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Early sowing systems can boost Australian wheat yields despite recent climate change

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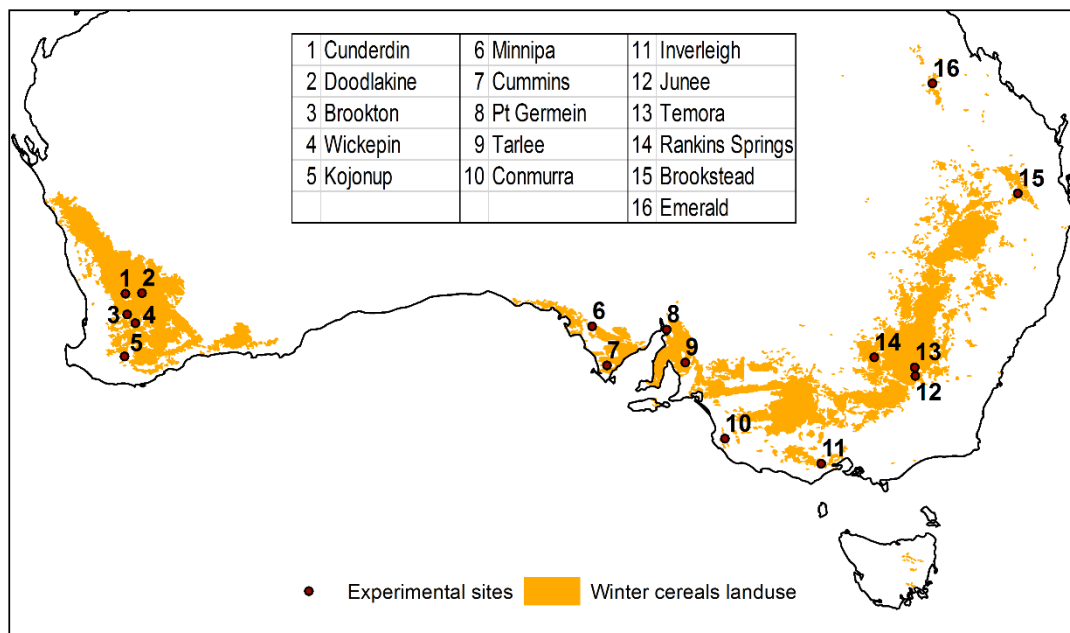


Figure S1. A map of the Australian wheat belt showing the location of the field experiments. Map outline © Commonwealth of Australia (Geoscience Australia) 2018.

Table S1. Alleles of the major genes which govern response to vernalisation (Vrn; *v*=sensitive, *a*=insensitive) and photoperiod (Ppd; *b* and *c*=sensitive, *a*=insensitive) in the four near-isogenic lines.

Line	Photoperiod		Vernalisation		
	Ppd-B1	Ppd-D1	Vrn-A1	Vrn-B1	Vrn-D1
Mid winter	<i>a</i>	<i>c</i>	<i>v</i>	<i>v</i>	<i>v</i>
Fast winter	<i>a</i>	<i>a</i>	<i>v</i>	<i>v</i>	<i>v</i>
Very slow spring	<i>b</i>	<i>b</i>	<i>e</i> *	<i>a</i>	<i>a</i>
Fast spring (cv. Sunstate)	<i>a</i>	<i>a</i>	<i>v</i>	<i>a</i>	<i>a</i>

*Insensitive Langdon allele of Vrn-A1

Table S2. Locations, coordinates, elevation above sea-level (ASL), year of small plot experiments and corresponding annual rainfall and times of sowing and grain yield of the four near-isogenic lines derived from Sunstate at all experimental sites used in the study. P-values and LSD are for the interaction between sowing time and line. All sites had four replicates of each treatment (n=4) with the exception of Junee (n=1).

Environment	Site	Year	Sowing calendar date	Sowing relative to fast spring optima (days)	Grain yield (t/ha) at 12.5% moisture				P-value & LSD (P=0.05) sowing x line
					Mid winter	Fast winter	Very slow spring	Fast spring (Sunstate)	
Southern	Cunderdin	2015	14-Apr	-40	-	2.3	1.8	0.8	<0.001
Mediterranean	-31.6°, 117.2° 240 m ASL	242 mm	28-Apr	-20	-	2.5	1.4	2.8	0.3
			22-May	0	-	1.7	0.8	2.7	
	Doodlakine -31.6°, 117.9° 280 m ASL	2014 219 mm	17-Apr*	-30	0.5	0.8	0.7	0.8	<0.001
			05-May	-20	0.4	0.6	0.3	1.1	0.1
			21-May	0	0.4	0.6	0.1	0.6	
		2015 167 mm	15-Apr	-40	1.3	2.1	1.3	1.9	<0.001
			28-Apr	-20	1.6	2.1	1.5	2.3	0.2
			22-May*	0	0.8	1.3	0.4	1.8	
	Wickepin -32.7°, 117.6° 297 m ASL	2014 390 mm	16-Apr*	-30	3.6	3.7	3.6	3.1	<0.001
			06-May	-10	3.2	3.2	3.3	2.8	0.3
			20-May	0	3.1	3.2	3.1	3.1	
	Kojonup -34.0°, 117.2° 355 m ASL	2014 491 mm	16-Apr*	-30	4.1	4.4	4.3	3.9	<0.001
			11-May	-10	4.5	4.3	4.3	4	0.5
			02-Jun	10	3.8	3.8	4	4.4	
		2015 -33.7°, -117.0° 428 mm 313 m ASL	16-Apr	-40	4.3	3.1	4.3	1.6	<0.001
			04-May	-20	3.9	3.9	4.2	3.4	0.6
			22-May	0	3.9	3.8	2.8	3.7	
	Minnipa -32.8°, 135.2° 171 m ASL	2014 338 mm	11-Apr	-30	2.4	2.9	2.3	2.3	<0.001
			13-May	0	1.6	1.9	1.2	2.1	0.2
			28-May	20	1.5	1.6	1	1.9	
		2015 -32.8° 135.2° 314 mm	13-Apr	-30	2.2	2.7	2.2	2.1	<0.001
			29-Apr	-10	1.8	2.6	1.8	3.1	0.3
			13-May	0	1.3	2	0.8	2.4	
	Cummins -34.3°, 135.7° 66 m ASL	2014 430 mm	15-Apr*	-40	3.8	3.6	2.4	3	<0.001
			06-May	-20	3.5	3.7	1.2	4.2	0.6
			29-May	0	2.5	3.3	1.9	3.2	
		2015 360 mm	10-Apr	-30	2.9	3.4	1	2.8	0.012
			29-Apr	-20	2.2	2.8	1.1	3.1	0.5
			14-May	0	2.5	2.8	1.5	3.2	

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Environment	Site	Year	Sowing calendar date	Sowing relative to fast spring optima (days)	Grain yield (t/ha) at 12.5% moisture				P-value & LSD (P=0.05) sowing x line
					Mid winter	Fast winter	Very slow spring	Fast spring (Sunstate)	
Southern Temperate	Pt Germein -32.9°, 138.0° 40 m ASL	2014	11-Apr	-20	2.8	2.8	2.2	2.3	<0.001
			30-Apr	0	1.9	1.7	1.6	2.4	0.5
			20-May	20	0.6	0.9	1.2	2.5	
		2015	08-Apr	-20	2.4	3.1	2.2	2.6	<0.001
			27-Apr	0	1.9	2.3	2	3.6	0.2
			19-May	20	1.3	1.8	0.2	2.2	
	Tarlee -34.2°, 138.7° 250 m ASL	2013	28-Mar*	-40	4.7	5.4	3.7	3.5	0.003
			16-Apr	-20	4.3	4.7	3.1	2.4	0.6
			01-May	-10	4.1	4.2	3.7	3.8	
			17-May	10	3.9	4.3	3.1	3.9	
			31-May	20	3.5	4.1	3	3.6	
		2014	14-Apr	-30	-	6	-	3.8	<0.001
			29-Apr	-10	-	6.1	-	6.3	0.6
			12-May	0	-	4.7	-	4.8	
			30-May	20	-	3.5	-	3.7	
	Brookton -32.4°, 117.3° 243 m ASL	2015	15-Apr	-40	2.8	2.5	2.4	1.2	<0.001
			29-Apr	-20	2.4	2.9	2.7	1.3	0.3
			23-May	0	1.7	2.6	1.8	2.5	
	Rankins Springs -34.0°, 146.0° 137 m ASL	2014	17-Apr	-30	5.1	5.1	3.4	3.3	<0.001
			22-May	10	-	3.4	-	4	0.4
		2013	26-Mar*	-40	5.9	4.8	2.5	3.4	0.007
			08-Apr	-30	6.2	4.9	2.1	3.2	1.0
			24-Apr	-20	5.7	5.5	2.4	3.8	
			10-May	0	6.2	6.2	2.9	4.9	
	Juneë -34.7°, 147.5° 304 m ASL	2012	18-Apr	-30	5.5	5.3	5.5	4.7	NA
			26-Apr	-20	5.3	5	5.2	5.4	NA
			08-May	-10	4.1	5.1	4.1	4.6	
			17-May	0	4	4.4	4.1	4.3	
	Temora -34.4°, 147.5° 273 m ASL	2015	17-Apr	-30	3	3.4	3.4	4	<0.001
			27-Apr	-20	3.6	3.9	3.5	4.1	0.4
			07-May	-10	2.9	3.4	3.3	3.1	
			15-May	0	2.8	3.2	3.1	3.4	
		2016	15-Apr	-30	7.4	5.2	5.5	2.1	<0.001
			27-Apr	-20	6.8	7.4	5.2	6.8	0.9
			06-May	-10	6.5	7.3	5.0	6.7	
			15-May	0	5.4	6.6	4.5	6.5	
	Conmurra -37.1°, 140.2° 25 m ASL	2015	13-Apr	-30	3.2	1.7	2.1	1.2	<0.001
			28-Apr	-20	3.4	3.2	2.5	2.3	0.5
			15-May	0	4	3.8	3	3.6	

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Environment	Site	Year	Sowing calendar date	Sowing relative to fast spring optima (days)	Grain yield (t/ha) at 12.5% moisture				P-value & LSD (P=0.05) sowing x line
					Mid winter	Fast winter	Very slow spring	Fast spring (Sunstate)	
Northern	Emerald	2014	29-Apr*	-30	1.7	2.1	3.3	3.7	<0.001
Sub-tropical	-23.5°, 148.2° 175 m ASL	548 mm	13-May*	-20	1.8	2.7	4	3.5	0.6
			30-May*	0	2.6	2.6	3.6	3.8	
		2015	20-Apr*	-40	0.3	0.5	1.7	2.2	<0.001
		381 mm	1-May*	-30	0.4	0.5	1.6	2.6	0.3
			11-May*	-20	0.3	0.7	1.8	2.3	
	Brookstead -27.7°, 151.5° 393 m ASL	2014	17-May	-20	1.7	1.7	1.9	1.2	<0.001
		706 mm	4-Jun*	-10	1.7	1.7	1.9	1.5	0.2
			24-Jun*	10	1.5	1.8	1.5	1.6	
		2015	10-May	-30	3.8	3.9	4.1	3.7	<0.001
		730 mm	25-May	-20	3.1	3.2	3.4	3.3	0.2
			10-Jun	0	3.2	3.5	3.6	3.7	

*Irrigation used to establish

Table S3. The number of samples (n) used to calculate predicted yield mean presented in Figure 1.

Agro-climatic group	Sowing relative to fast spring optima (days)	Fast spring	Fast winter	Mid winter	Very slow spring
Southern Mediterranean (Figure 1a)	-40	20	20	16	-
	-30	28	28	24	-
	-20	36	36	32	-
	-10	20	20	16	-
	0	48	48	40	-
	10	8	8	8	-
	20	20	20	16	-
Southern Temperate (Figure 1b)	-40	4	4	4	-
	-30	21	21	21	-
	-20	17	17	17	-
	-10	9	9	9	-
	0	17	17	17	-
Northern sub-tropical (Figure 1c)	-40	4	4	4	4
	-30	8	8	8	8
	-20	15	16	16	16
	-10	4	4	4	4
	0	16	16	14	15

Table S4. Details of 23 locations where APSIM simulations were conducted, sowing rules and cultivars used. APSIM phenology parameters for the sown cultivars are shown in Table S5.

Environment	Location	Annual rainfall (1955-2012) (mm)	APSoil file no.	PAWC (mm) to (depth (m))	Earliest sowing date for current practice	Dry sowing start date	Cultivars chosen for current and early sowing system	Percent of crops sown to early cultivar	Average date sowing commenced in current practice	Average date sowing commenced in early sowing system	% crops in early strategy where yield <0.5 t/ha	% crops in current practice where yield <0.5 t/ha	Percent of years early sowing occurs
Southern Mediterranean	Mingenew	389	432	148 (2.5)	10-May	25-May	FS3, VSS2	63%	13-May	15-Apr	0%	0%	75%
	Wongan Hills	364	400	140 (2.5)	10-May	25-May	FS3, FW	62%	12-May	15-Apr	1%	0%	90%
	Cunderdin	362	486	61 (1.3)	10-May	25-May	FS3, MW1	80%	16-May	14-Apr	8%	15%	90%
	Merredin	326	401	84 (1.2)	10-May	25-May	FS2, FW	79%	15-May	13-Apr	1%	1%	85%
	Hyden	355	1152	47 (1.0)	10-May	25-May	FS2, FW	72%	11-May	14-Apr	20%	20%	85%
	Kojonup	498	473	134 (2.1)	15-May	25-May	FS3, MW3	63%	16-May	18-Apr	0%	0%	85%
	Esperance	631	455	69 (1.4)	20-May	25-May	FS3, FW	96%	22-May	06-Apr	0%	0%	100%
	Minnipa	328	909	138 (1.2)	01-May	25-May	FS1, FW	29%	13-May	02-May	11%	10%	35%
	Cummins	411	EL037	121 (1.7)	05-May	25-May	FS3, MW1	61%	07-May	12-Apr	0%	0%	85%
	Port Germein	325	602	139 (1.1)	01-May	25-May	FS3, MW2	62%	10-May	13-Apr	0%	0%	70%
	Tarlee	458	279	225 (1.5)	10-May	25-May	FS3, MW2	80%	12-May	08-Apr	0%	0%	90%
	Longerenong	414	746	209 (1.6)	15-May	25-May	FS2, MW3	39%	19-May	02-May	45%	43%	50%
	Birchip	375	733	190 (1.6)	01-May	25-May	FS4, FW	39%	15-May	30-Apr	28%	28%	45%
	Kerang	401	733	190 (1.6)	01-May	25-May	FS4, FW	45%	13-May	21-Apr	11%	15%	65%
Southern Temperate	Conmurra	581	344	253 (1.4)	20-May	25-May	FS3, SW1	93%	20-May	26-Mar	0%	0%	100%
	Lake Bolac	556	914	163 (1.8)	20-May	25-May	FS3, SW2	70%	20-May	07-Apr	9%	9%	90%
	Temora	536	modified 179	174 (1.8)	05-May	25-May	FS3, MW3	78%	15-May	31-Mar	25%	28%	80%
	Condobolin	458	688	207 (1.5)	05-May	25-May	FS3, MW1	41%	11-May	26-Apr	19%	22%	55%
Northern Sub-tropical	Trangie	514	683	141 (1.8)	05-May	25-May	FS3, MW2	82%	06-May	08-Apr	2%	3%	100%
	Goondiwindi	605	29	156 (1.5)	20-May	15-Jun	FS3, FW	87%	23-May	16-Apr	18%	9%	90%
	Oakey	643	30	286 (1.8)	20-May	15-Jun	FS3, MW1	90%	22-May	08-Apr	16%	6%	90%
	Roma	578	851	146 (1.5)	20-May	15-Jun	FS3, MW1	52%	31-May	07-May	26%	30%	60%
	Emerald	613	911	287 (1.8)	20-May	15-Jun	FS3, VSS1	90%	22-May	17-Apr	18%	9%	90%

Table S5. APSIM phenology parameters for the range of cultivars sown across 23 locations. Parameters were chosen to ensure that flowering occurred during the optimal flowering period for the location for the current practice and early sowing dates.

Cultivar development class	cultivar code	vern_sens	photop_sens	tt_end of juvenile to floral initiation	tt_floral initiation to flowering	tt_flowering to start of grain fill	tt_grain filling (start to end)
Fast spring	FS1	1.5	2.7	400	555	120	545
Fast spring	FS2	1.5	2.8	400	555	120	545
Fast spring	FS3	1.5	3	400	555	120	545
Fast spring	FS4	2.8	2.9	400	426	91	612
Very slow spring	VSS1	2.4	2.5	600	655	250	500
Very slow spring	VSS2	2.5	2.5	600	655	250	500
Fast winter	FW	4	0	400	380	120	545
Mid winter	MW1	4	2	400	380	120	545
Mid winter	MW2	3.9	3.7	400	380	120	545
Mid winter	MW3	3.9	3.9	400	380	120	545