	23 September	10 October	6903	10 May	7 June
Kerang	Early	Dryland	16 September	3 October	3267	3 May	24 May
		Irrigated	3 October	23 October	6093	24 May	5 July
	Late	Dryland	10 September	26 September	3715	19 April	3 May
		Irrigated	2 October	25 October	6678	10 May	28 June
Finley	Early	Dryland	27 September	7 October	4140	10 May	24 May
		Irrigated	11 October	26 October	6527	31 May	5 July
	Late	Dryland	23 September	6 October	4536	26 April	10 May
		Irrigated	6 October	30 October	7109	10 May	5 July
Keith	Early	Dryland	23 September	8 October	3369	17 May	7 June
		Irrigated	16 October	23 October	5637	21 June	5 July
	Late	Dryland	21 September	3 October	3944	3 May	17 May
		Irrigated	15 October	28 October	6202	7 June	5 July
Coleambally	Early	Dryland	8 October	22 October	4399	17 May	14 June
		Irrigated	19 October	30 October	6989	7 June	5 July
	Late	Dryland	5 October	22 October	4817	3 May	31 May
		Irrigated	19 October	3 November	7527	24 May	5 July
Yarrawonga	Early	Dryland	18 October	30 October	2458	24 May	21 June
		Irrigated	25 October	4 November	4743	7 June	5 July
	Late	Dryland	18 October	25 October	2704	10 May	24 May
		Irrigated	22 October	8 November	5056	17 May	5 July
Frances	Early	Dryland	17 October	31 October	4481	7 June	5 July
		Irrigated	21 October	31 October	5736	14 June	5 July
	Late	Dryland	13 October	27 October	5071	17 May	14 June
		Irrigated	21 October	5 November	6287	31 May	5 July
Hagley	Early	Dryland	1 November	11 November	5937	7 June	5 July
		Irrigated	6 November	11 November	7536	21 June	5 July
	Late	Dryland	27 October	13 November	6481	10 May	28 June
		Irrigated	7 November	15 November	8272	7 June	5 July

3. Results

3.1. Effects of irrigation and maturity on optimal flowering periods (OFPs) and yield

Across sites, sowing times, years and climates, irrigated late maturity winter and early maturity summer genotypes generally had higher mean yields, while dryland early maturity winter and late maturity summer genotypes had the lowest peak mean yield (tables 5–7 and S1–S3). The highest peak mean yields were attained in the State of Tasmania (Hagley) by the irrigated early maturity summer genotype of maize and for most winter crops (spring barley, durum wheat, chickpea and canola). The lowest peak mean yields were attained at Yarrawonga (Victoria) by the dryland early maturity winter genotypes (canola, barley, chickpea, durum wheat and fababean) and at Frances (South Australia) by the dryland late summer genotypes of maize. Dryland maize crops were basically a failure at most sites, because in contrast to dryland crops sown in winter that have sufficient rainfall, summer conditions in Australia have low rainfall and excessive vapour pressure deficit (Ho

et al 2014, Harrison *et al* 2016b) that when combined cannot support the significant growth requirements of maize.

The duration of OFPs varied significantly between crop genotypes under irrigation and rainfed conditions across sites (tables 5–7 and S1–S3). Generally, irrigation extended the OFP window compared with dryland crops, particularly for the late winter genotypes. The latest start of the OFP was at Hagley for irrigated late winter genotypes of durum wheat (7 November), spring barley (3 November), chickpea (5 October), fababean (4 August) and irrigated early canola (6 September).

Griffith had the latest start of OFP for irrigated late summer maize (8 March). The earliest OFPs were observed under dryland conditions for late winter genotypes of durum wheat (30 August), spring barley (24 August), early chickpea (24 June) and fababean (11 May) at Griffith. Similarly, earlier OFP were observed at Yarrawonga and Frances for dryland early canola (22 June) and maize (26 December).

Across years, sites and crops, irrigation-induced water stress relief delayed OFPs by 3–25 d or 11–30 d

Table 6. Optimal sowing and flowering periods for early and late maturity genotypes of chickpeas for dryland and irrigated sites across the Australian cropping zone.

Region	Genotypes	Regime	Optimal range of flowering period		Maximum yield (kg ha^{-1})	Optimal range of sowing dates	
			Start	Close		Earliest	Latest
Griffith	Early	Dryland	24 June	29 July	2467	5 April	26 April
		Irrigated	29 July	3 September	3899	26 April	31 May
	Late	Dryland	29 June	25 July	2646	29 March	12 April
		Irrigated	25 July	5 September	4256	12 April	17 May
Kerang	Early	Dryland	16 July	13 August	3011	12 April	3 May
		Irrigated	13 August	17 September	4085	3 May	14 June
	Late	Dryland	10 July	12 August	3286	29 March	19 April
		Irrigated	2 August	15 September	4378	12 April	24 May
Finley	Early	Dryland	30 July	24 August	3373	19 April	10 May
		Irrigated	17 August	20 September	4224	3 May	14 June
	Late	Dryland	25 July	24 August	3637	5 April	26 April
		Irrigated	16 August	19 September	4536	19 April	24 May
Keith	Early	Dryland	11 July	14 August	2964	12 April	10 May
		Irrigated	14 August	22 September	3816	10 May	28 June
	Late	Dryland	6 July	13 August	3253	29 March	26 April
		Irrigated	13 August	26 September	4097	26 April	14 June
Coleambally	Early	Dryland	4 August	5 September	3490	19 April	17 May
		Irrigated	22 August	29 September	4219	3 May	21 June
	Late	Dryland	31 July	7 September	3731	5 April	3 May
		Irrigated	22 August	4 October	4522	19 April	7 June
Yarrawonga	Early	Dryland	3 August	11 September	2314	12 April	17 May
		Irrigated	5 September	29 September	3555	10 May	14 June
	Late	Dryland	10 August	14 September	2325	5 April	3 May
		Irrigated	14 September	30 September	3789	3 May	24 May
Frances	Early	Dryland	22 August	18 September	3620	10 May	14 June
		Irrigated	9 September	2 October	4273	31 May	5 July
	Late	Dryland	22 August	17 September	3867	26 April	24 May
		Irrigated	11 September	11 October	4581	17 May	28 June
Hagley	Early	Dryland	16 September	10 October	4904	24 May	5 July
		Irrigated	29 September	10 October	5498	14 June	5 July
	Late	Dryland	26 September	17 October	5175	17 May	21 June
		Irrigated	5 October	24 October	6098	31 May	5 July

for early and late maturity winter crops, respectively, although there was no relationship between irrigation and the duration of OFP for each crop type. For example, under dryland conditions the longest OFP was at Yarrawonga for late fababean (70 d) and early canola (66 d), at Frances for late barley (33 d) and at Keith for early maize (27 d). In contrast, under irrigation the longest OFP duration was at Kerang and Finley for late genotypes of chickpea (44 d) and wheat (24 d), respectively.

3.2. Effects of frost, heat and water stress on OFP

For the majority of dryland environments, OFPs of winter crops (durum, barley, chickpea canola and fababean) were defined by decreasing frost risk with increasing water and heat stress. Hagley (Tasmania) was an exception to this; the main stress influencing OFP at this site was frost while heat stress was mostly absent (figure 2). In the southern-most Australian state of Tasmania, optimal sowing times for the fast- and slow- genotypes (i.e. relatively later and earlier sowing respectively) reduced frost risk in November and, when combined with minimal risk of heat and

water stress, were conducive to greater yields for most winter crop types compared with other sites. Across most other (Australian mainland) locations, water and heat stress increased significantly when flowering occurred later than September.

Irrigation negated terminal water stress such that OFPs of winter crops were defined primarily by risk of frost and heat (figure 2). Alleviation of water stress from September onward facilitated later OFP (optimal flowering times October to early November), allowing avoidance of late seasonal frost but also the predominance of heat shocks from mid-November onwards that were common at most sites. Overall, grain legumes (chickpea and fababean) had wider OFPs compared with other winter and summer crops in this study (figure 3).

The OFP for dryland summer maize crops was dictated by increasing frost risk and the concurrent decline in risk of heat and water stress towards the start of autumn (March/April; figure 4). In general, dryland maize was unviable; for all sites, crops failed due to lack of rainfall, high temperature exposure and high vapour pressure deficit that typifies Australian

Table 7. Optimal sowing and flowering periods for early and late maturity genotypes of maize for dryland and irrigated sites across the Australian cropping zone.

Region	Genotypes	Regime	Optimal range of flowering period		Maximum yield (kg ha^{-1})	Optimal range of sowing dates	
			Start	Close		Earliest	Latest
Griffith	Early	Dryland	5 March	5 March	1518	12 January	12 January
		Irrigated	5 March	15 March	10 686	12 January	19 January
	Late	Dryland	2 March	9 March	222	15 December	22 December
		Irrigated	8 March	8 March	6779	22 December	22 December
Kerang	Early	Dryland	4 March	4 March	973	5 January	5 January
		Irrigated	4 March	4 March	10 775	5 January	5 January
	Late	Dryland	21 February	21 February	143	24 November	24 November
		Irrigated	25 February	4 March	6697	1 December	8 December
Finley	Early	Dryland	24 February	3 March	1091	29 December	5 January
		Irrigated	23 February	2 March	11 863	29 December	5 January
	Late	Dryland	20 February	25 February	195	24 November	1 December
		Irrigated	24 February	2 March	7355	1 December	8 December
Keith	Early	Dryland	15 February	14 March	83	8 December	5 January
		Irrigated	3 March	3 March	9293	29 December	29 December
	Late	Dryland	8 March	8 March	16	24 November	24 November
		Irrigated	23 February	7 March	5040	17 November	1 December
Coleambally	Early	Dryland	15 February	22 February	1498	22 December	29 December
		Irrigated	22 February	22 February	11 527	29 December	29 December
	Late	Dryland	18 February	18 February	234	24 November	24 November
		Irrigated	16 February	22 February	6825	24 November	1 December
Yarrawonga	Early	Dryland	9 February	9 February	314	8 December	8 December
		Irrigated	7 February	13 February	6100	8 December	15 December
	Late	Dryland	22 February	27 February	85	17 November	24 November
		Irrigated	7 February	12 February	3183	3 November	10 November
Frances	Early	Dryland	26 December	26 December	342	15 September	15 September
		Irrigated	8 February	19 February	8777	24 November	8 December
	Late	Dryland	10 February	10 February	7	29 September	29 September
		Irrigated	10 February	19 February	4968	13 October	27 October
Hagley	Early	Dryland	5 January	5 January	4601	15 September	15 September
		Irrigated	2 January	14 January	21 672	15 September	6 October
	Late	Dryland	21 February	21 February	429	15 September	15 September
		Irrigated	7 February	7 February	7001	15 September	15 September

summer conditions. At Hagley, frost was the main stress index defining OFP; frost at Hagley occurred frequently in March, much earlier in the year than other regions. Irrigation had little effect on the timing and duration of maize OFP, but irrigation was clearly necessary for growth under conditions of frequent extreme heat and drought that typify summer conditions on mainland Australia (Harrison *et al* 2016a). At Yarrawonga in Victoria, the high exposure of crops to both heat and frost stress severely reduced yield, even under irrigation.

3.3. Effects of irrigation on optimal sowing windows

In general irrigation broadened the sowing window with which OFP could be attained (with the exception of summer maize and late fababean genotypes). For spring barley and durum wheat, earlier sowing was optimal for slower maturing (late) genotypes under irrigation (from 24 May) across all locations whereas, for the fast maturity (early) genotypes, optimal sowing was later (from 21 June; figure 5). Under dryland conditions, the late genotypes for the winter

grains had earlier sowing dates compared with faster developing genotypes. For example, optimal sowing dates at Kerang, Finley and Griffith for late genotypes were after 19 April, while for early genotypes sowing commenced after 3 May. The greatest yields for the dryland winter grains were obtained at Hagley (high rainfall region) in Tasmania for optimal sowing on 10 May (for late wheat genotypes), 7 June (early wheat), 17 May (late barley) and 28 June (early barley) as shown in figure 5.

Use of irrigation also extended the sowing window duration in which OFPs could be attained for canola. The highest canola yields were obtained at Hagley for the late (5351 kg ha^{-1}) and early (3804 kg ha^{-1}) genotypes across an optimal sowing window of 70 d (26 April to 5 July) and 35 d (31 May to 5 July), respectively. Under dryland conditions, optimal sowing periods of canola were relatively shorter and earlier compared with the irrigated sowing range. For example, the optimal sowing period for dryland canola at Hagley ranged from 19 April to 17 May (28 d) for long-season genotypes and 10 May to 12 June (33 d) for short-season
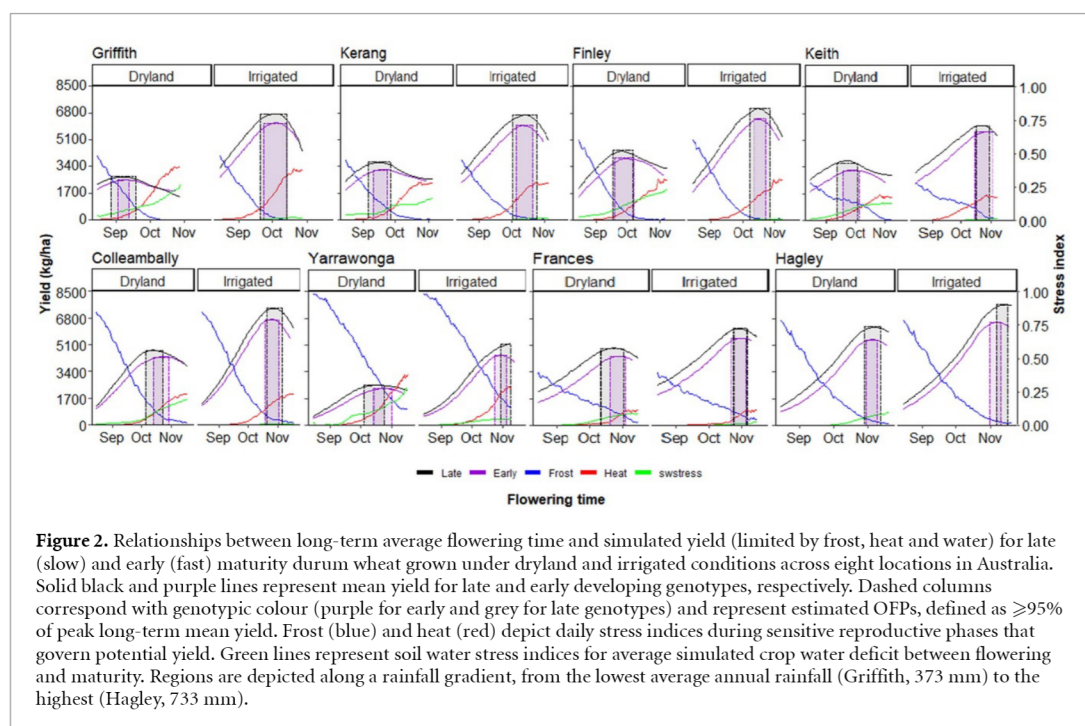
Figure 2. Relationships between long-term average flowering time and simulated yield (limited by frost, heat and water) for late (slow) and early (fast) maturity durum wheat grown under dryland and irrigated conditions across eight locations in Australia. Solid black and purple lines represent mean yield for late and early developing genotypes, respectively. Dashed columns correspond with genotypic colour (purple for early and grey for late genotypes) and represent estimated OFPs, defined as ≥95% of peak long-term mean yield. Frost (blue) and heat (red) depict daily stress indices during sensitive reproductive phases that govern potential yield. Green lines represent soil water stress indices for average simulated crop water deficit between flowering and maturity. Regions are depicted along a rainfall gradient, from the lowest average annual rainfall (Griffith, 373 mm) to the highest (Hagley, 733 mm).
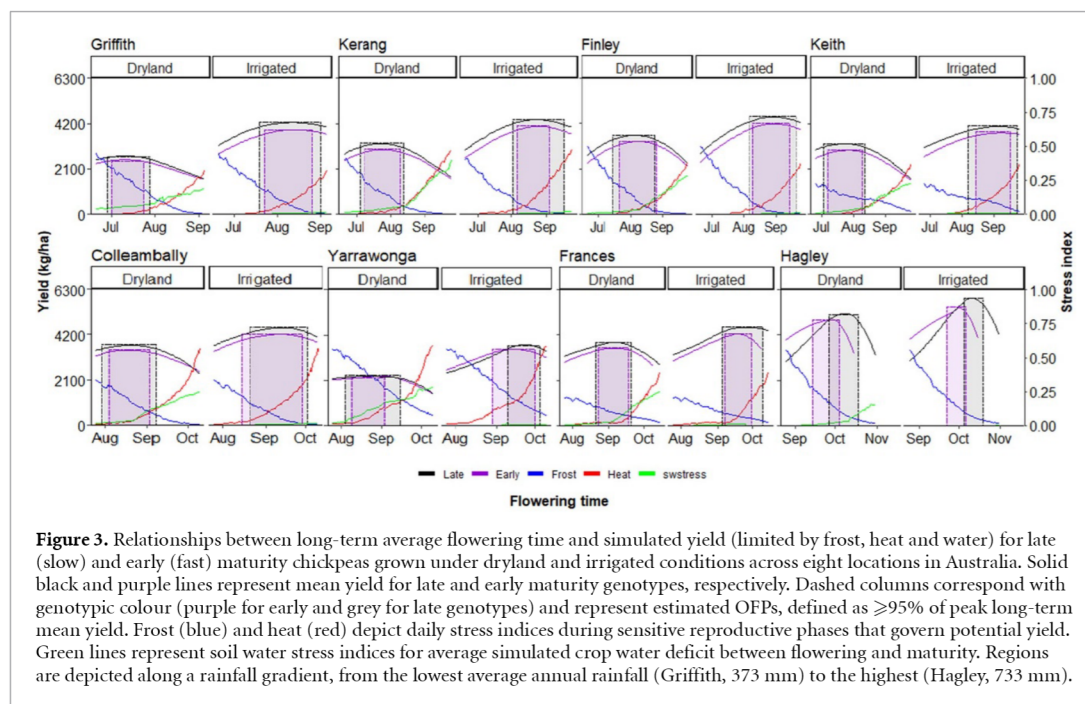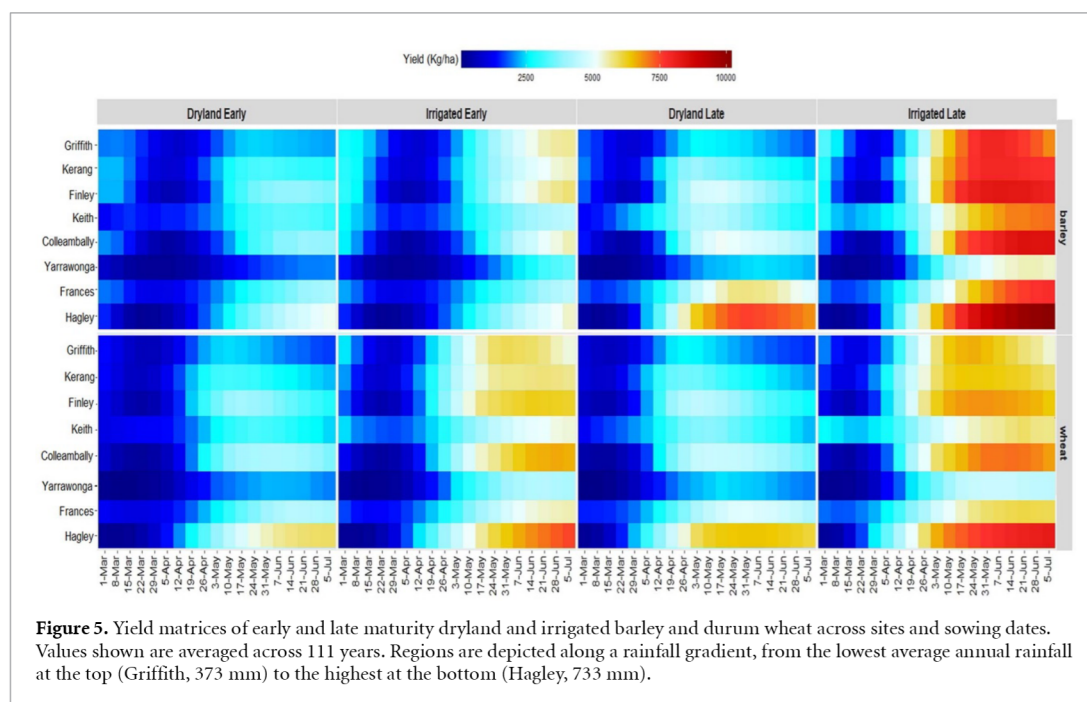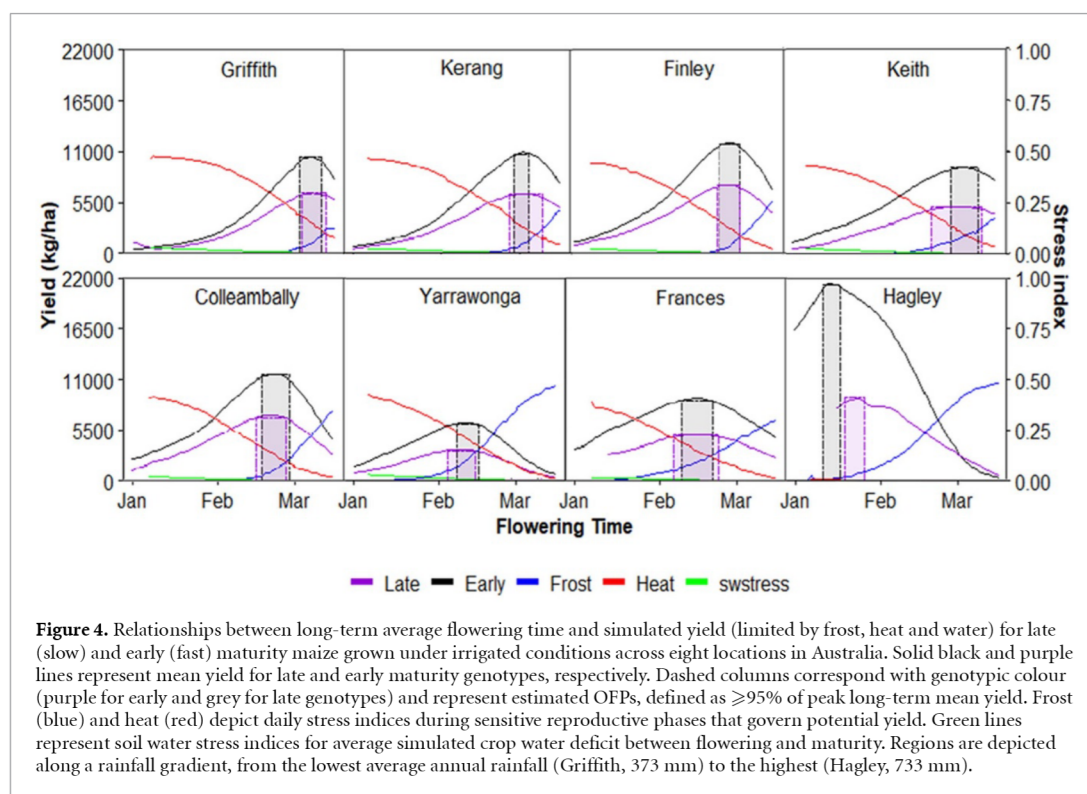

Figure 3. Relationships between long-term average flowering time and simulated yield (limited by frost, heat and water) for late (slow) and early (fast) maturity chickpeas grown under dryland and irrigated conditions across eight locations in Australia. Solid black and purple lines represent mean yield for late and early maturity genotypes, respectively. Dashed columns correspond with genotypic colour (purple for early and grey for late genotypes) and represent estimated OFPs, defined as ≥95% of peak long-term mean yield. Frost (blue) and heat (red) depict daily stress indices during sensitive reproductive phases that govern potential yield. Green lines represent soil water stress indices for average simulated crop water deficit between flowering and maturity. Regions are depicted along a rainfall gradient, from the lowest average annual rainfall (Griffith, 373 mm) to the highest (Hagley, 733 mm).

genotypes. The lowest dryland canola yields were achieved when sowing was conducted on 26 April for late genotypes at Griffith in New South Wales and 29 March for early genotypes at Yarrawonga in Victoria (figure 6).

Chickpea crops similarly achieved the greatest average yields at Hagley. Typically, rainfed chickpea genotypes had lower average yields and earlier sowing dates e.g. at Hagley from 17 May (5175 kg ha^{-1}) for late and 24 May (4904 kg ha^{-1}) for early maturing

genotypes, respectively, whereas irrigated chickpeas had higher yields and later sowing dates i.e. from 31 May (6098 kg ha^{-1}) for late and 14 June early (5498 kg ha^{-1}) genotypes (figure 6). Similar trends were observed for the lowest chickpea yields attained at Yarrawonga, where dryland genotypes had OFPs with earlier sowing dates (05 April; 2325 kg ha^{-1} for late and 12 April; 2314 kg ha^{-1} for early genotypes) compared with later optimal sowing times of irrigated genotypes (03 May; 3789 kg ha^{-1} for late and 10 May;

Figure 4. Relationships between long-term average flowering time and simulated yield (limited by frost, heat and water) for late (slow) and early (fast) maturity maize grown under irrigated conditions across eight locations in Australia. Solid black and purple lines represent mean yield for late and early maturity genotypes, respectively. Dashed columns correspond with genotypic colour (purple for early and grey for late genotypes) and represent estimated OFPs, defined as ⩾95% of peak long-term mean yield. Frost (blue) and heat (red) depict daily stress indices during sensitive reproductive phases that govern potential yield. Green lines represent soil water stress indices for average simulated crop water deficit between flowering and maturity. Regions are depicted along a rainfall gradient, from the lowest average annual rainfall (Griffith, 373 mm) to the highest (Hagley, 733 mm).

Figure 5. Yield matrices of early and late maturity dryland and irrigated barley and durum wheat across sites and sowing dates. Values shown are averaged across 111 years. Regions are depicted along a rainfall gradient, from the lowest average annual rainfall at the top (Griffith, 373 mm) to the highest at the bottom (Hagley, 733 mm).
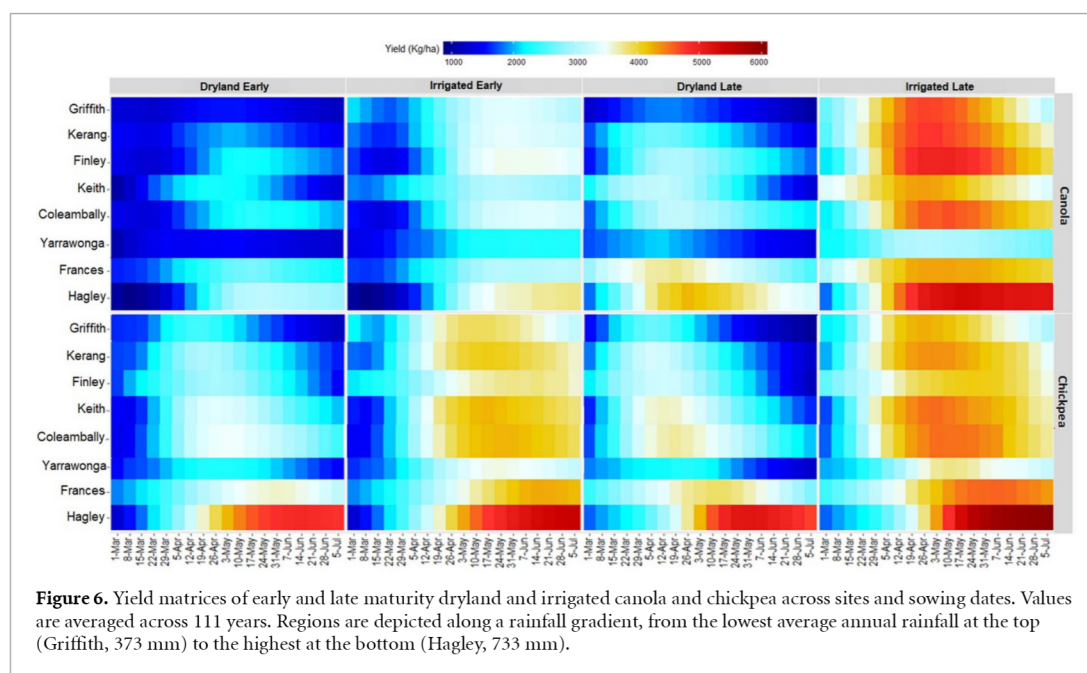
3555 kg ha^{-1} for early genotypes). Similar effects of irrigation on chickpea yields via optimal sowing windows were observed for other locations.

Optimal sowing times of fababean varied significantly across regions but were little effected by watering regime (figure S1). While irrigated yields were greater than those of rainfed yields, irrigation

ostensibly had little effect on the OFP of early maturity varieties, and only slightly delayed OFPs of later maturity varieties.

Yields of dryland maize were extremely low (7–1518 kg ha^{-1}) representing failed crops across mainland regions due to lack of summer rainfall (figure S2). Early maturity maize at Hagley was

Figure 6. Yield matrices of early and late maturity dryland and irrigated canola and chickpea across sites and sowing dates. Values are averaged across 111 years. Regions are depicted along a rainfall gradient, from the lowest average annual rainfall at the top (Griffith, 373 mm) to the highest at the bottom (Hagley, 733 mm).

the only viable rainfed option of all maize simulations conducted. Overall, early maturing genotypes resulted in greater yields than slower maturing genotypes. The highest irrigated yield (21 672 kg ha^{-1}) was obtained by the early maturity genotype at Hagley for an optimal sowing period of between 15 September and 6 October, whereas late maturity genotypes attained greatest yield (7355 kg ha^{-1}) at Finley in New South Wales for later optimal sowing periods of 1–8 December. Optimal sowing periods for other sites for the irrigated early and late genotypes were relatively clear: 24 November at Colleambally and Frances for late and early genotypes respectively, 1–8 December at Kerang and Finley for late genotypes, 22 December at Griffith for late genotypes, 29 December (Keith, Colleambally and Finley) for early genotypes and 12–19 January at Griffith for early genotypes.

3.4. Global warming shifts forward optimal flowering times and reduces yield, even for irrigated crops

Our results reveal significantly earlier OFPs over the 111 years simulation at all locations (figure 7 and table S4). Shifts in OFPs under changing climates were greater for dryland scenarios compared with irrigated conditions; forward shifts in OFPs of winter crops ranged from 2 to 43 d in dryland environments and from −6 to 19 d under irrigation. For maize, OFPs shifted by 2–40 d under rainfed conditions and by −9–13 d under irrigation. In some regions (e.g. Yarrawonga and Keith) irrigation delayed OFPs under current conditions. At the majority of sites, the decline in peak yield over the simulation was greater under dryland conditions (24%) compared with that under irrigation (13%; figure S3).

4. Discussion

The aims of this study were (a) to identify OFPs and optimal sowing times of early and late maturity genotypes of several crops under irrigated and dryland conditions, and (b) to elicit climate change impacts on OFPs. To the best of our knowledge, there are no previous studies of this kind. We showed that generally irrigation alleviated water stress, which increased growing seasons and delayed OFPs of winter crops. Compared with dryland crops, OFPs of irrigated winter crops occurred when heat stress was higher (e.g. after September or October). Similar results were observed by Hu *et al* (2021) in which flowering times of spring wheat were delayed in irrigated mega-environments globally, and by Peake *et al* (2021), who documented earlier flowering of chickpeas in rainfed treatments compared with irrigated crops in NSW. Together these results suggest that water stress not only limits yield due to growth inhibition *per se* but also penalises yield due to a truncation effect on growing season duration.

We simulated irrigated and rainfed fababean, durum wheat, spring barley, canola and maize across eight regions in New South Wales, Victoria, South Australia and Tasmania (figure 1). The total average area sown to these crops (dryland) is greatest in NSW and lowest in Tasmania (figure S4; ABARES 2021). Areas of dryland maize are low for Tasmania and Victoria due to lack of adequate summer rainfall, exposure to increased temperature and vapour pressure deficit during typical Australian summer. Consequently, summer C4 crops such as maize are often irrigated; here, we simulated rainfed maize for completeness only (failure of dryland maize in summer was expected due to the aforementioned climatic

factors). Irrigated cropping areas in NSW, Victoria and South Australia each comprise more than 30% of the total cropped area within each state (figure S4). In our study, crop types were chosen based on expert input from leading irrigation farmers and research development corporations, representing significant industry demand for knowledge on these crop types. Our study has helped fulfil these knowledge gaps.
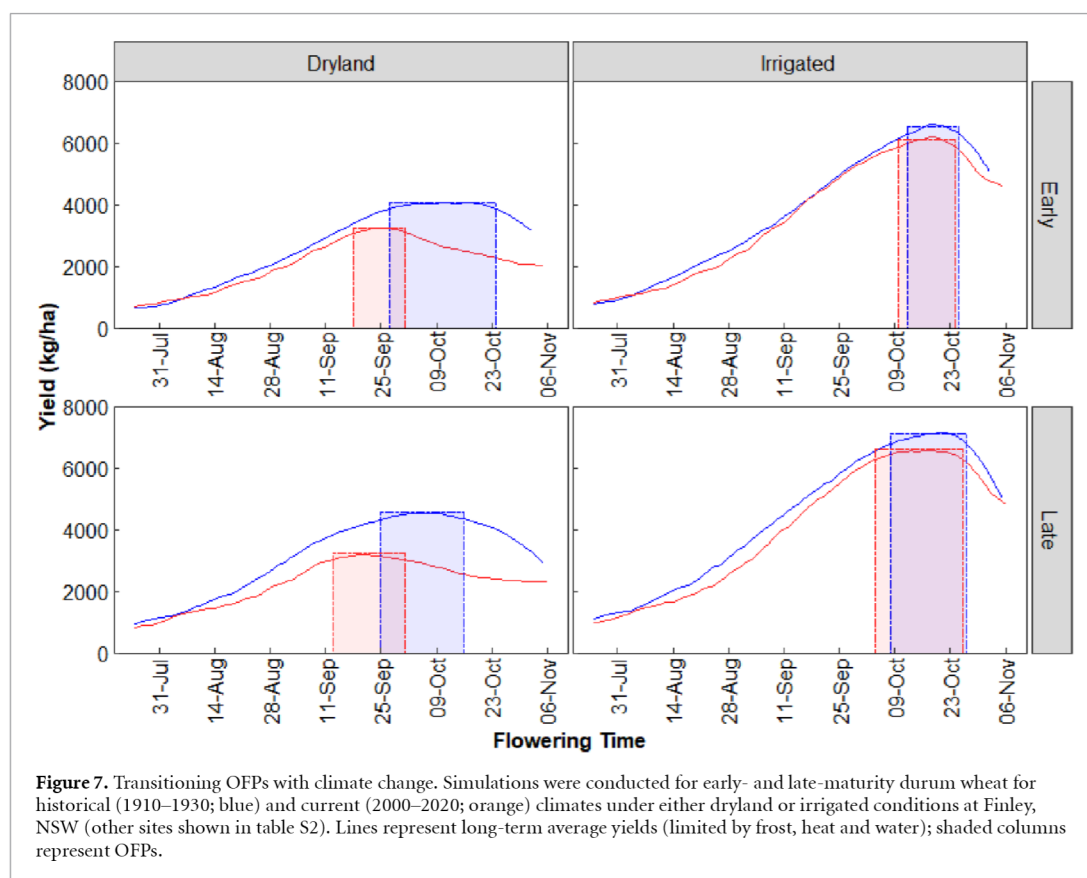
Australian winter crops are generally planted from March through to early July; most farmers have completed sowing before the end of June to ensure sufficient crop growth prior to spring (Fletcher *et al* 2016b, BCG 2018, Flohr *et al* 2018). In this study, OFPs we identified (figure 2) are within optimal flowering times observed in field studies. Porker *et al* (2020) conducted experiments 104 km south of Kerang and observed the highest dryland wheat yields when crops flowered between 10 September and 20 September. These dates fall within OFPs observed here (figure 2). BCG (2018) conducted an experiment at Corack near Kerang in Victoria, recording barley OFPs of 15–30 September with late May/early June sowing times, in line with the results we observed here for spring barley at Kerang (table S1). The OFP of canola we identified encompassed optimal flowering times in recent field experiments observed by Brill *et al* (2018) that were conducted in a diverse range of seasons and locations located near Griffith. Flowering dates resulting in the greatest yields fell within our simulated OFP. In another field experiment, Brand *et al* (2009) found that five chickpea genotypes realises maximal yields (2.4–2.6 t ha^{-1}) for sowing around 7 May, again corresponding to our optimal sowing time for attaining peak mean yield at Griffith. Similar results were observed for fababean by Armstrong *et al* (2015), who reported peak mean yields of 2.6 t ha^{-1}. Collectively, the alignment of our results with those observed in previous studies lends confidence to the analytical approaches applied here.

The overall yield advantage of irrigated crops shown here (ca. 44%) was partly attributed to reduced water stress during crop reproductive phases. These findings align with previous studies of mechanisms underlying yield improvement associated with irrigation (Husain *et al* 1988, Sissons *et al* 2014, Amiri *et al* 2016). Reduced heat stress of irrigated crops may also play a role (Phelan *et al* 2015, Taylor *et al* 2016, Langworthy *et al* 2020, Luan and Vico 2021), although the interplay between effect of irrigation on heat stress within the APSIM framework are currently not accounted for in the model. In cool temperate environments where heat stress is less frequent (e.g. at Hagley in Tasmania), irrigation resulted in greater yields than other high-temperature and water-limited regions. Under extreme heat stress (>0.25 stress indices beyond mid-October across most study sites; figures 2 and 3), yields of both irrigated and dryland crops were severely reduced, implying that

even irrigation was unable to entirely negate the detrimental impacts of high temperatures on yield. These observations agree with results of Luan and Vico (2021), who reported that irrigation could not completely nullify heat stress in environments where long-term average air temperature was 25 °C or higher. These results are however contrary to those shown by Tack *et al* (2017), in which irrigation completely offset the 8% decrease in winter wheat yield for every 1 °C increase in temperature. This divergence between studies is likely because the study by Tack *et al* (2017) was conducted under environments with cooler ambient conditions (similar to those in Tasmania), while the study of Luan and Vico (2021) more closely resembled environments in mainland Australia.

We also revealed wider OFPs for pulses (chickpea and fababean) compared with other monocotyledon cereal crops in most regions, except for highly frost prone sites (figure 3 and tables 6, S2). These results align with results of Smith (1982) who found that irrigated fababeans had longer flowering periods and delayed pod set compared with non-irrigated plants. Smith (1982) postulated that variation in the OFP duration for a given crop across contrasting environments underpinned seasonal variability at individual sites; underlying drivers of climatic variability at any given site can be widespread (Flohr *et al* 2017, Chen *et al* 2020, Liu *et al* 2020). Flohr *et al* (2017) suggest that wider OFPs may arise because long-term soil water, frost and heat are more variable. Alternatively, broad OFPs may be interpreted as highly variable seasonal conditions that, from 1 year to the next, make it difficult to discern a stable and relatively stress-free optimal flowering window. Indeed, increasingly variable climatic conditions associated with climate change have been well documented in Australia and elsewhere (Harrison 2021). On the other hand, narrower OFPs suggest environments that have lower inter-annual variability such that optimal flowering times and peak yields occurred around the same time each season (e.g. Hagley; figure 3). Narrow OFPs may also suggest a relatively fast seasonal transition between frost and occurrence of heat or water deficit (Flohr *et al* 2017). Wider OFPs for winter pulses compared with cereals and oilseeds could also underpin differences in crop sensitivity to abiotic stresses. Generally, cool-season pulses (chickpea and fababean) are highly responsive to extreme temperature (heat and frost) during reproductive stages (Nadi 1969, Siddique *et al* 1999, Dreccer *et al* 2018) which induce flowering over broader range of dates.

In contrast to winter crops, OFPs of irrigated summer crops were defined here as the point at which heat was declining and frost risk was increasing. Water stress was also accounted for in our assessments of dryland summer crops (figure 4). Maize OFPs occurred between mid-February to early March across most sites, although in high rainfall regions

Figure 7. Transitioning OFPs with climate change. Simulations were conducted for early- and late-maturity durum wheat for historical (1910–1930; blue) and current (2000–2020; orange) climates under either dryland or irrigated conditions at Finley, NSW (other sites shown in table S2). Lines represent long-term average yields (limited by frost, heat and water); shaded columns represent OFPs.

(e.g. Hagley) the OFP occurred much earlier (January) primarily due to increasing frost stress. Few studies have examined OFPs of rainfed and irrigated summer maize in Australia, possibly because the use of irrigated maize in Australia is relatively new. In contrast, flowering times of maize crops have been well documented in Europe (Harrison *et al* 2014c, Parent *et al* 2018) and the USA (Schauberger *et al* 2017, Baum *et al* 2019) for both rainfed and irrigated conditions.

We found a general trend for early-sown late maturity winter genotypes to have yield advantage over later sown early maturity genotypes, in line with past agronomic studies which have shown that well-adapted, slow-developing winter cultivars are required for early sowing to be viable in Australia (Anderson *et al* 1996, Kirkegaard and Hunt 2010, Ludwig and Asseng 2010, Bell *et al* 2015, Fletcher *et al* 2016a, Hunt 2017, Flohr *et al* 2018, Hunt *et al* 2019, Chen *et al* 2020). Contrarily, early maturity maize genotypes (CRM < 100) achieved higher yield than late maturity genotypes (CRM > 110) in dryland and irrigated conditions. These findings are consistent with those reported by Pembleton and Rawnsley (2012) in which earlier sown maize crops and faster maturing hybrids were high yielding, viable options to manage the risk of frost stress than the later sown crops and slower maturing genotypes in Tasmania.

Parent *et al* (2018) showed that by adapting maize genetics over time, European farmers have effectively mitigated site-specific impacts of climate change by adapting flowering times of maize through adoption of new genetics and sowing times. The forward shifts in OFPs observed in the present study (figure 7 and table S4) were greater for dryland environments (2–43 d) compared with those under irrigation (−6–19 d). Our results agree with flowering time projections under future climates (Chen *et al* 2020, Liu *et al* 2021) which suggest that under rainfed scenarios, OFPs tend to occur earlier than OFPs under wetter scenarios. Our findings suggest that irrigation partially mitigates the impact of increasing temperatures and declining rainfall on crop growth, analogous to findings of Schauberger *et al* (2017). Yield penalties caused by climate change in the present study were higher under dryland conditions (24%) than under irrigation (13%, see figure S3 and table S4) suggesting that farmers will need more than shifts in sowing time, genetics and irrigation to completely negate (or reverse) future impacts of climate change in Australia.

Plant stress related to water deficit (referred to as drought stress by some) can cause reversible declines in leaf water potential, membrane stability, leaf transpiration and photosynthetic activity, leading to increased reactive oxygen species, anti-oxidative functions, lipid peroxidation and membrane injury

(Abid *et al* 2018). Drought stress also causes stomatal closure, decreasing CO_2 availability within the chloroplast, inhibiting photosynthesis (Abid *et al* 2018). These effects reduce carbon assimilation and may cause saturation of the electron transport system (Reddy *et al* 2004). Water stress alleviation through rainfall or irrigation allows stomata to open, increases leaf turgor, transpiration and leaf osmotic potential, resulting in higher canopy evapotranspiration and evaporative cooling, and increased net leaf and canopy photosynthetic rates (Harrison *et al* 2010). Plant recovery from water stress is however also a function of the extent and duration of stress exposure and the timing of re-watering relative to plant stage (Langworthy *et al* 2019, Sah *et al* 2020); recovery induced by irrigation is particularly effective if watering occurs during later crop stages or during long dry spells (Jha *et al* 2018). Moderate water deficit applied both at crop tillering and jointing tends to have little effect on days to anthesis, grain filling duration, dry matter and grain yield (Jha *et al* 2018). In contrast, severe water deficit at tillering and jointing results in earlier anthesis and shifts forward grain filling durations (Abid *et al* 2018). Crop development under severe water stress is hastened, underpinned by earlier leaf node appearance and less leaf nodes. During reproductive development, water stress increases relative assimilate partitioned to kernels, at the expense of that partitioned to leaves and nodes (Desclaux and Roumet 1996). Water stress at tillering has less effect on stomatal conductance and photosynthesis compared with when water stress occurs at jointing or flowering. Indeed, water stress exposure during flowering inhibits potential kernel set and filling, reducing kernel number and weight (Pedersen and Lauer 2004). Our results align well with these observations together with those of Desclaux and Roumet (1996) and Foulkes *et al* (2007), who showed that water stress during vegetative phases results in faster development and less canopy architecture and earlier senescence. These factors reduce assimilate available for re-translocation to developing kernels, again decreasing kernel number and weight. Jha *et al* (2018) suggested that earlier moisture stress exposure during the vegetative stage had a greater effect on the timing of maturity compared with moisture stress during flowering or pod filling, with moisture stress during vegetative stages of soybean delaying flowering by 7–8 d. In our study, the range in forward shifts flowering were wider, because we examined more year × site × crop combinations.

5. Conclusions

Alleviation of water stress by irrigation increased crop growing season durations, delayed OFPs of winter crops and increased yields by 44% compared with dryland environments. Our results indicate that forward transitions of OFPs with global warming are greater under dryland conditions compared with environments with irrigation. We showed that early-sown late-maturity winter crops and later-sown early-maturity maize (summer) genotypes are preferable to achieve the desirable later OFPs that are conducive to maximising yield potential. We also revealed the fortuitous observation that irrigation can broaden OFPs, allowing more flexibility with sowing times, and perhaps more forgiveness with late sowing. Nonetheless, use of irrigation *per se* was not enough to prevent yield penalties caused by climate change (13% average reduction), suggesting that other holistic adaptations—including genetics, management and whole farm planning—will be required to completely negate future impacts of climate change on irrigated crop yields.

Data availability statement

The data developed in this study are available upon reasonable request from the authors.

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no conflict of interest.

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