Field Crops Research 239 (2019) 82–91

Contents lists available at ScienceDirect

Field Crops Research

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

Potential yield benefits from increased vernalisation requirement of canola in Southern Australia

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ARTICLE INFO

Keywords:
Rapeseed
Photoperiod
Phenology
Daylength

ABSTRACT

Long season, winter-type canola cultivars have the potential for significantly higher yields than short-season, spring-type canola, yet until recently, breeding of new canola cultivars in Australia has focussed on spring-type canola. This has been to accommodate the typically drier, warmer conditions across the Australian cropping belt where long-season varieties do not perform well due to delayed flowering and risk of water-stress during grain fill. However, as cropping continues to expand into the Australian High Rainfall Zone (500–900 mm, HRZ), breeders have become increasingly interested in developing winter-spring crosses (not yet commercially available) which have an intermediate phenology between that of a spring and winter-type canola. As the vernalisation requirement for these crosses is lower than winter-type canola, the areas where such cultivars can be grown profitably in Australia is potentially much wider than for winter-type canola. Field experimentation and crop simulation studies across the potential cropping region of southern Australia were used to determine the yield potential of these winter-spring canola crosses compared with currently available spring-type and winter-type cultivars. Our analysis showed that the four winter-spring crosses evaluated had a range of vernalisation requirements which were between the small requirements of spring-types and the large requirement of winter-types. In this study the Catchment Analysis Tool (CAT) spatial modelling framework was used to determine the expected canola yields of four cultivars across the entire cropping region of southern Australia. These cultivars were the spring-type 45Y88CL, winter-type Hyola® 970CL and two winter-spring crosses K50057 and K50058 with vernalisation requirements at the higher end and the lower end of the range of winter-spring crosses, respectively.

The potential benefit of some increase in the vernalisation requirement, based on the area currently sown to canola, was an additional 381 M tonnes per year (based on 50-year average) of canola, if K50058 was sown in areas where it proved superior to 45Y88CL. At the 5-year average canola price of \$486 t^{-1}, this would provide an additional AUD 185 Mil/annum for the industry. In general, the modelled yield advantage from canola cultivars with increased vernalisation requirement was greater in the areas of southern Australia that had milder climates and higher rainfall. The value to the Australian canola industry of substituting spring cultivars (e.g. 45Y88CL) with winter x spring (K50057) or winter (Hyola970CL) cultivars where they had a yield advantage, was AUD 82.8 M and AUD 29.2 M, respectively.

1. Introduction

Current cultivars of canola (*Brassica napus* L.) that are available in Australia tend to be short-season types aimed at early maturation to escape water-stress during grain filling in the drier regions of the cropping belt (Salisbury et al., 2016). These Australian cultivars are spring-type canola, derived from Asian, European and Canadian ancestry, with breeding goals primarily focused on blackleg resistance and reduced photoperiod requirement for flowering (Cowling, 2007). The expansion of cropping into the Australian High Rainfall Zone

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https://doi.org/10.1016/j.fcr.2019.05.015
Received 29 August 2018; Received in revised form 15 April 2019; Accepted 18 May 2019
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(500–900 mm yr^{-1}, HRZ) over the past 25 years has created additional challenges for breeders to provide longer season cultivars to better match the growing conditions within this zone (Light et al., 2011). Research aimed at meeting these challenges in the HRZ, has demonstrated that the introduction of longer season winter-type canola cultivars will yield 20% more than spring-types at Hamilton, Victoria, Australia (Riffkin et al., 2012). This yield advantage of winter-type canola has been shown to have a wide applicability to the HRZ (Christy et al., 2013; Lilley et al., 2015), however seed companies in Australia generally directly import winter-type canola from Europe and continue to focus breeding efforts on spring-type canola (Salisbury et al., 2016).

The HRZ can sustain a later maturing canola, as it is cooler, with a more even rainfall distribution, providing less exposure to terminal drought during grain filling. In addition, the HRZ can support earlier sowing than in lower rainfall regions. Earlier sowing can be more productive as long as crops still flower within the safe flowering window to minimize the risks of early frost and subsequent high temperatures (Kirkegaard et al., 2016). The ability to plant earlier and flower later allows the HRZ to grow a more diverse range of cultivars than other Australian cropping regions where phenology tends to be more tightly prescribed. Thus, in the HRZ cultivars may have a wider range of sensitivities to photoperiod and vernalisation to regulate their phenological development. In wheat, Fischer (2011) challenged breeders to develop cultivars with a consistent and optimally stable date of anthesis across a broad range of establishment dates. Fischer's (2011) idea that some level of vernalisation sensitivity would be required to achieve this is just as relevant for canola.

For growers to fully realise the benefits of the trend towards earlier sowing dates, greater breeding emphasis is needed on cultivars that can achieve a site-specific optimal flowering period from earlier sowing (Yang et al., 2014; Kirkegaard et al., 2016). Spring-type canola are quantitative long day plants, with a potential response to vernalisation and long days, but without an absolute requirement for either (Myers et al., 1982; Nelson et al., 2014). In contrast, the vernalisation requirement of winter-type canola is large. Like spring-type canola, winter-types are long day plants, therefore phenological development rates are sensitive to photoperiod (Robertson and Lilley, 2016). In Australia, breeders have been developing a range of winter-spring crosses (not yet commercially available) which have an intermediate phenology between that of spring and winter-type canola (Lilley et al., 2015). This intermediate phenology provides opportunity for such a canola to be planted much earlier than current practice and to flower at a site-specific optimal flowering period (Lilley et al., 2015). Additionally, if the vernalisation requirement for these winter-spring crosses were lower than in winter-type canola, the areas where such cultivars could be grown profitably may be much wider than shown for winter-type canola by Christy et al. (2013).

The aim of this paper is to determine where winter-spring crosses and winter-type canola cultivars outperform the spring-type canola cultivars with a focus on the HRZ of southern Australia. This will inform breeders selecting (higher yielding,) better adapted germplasm and provide recommendations to growers on the optimum sowing times for different genotypes across different environments. This paper incorporates experimental data on the growth and phenology response of winter-spring, winter and spring-type cultivars with modelling to predict likely performance over a range of seasons and locations.

2. Materials and methods

2.1. Field experiments location

Field experiments were sown under rainfed (Rf) conditions in a range of years between 2014 and 2017 at eight locations across the HRZ of south-eastern Australia: Bool Lagoon, South Australia; Cressy, Tasmania; Inverleigh, Westmere and Hamilton, Victoria; and Perth, Kojonup and Merredin, Western Australia (Fig. 1). The sites range in latitude / longitude from 31.49 °S / 118.24 °E at Merredin in WA to 41.68 °S / 147.08 °E at Cressy in Tasmania and represent a large climatic range. For the growing season (May to Nov) the long-term Average (LTA) rainfall ranges from 218 mm at Merredin to 624 mm at Floreat, mean growing season minimum temperatures range from 3.8 °C at Cressy to 11.0 °C at Floreat and mean maximum temperatures range from 14.7 °C at Cressy to 21.2 °C at Merredin (Table 1). Average day lengths between May and August ranged from 10.75 h at Cressy to 11.37 h at Merredin. Irrigation was provided at Kojonup in 2015 (more detail in Zhang et al. (2017)) as a treatment, however in 2017 the irrigation was applied at the first sowing time only to initiate germination and had no further effect on biomass. At Hamilton, additional rainfall exclusion treatments (Ex) were applied in 2015, 2016 and 2017 and irrigation treatments (Ir) in 2015 and 2017 using a multi-environment facility (MEF). Water stress (waterlogging or dry conditions) within a crop's growth cycle can potentially hasten phenological development. The three different water regimes imposed by the MEF, under the same soil type, temperature and day length conditions allowed the consideration of the impact of water availability on phenological development. For the rainfall exclusion treatments, rain was excluded from the plots using three independent, automated rain out shelters which each covered an area of 42 m^2. Shelters were powered by a solar system and were activated to move along tracks when rain hit a sensor (Kant et al., 2017). In the absence of rain, the shelters moved to a parked position south of the plots. For the irrigation treatment, water was supplied through surface drip irrigation with a target of maintaining a soil water tension at 50 K Pa. Irrigation scheduling decisions were based on hourly logged data from gypsum blocks placed at a depth of 30 cm.

2.2. Controlled environment studies

The combined field measured phenology dataset has a great deal of data from short day (SD) environments (< 12 h) across a wide, evenly distributed range of growing season temperatures (ca. 9–15 °C). A controlled environment study was conducted to allow the assessment of the effects of daylength and temperature in a balanced manner. Accordingly, this was addressed by running high temperatures (15 and 20 °C) for a short day treatment (10 h) (CEF1 and CEF2) (Table 2) and a temperature treatment (13 °C) for long day treatments (13 & 16 h) in growth cabinets for all common genotypes in 2017 (CEF3 and CEF4) (Table 2). For each temperature/daylength treatment, cultivars were tested as a single plant in a pot with four replicates arranged in a randomised complete block design. Dates of emergence and flowering were recorded at two-day intervals.

2.3. Cultivars

Table 1 shows which cultivars were sown in each year at each site. The phenological response of ten canola (*Brassica napus* L) cultivars: three spring types (45Y88CL (A), Hyola® 577CL (B) and Hyola® 635CC (C)), four winter-spring crosses (K50055 (D), K50056 (E), K50057 (F) and K50058 (G) - seed sourced from Pacific Seeds, now Advanta Seeds www.pacificseeds.com.au) and three winter types (EdimaxCL (H), Hyola® 970CL (J) and Pheonix (K)) were assessed in the field. In the controlled environment experiment all cultivars were tested apart from K50057 (Table 2).

2.4. Crop measurements

Dates to first flower and maturity (seeds 50% brown) were recorded according to (Sylvester-Bradley and Makepeace, 1985). Date of start of flower (SOF, GS4.1) was recorded when 10% of plants within the plot were flowering on the main raceme. End of flowering (EOF) was assessed with 5% of flowers remaining at a plot level. Grain yield was taken from hand harvests at GS6.8. Two samples of four rows (15 or 20 cm depending on location) by 50 cm per plot were cut to ground

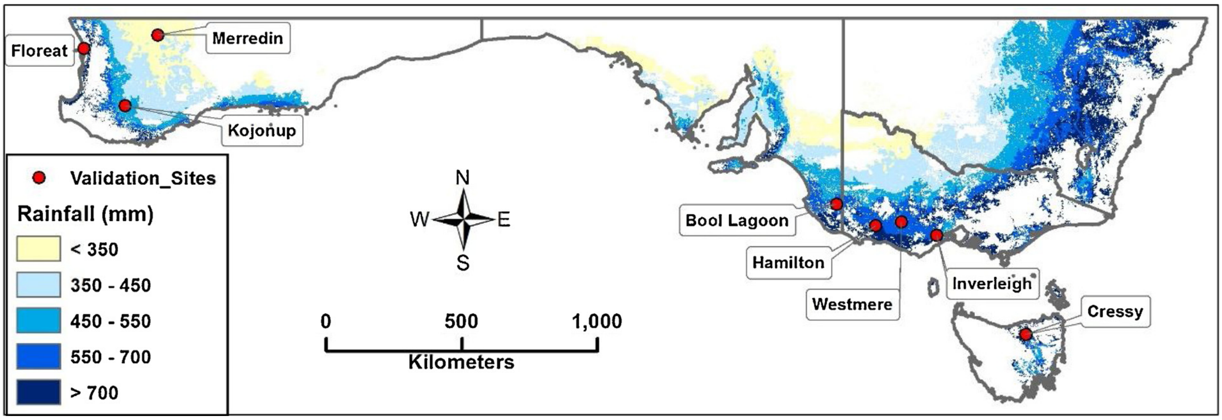

Fig. 1. The area evaluated above 350 mm yr^{-1} rainfall within cropping belt for the canola cultivars and the location of the field experimental locations (validation sites) used for CAT model parameterisation.

Table 1
Details of site used in the study including day length (with civil twilight), rainfall and air temperatures (means of historical records from 1980 to 2017 from the Australian Bureau of Meteorology during the May to November growing season), year sown, sowing dates (DOY = day of year), water treatment (Rf = rainfed, Ir = irrigation, Ex = rainout shelters to exclude rain at Hamilton from 29 September 2015, 18 August 2016 and 1 October 2017) and cultivars sown.[a]

Site	Lat °S	Long °E	Day length (May-Aug) Average h:min	Long term (May-Nov)			Rain (May-Nov)		Sow Year	Sowing dates DOY	Water Treatment	Cultivar Sown
				Rain mm	MinT °C	MaxT °C	mm	% of LTA				
Bool Lagoon	37.11	140.77	11:03	438	6.8	17.2	313	71	2015	135; 167	Rf	A; B; H; J
Cressy	41.68	147.08	10:45	402	3.8	14.7	254	63	2015	113; 152	Rf	B; H; J
							334	83	2017	118; 131; 155	Rf	B; C; F; J; K
Perth	31.94	115.79	11:21	624	11.0	20.9	472	76	2015	141	Rf	C; H; J
							648	104	2016	165	Rf	C
Hamilton	37.83	142.06	11:05	468	6.0	15.4	334	71	2014	128	Rf	A; B; C
							354	76	2015	119; 163	Rf; Ir; Ex	A; B; C; D; E; F; G; H; J; K
							652	139	2016	123; 126; 167	Rf; Ex	B; C; D; E; F; G; H; J; K
							462	99	2017	101; 123; 158	Rf; Ir; Ex	B; C; D; J; K
Inverleigh	38.14	144.08	10:59	376	7.7	16.2	250	66	2015	114; 158	Rf	A; B; H; J
							475	126	2016	121	Rf	B; C; D; E; F; G; H; J; K
							267	71	2017	127	Rf	C; D; E; F; G; H; J; K
Kojonup	33.83	117.15	11:14	392	7.0	18.1	286	73	2015	119	Rf; Ir	A; B; C; H; J
							398	102	2016	106; 133	Rf	A; B; C; D; E; G
							382	97	2017	129; 157	Rf; Ir	A; B; C; D; E; F; G; H; J; K
Merredin	31.49	118.24	11:22	218	8.1	21.2	222	102	2015	125; 161	Rf	A; B; C; H; J
Westmere	37.69	142.92	11:01	370	5.8	15.7	238	64	2015	113; 166	Rf	A; B; H; J

[a] spring types: (45Y88CL (A); Hyola® 577CL (B); Hyola® 635CC (C)), winter x spring crosses: (K50055 (D); K50056 (E): K50057 (F); K50058 (G)) and winter types: (Hyola® 970CL (H); Edimax (J); Phoenix (K).

level, bulked and oven dried to a constant weight at 60 °C prior to threshing. Grain yield and weight of the non-grain material were recorded.

2.5. Phenological modelling

Phenological development to SOF and EOF was measured in 45 crop experiments made up of the eight different locations with multiple times-of-sowing over 4 years (2014–2017) (Table 1) and the controlled environment studies (Table 2). A phenological model with varying sensitivities to basic temperature, photoperiod and vernalisation was applied to the measured phenological data for cultivars within these 45 crop experiments. The phenological model for a cultivar was adjusted via optimisation (Generalized Reduced Gradient Nonlinear method) to minimise the least square difference between the measured date and predicted date of both SOF and EOF.

Rates of development within the phenological model are driven by photoperiod-corrected temperature, photoperiod and vernalisation to

Table 2
Details of temperature and photoperiod controlled environment studies and cultivars sown.[a]

Controlled Environment Facility	Sow Year	Temperature (°C)	Photoperiod (h)	Crop Sown
CEF1	2016	15	10	A; B; C; D; E; G; H; J; K
CEF2	2016	20	10	A; B; C; D; E; G; H; J; K
CEF3	2017	13	13	A; B; C; D; E; G; H; J; K
CEF4	2017	13	16	A; B; C; D; E; G; H; J; K

[a] spring types: 45Y88CL (A); Hyola® 577CL (B); Hyola® 635CC (C), winter- spring crosses: K50055 (D); K50056 (E): K50057 (F); K50058 (G) and winter types: Hyola® 970CL (H); Edimax (J); Phoenix (K).

calculate the time taken for two development stages, being Sow-SOF and from SOF-EOF.

For each cultivar, the daily phenological development rate is determined from the accumulated photo-thermal sum (TT_{PP}, °Cd, Eq. (1)) incorporating base temperature (PTT_{B0}, °Cd), photoperiod (F_{PP}, $h^2 h^{-2}$) and vernalisation (F_v, dd^{-1}) requirements as follows:

$$TT_{PP} = \sum (PTT_{B0} \times F_{PP} \times F_v) \tag{1}$$

Temperature development rate is based on a daily averaged temperature (TT_{BO}) from a 0 °C base temperature to an optimum 26 °C temperature within which development proceeds at the optimum rate (White et al., 2008). A 0 °C base temperature was used due to the uncertainty regarding the variation of base temperature among genotypes and development stages (McMaster et al., 2008). Account was made of the effect of photoperiod (PP_h) on the duration of thermal time through a calculation of day length (including civil twilight) using the site-specific latitudes for each day (Eq. (2)).

$$PTT_{BO} = \sum (TT_{BO} \times PP_h \times 24^{-1}) \tag{2}$$

Additionally, sensitivity to photoperiod among cultivars varies non-linearly up to a maximum of around 20 h (Weir et al., 1984; McMaster et al., 2008). If the photoperiod (PP_h) exceeds 20 h then it is set to a maximum of 20 h for the purposes of determining photoperiod sensitivity (Eq. (3)). To allow for photoperiod sensitivity within the optimization process, a cultivar specific sensitivity to photoperiod (PP_{sen}) was introduced (ranging between 0 to 0.9 h^{-2}) and used in the optimisation process. A higher PP_{sen} value indicates greater photoperiod sensitivity. Using this PP_{sen} and day length, a daily photoperiod factor (F_{PP}, $h^2 h^{-2}$) is calculated as:

$$F_{PP} = 1 - (0.01 \times PP_{sen})^* (20 - PP_h)^2 \tag{3}$$

The effect of vernalisation was incorporated into the model using a daily vernalisation factor (F_v). Using the method described in White et al. (2008) a cultivar specific sum of vernalisation days ($\mathrm{Vern_{sen}}$, d) required to reach full vernalisation is used within the optimisation process. The process of vernalisation was assumed to occur when average daily temperatures were between -4 and 15 °C with average daily temperatures between 2 and 9 °C assigned a vernalisation unit (V_d) of 1. For temperatures greater than 9 °C, V_d decreases linearly from 9 to 15 °C where its value is zero. Likewise, for temperatures less than 2 °C, V_d decreases linearly from 2 to −4 °C where its value is zero. For each day after sowing V_d is accumulated to produce a sum of vernalisation achieved ($V_\triangle$, d, Eq. (4)).

$$V_\Delta = \sum V_d - Devern \tag{4}$$

Based on the work of Ritchie (1991), devernalisation (*Devern*) was assumed to occur if the daily maximum temperature exceeds 30 °C and if $V_\triangle$ is less than 10 d, resetting $V_\triangle$ to the value of:

$$Devern = \min(0.5(T_{max} - 30),\ V_\Delta) \tag{5}$$

Using this $V_\triangle$ (d) and $\mathrm{Vern_{sen}}$ (d) a daily vernalisation factor (F_v, dd^{-1}, Eq. (6)) is calculated as:

$$F_v = \frac{V_\Delta}{Vern_{sen}} \tag{6}$$

Using the cultivar specific parameters of PP_{sen} and $Vern_{sen}$ the phenological phases of Sow-SOF and SOF-EOF were achieved when the cultivar specific TT_{PP} was reached for that phase.

2.6. Phenological modelling calibration

In the optimisation process for each cultivar, the three parameters that were altered were PP_{sen}, $Vern_{sen}$ and TT_{PP}. Sensitivity to photoperiod is inferred by PP_{sen} (a factor of zero infers insensitivity whereas a value of 0.8 h^{-2} infers a strong sensitivity to photoperiod). Vernalisation sensitivity is the $Vern_{sen}$ needed for vernalisation saturation (a sum near zero being insensitive and a sum near 50 d being very sensitive). These parameters were calculated for both Sow-SOF and SOF-EOF.

The goodness of fit of the model can be judged by the model's ability to predict the duration from sowing to SOF and EOF at each site. A root mean square error (RMSE) of five days between the measured and predicted flowering dates on a national basis is similar to other canola models (Habekotté, 1997; Deligios et al., 2013; Robertson and Lilley, 2016).

2.7. The CAT model

The CAT model (Weeks et al., 2008) was used to assess phenological development and biomass accumulation of canola, as it has a high utility in spatial analyses of crop growth response across landscapes (Christy et al., 2013, 2018). It includes modules for phenological development, crop growth and yield, together with dynamics of water and nitrogen in the crop and soil. The model was based on a generic annual crop model to enable the simulation of any crop and is based on extensively used contemporary models (Williams et al., 1989; Littleboy et al., 1992). It operates by first simulating the phenological progress, above-ground biomass accumulation and then partitioning to grain yield. Phenological development is driven by temperature, photoperiod and vernalisation using the model defined above. Biomass accumulation is determined from intercepted radiation, transpiration and radiation use efficiency, water and nutrient stress factors and a photoperiod factor (Christy et al., 2018).

2.8. Phenological modelling application at a location

To explore the phenological response of modelling based on four canola cultivars (45Y88CL, K50058, K50057 and Hyola® 970CL), the model was applied to five locations across Australia (Merredin, Kojonup, Bool Lagoon, Hamilton and Cressy) for eight times of sowing (Apr 01, Apr 15, May 01, May 15, Jun 01, Jun 15, Jul 01 and Jul 15) using 50 years of historical climate data (1968–2017) sourced from nearby Bureau of Meteorology sites (https://www.longpaddock.qld.gov.au/silo/). Model predictions of dates of SOF and EOF were calculated.

2.9. Phenological modelling application across Australia

The long-term analysis at the five locations (Merredin, Kojonup, Bool Lagoon, Hamilton and Cressy) was extended across Australia over a 50-year period using historic climate (1968–2007). Model simulation was conducted on all privately owned, arable agricultural land (defined as slope < 5%) within the spatial region identified in Fig. 1. The spatial area was divided into 1-km^2 grid cells for modelling. For each grid-cell within this region, the CAT model was applied for the four canola cultivars sown each year after the 'autumn-break' (Sowing occurred at the site if 15 mm of rain had fallen within the previous five days and the soil held at least 20 mm of plant available water (calculated to a depth of 400 mm)), with crop yield response demonstrating intra-and inter-seasonal variability associated with climate patterns and soil water availability.

The dominant soil type for each grid cell (sourced on June 2013 from http://www.asris.csiro.au/themes/Atlas.html) was described and mapped under a Northcote (1979) classification and attributed using the 50 percentile predictions of soil properties described in McKenzie et al. (2000). For each year of simulation at each grid cell, simulations were conducted with unlimited nitrogen to avoid confounding sequencing factors that can be managed by farmers. To reduce the confounding effect of 'carry-over' stored soil water from the previous year's crop, the stored soil water status was reset 75 days before sowing to 10% plant available water for each soil depth increment to a total depth of 1 m, and a full plant available water profile below that depth. The resultant soil water content at sowing varied at a grid cell due to subsequent seasonal rainfall and soil evaporation over these 75 days to represent a summer fallow prior to sowing.

The model assumed that the 4 cultivars were always sown at a site on the same day of the autumn break. Average annual crop yield over the 50-year simulation period was calculated for each cultivar at each site and sowing time, using data for each crop sown. Accordingly, all forms of crop failure post-sowing were included in the calculation of average annual crop yield. This provided a realistic comparative analysis across the landscape, irrespective of whether crop failure was due to a false break in the sowing window or subsequent stress.

3. Results

3.1. Climate

In 2015, all locations except Merredin received less than the average growing season rainfall (May to Nov), particularly Westmere (64%), Inverleigh (66%), Cressy (68%), Bool Lagoon (71%) and Hamilton (71%). At these five sites the spring rainfall in 2015 was near the driest on record, in contrast to Kojonup and Merredin in Western Australia which received very favourable spring rainfall (Table 1). In 2016, widespread winter water logging occurred in the HRZ of SE Australia that resulted in the failure of crops grown at the Bool Lagoon and Cressy sites, however at Hamilton and Inverleigh the cool and relative dry spring of 2016 allowed the crop to recover and yield well (Table 1). At all sites, 2017 crops were high yielding due to good starting soil moisture, despite Cressy and Inverleigh receiving lower than average growing season rain (Table 1). Greater detail of the growing season climatic conditions experienced at the sites evaluated can be found in Riffkin et al. (Submitted) for Cressy, Bool Lagoon, Hamilton, Inverleigh and Westmere and in Zhang et al. (2017) for Kojonup and Merredin.

Yield ranged widely across sites, years, time-of-sowings and cultivars (Fig. 2). For 45Y88CL the lowest yield harvested was 242 kg ha^{-1} for the second time of sowing at Bool Lagoon in 2015, while the greatest yield (6154 kg ha^{-1}) was the irrigated first time-of sowing in 2015 at Hamilton.

3.2. Phenology modelling

A photo-thermal phenological model with varying sensitivities to photoperiod and vernalisation was developed for the ten cultivars tested across locations. Across all experiments, the optimized parameters of the photo-thermal phenological model had an average predictive ability (RMSE) for determining timing from Sow-SOF and for SOF-EOF of 3.8 d and 4.7 d respectively (Table 3). The predictions which achieved the lowest RMSE for Sow-SOF and SOF-EOF varied in their sensitivity to photoperiod with a value of 0.6 h^{-2} (spring cultivars) considered to represent moderate sensitivity and 0.8 h^{-2} (winter cultivars) considered high sensitivity to photoperiod. The photoperiod sensitivity for the winter-spring crosses was found to be in the middle of the spring and winter cultivars (Table 3). All spring cultivars showed a very weak sensitivity to vernalisation ranging from a 0.1 to 0.25 d vernalisation day requirement. The three winter cultivars all showed a strong sensitivity to vernalisation, needing 35 vernalisation days to achieve vernalisation. The vernalisation sensitivities of the four winter-spring crosses were 3, 7, 9 and 16 d for K50058, K50055, K50056 and K50057 respectively (Table 3).

Table 3
Photo-phenological model parameters for the cultivars which predicts the time taken from Sowing to Start-of-Flower (Sow-SOF) and Start-of-Flower to End-of-Flower (SOF-EOF). The root mean square error (RMSE) of the difference in days between measured and predicted values is provided.

Cultivar	PP_{sen} (h^{-2})	$Vern_{sen}$ (d)	Sow-SOF		SOF-EOF	
			TT_{PP} (°Cd)	RMSE (d)	TT_{PP} (°Cd)	RMSE (d)
45Y88	0.6	0.1	281	4.9	180	3.1
Hyola® 577	0.6	0.25	281	4.5	201	7.4
Hyola® 635	0.6	0.25	276	4.4	206	5.6
K50055	0.7	7	270	2.9	202	2.2
K50056	0.7	9	264	3.7	211	5.6
K50057	0.7	16	254	1.9	162	2.9
K50058	0.7	3	292	4.3	212	5.2
Hyola® 970	0.8	35	281	4.2	193	4.5
Edimax	0.8	35	280	4.1	169	6.4
Phoenix	0.8	35	254	2.6	176	3.8

3.3. Model performance against experimental data

Based on the determined photo-phenological parameters for each cultivar (Table 3), four cultivars were selected to explore the temporal and spatial yield response. Two extremes, spring type 45Y88CL and winter type Hyola® 970CL, and two winter-spring crosses (K50057 and K50058) were chosen covering the high and low end of the vernalisation sensitivity of the crosses. The model reproduced an accurate simulation of the observed start of flowering date and grain yield for these four cultivars across the wide range of locations, sowing time, irrigation and rainfall exclusion treatments (Table 1, Fig. 2). The slope of the simulated vs observed response was near unity (range of 0.96–1.06) with a calculated grain yield RMSE of 689, 536, 659 and 744 for 45Y88CL, K50057, K50058 and Hyola® 970CL respectively.

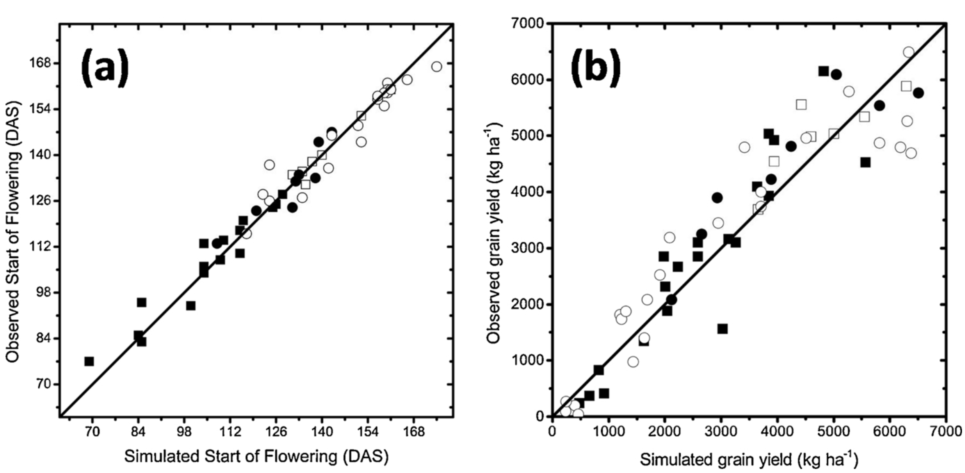

Fig. 2. Simulated *v.* observed (a) Start of Flowering (Days after sowing (DAS)) and (b) grain yield values of 45Y88CL (closed squares), K50057 (open squares), K50058 (closed circles) and Hyola® 970CL (open circles) for crops sown at sites shown in Table 1. The root-mean-square error (day) of simulated Start of Flowering date are 4.2, 2.0, 4.3 and 4.6 for 45Y88CL, K50057, K50058 and Hyola® 970CL respectively. The root-mean-square error (kg ha^{-1}) of simulated grain yield values are 689, 536, 659 and 744 for 45Y88CL, K50057, K50058 and Hyola® 970CL respectively.

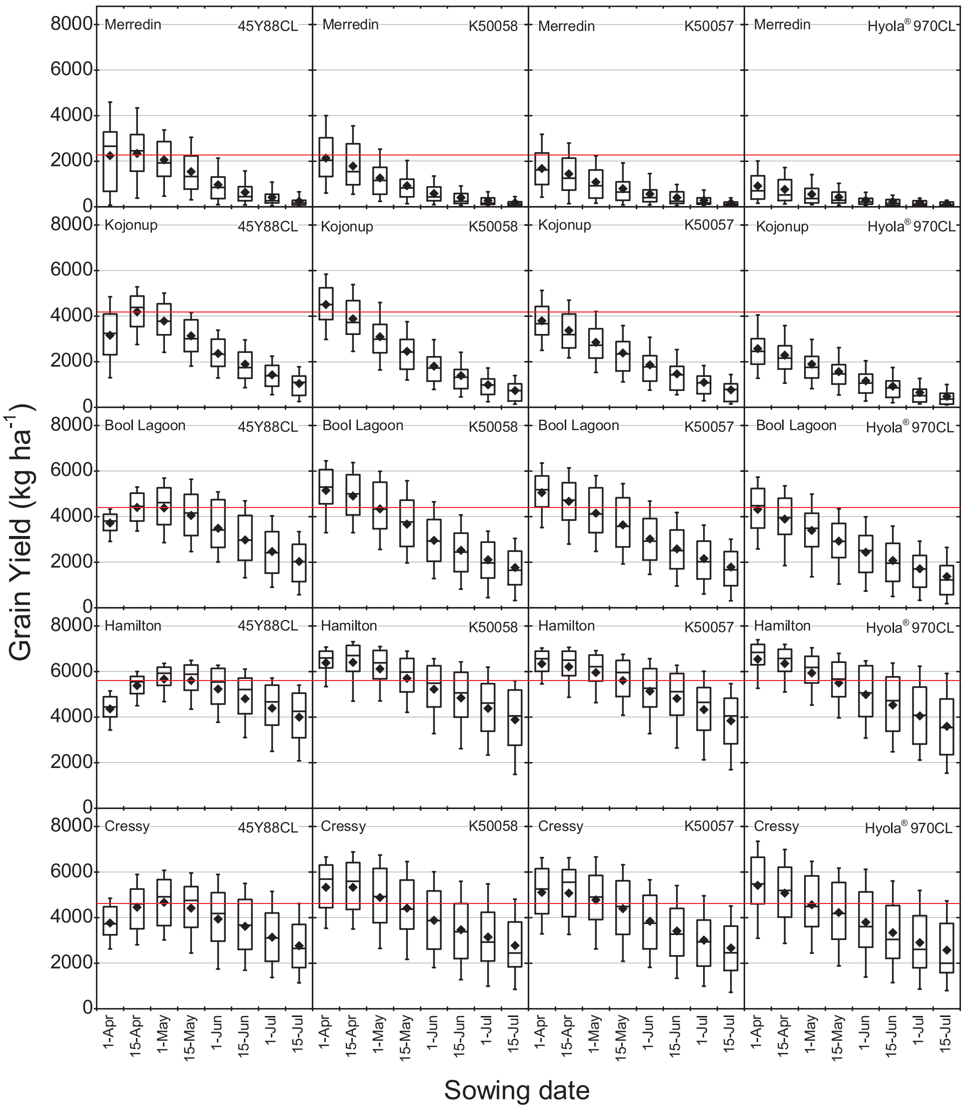

Fig. 3. Response in canola grain yield (kg ha^{-1}) to eight sowing times over 50 years (1968–2017) of four cultivars (45Y88CL, K50058, K50057 and Hyola® 970CL) at five locations (Merredin, Kojonup, Bool Lagoon, Hamilton and Cressy). Box range shows 25–75 percentiles, whisker range shows 10–90 percentiles and closed diamonds are the yield average per time sown. The red line represents the greatest average yield for the spring-type canola 45Y88CL. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4. *Long-term yield responses at experimental sites*

Having validated the CAT model against experimental data, we used the model to extend our understanding of winter, spring and winter-spring crosses across locations in a historical context. Thus, the four canola cultivars (45Y88CL, K50057, K50058 and Hyola® 970CL) were simulated in our five experimental locations across eight times of sowing (Apr 01, Apr 15, May 01, May 15, Jun 01, Jun 15, Jul 01 and Jul 15) using 50 years of historical climate data (1968–2017). Model predictions of annual yield were calculated and presented as box and whisker graphs for each time-of-sowing (Fig. 3). For the Jul 15 sowing date at Merredin, the vernalisation requirement of Hyola®970CL to initiate SOF was not achieved in four of the 50 years of simulation. For these four years, simulated canola vegetative growth continued through spring, resulting in crop death in early summer due to severe water stress. In these four years, zero yield was reported and included in the 50-year yield average of Fig. 3. The red line which extends across the graphs for a site represents the greatest average yield for the spring-type canola 45Y88CL. This is presented so that all other cultivar-sowing date combinations can readily be compared to spring-type canola. For Merredin and Kojonup in Western Australia, the highest mean yield for 45Y88CL was achieved by the Apr 15 sowing date, whereas at the other sites the May 1 sowing was higher yielding. For the Merredin site, grain yields for the other three cultivars (K50058, K50057 and Hyola® 970CL) were lower than the yield achieved by 45Y88CL, and all showed a linear decline in productivity as sowing date was delayed. At Kojonup, the grain yield of K50058 matched or exceeded the yield of 45Y88CL for an April sowing. While the 3 winter-spring or winter cultivars showed a linear decline in yield versus sowing date starting at April 1, there was a quadratic relationship in the spring type such that April 15 was higher yielding than April 1. These tendencies were even stronger in the Eastern HRZ locations, where the spring type had a marked quadratic response to sowing date with significant yield penalties when sown early, while the longer phenology cultivars with more vernalisation sensitivity tended to have a much more linear response to sowing date. Thus, at Bool Lagoon, both K50058 and K50057 out-yielded 45Y88CL with April sowings. At Hamilton and Cressy all three longer season cultivars (K50058, K50057 and Hyola® 970CL) out-yielded the spring cultivar (45Y88) when sown in April.

The distribution of date of SOF at the five locations at the eight sowing times for the cultivars of Hyola® 970CL, K50057, K50058 and 45Y88CL are shown in Fig. 4. The Hyola® 970CL cultivar, with its high

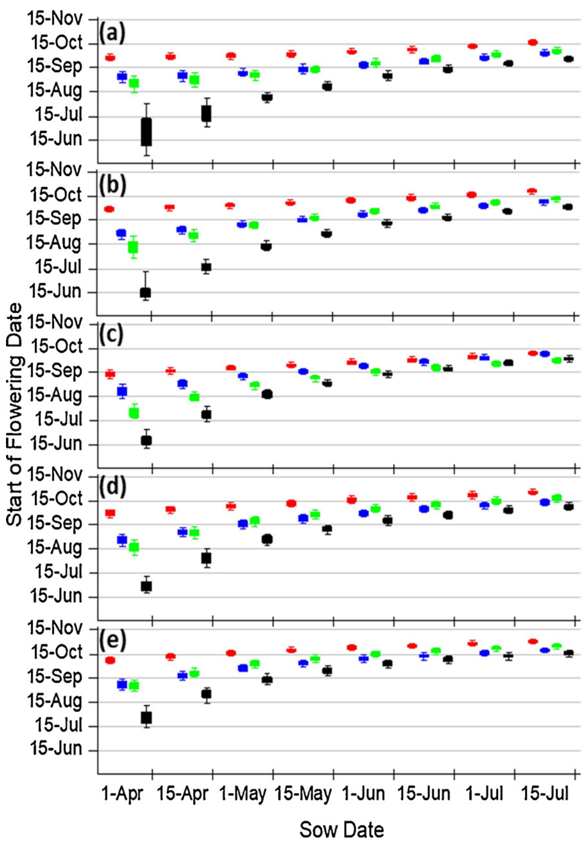

Fig. 4. Response to eight times of sowing for four cultivars (**Hyola® 970CL – Red box, K50057 – Blue box, K50058– Green box, 45Y88CL – Black box**) showing predicted date for start of flowering at: (a) Merredin; (b) Kojonup; (c) Bool Lagoon; (d) Hamilton; (e) Cressy. Box and whisker show the 25–75 percentiles and whiskers show the 10 and 90 percentiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vernalisation requirement produced a consistent mid-September to mid-October SOF window regardless of sowing date at all locations. This is in contrast with 45Y88CLwhere the SOF date was earlier for April sowing dates as its phenology was not delayed by vernalisation. This is in contrast with the spring cultivar (45Y88CL) where the SOF date was earlier for April sowing dates as its phenology was not delayed by vernalisation. The spring cultivar with little vernalisation requirement is developing relative to thermal time whereas the phenological development of the winter cultivar is delayed until vernalisation requirements are met. Winter-spring crosses SOF dates were mid-way between the spring and winter cultivars at all sites for each time-of-sowing (Fig. 4) which resulted increased yields in the cooler HRZ sites (Hamilton and Cressy) for sowing dates at or earlier than May 1 (Fig. 3). At Bool Lagoon and Kojonup, K50058 flowered earlier than K50057 with the early sowing dates. For all cultivars the variation in SOF date was much smaller for sowing dates from June onwards. The similar flowering time for all cultivars with late sowing resulted in similar grain yield (Fig. 3).

The grain yield results shown in Fig. 3 for the four cultivars, sown at the eight sowing dates over 50 years have been plotted in Fig. 5 relative to grouped 10 day SOF window for each of the five sites. For each of these SOF windows showing the percentage loss of yield potential from frost at flowering and terminal drought (Fig. 5). The grey boxes for simulated grain yield in Fig. 5 indicate the flowering window where average yield is within 10% of the maximum predicted average yield, for that site over the 50 years of simulation. This points towards a site-specific flowering window to target for optimum yields. Merredin has an early, very short flowering optimum, driven by yield loss from strong terminal drought when flowering occurs after July (Fig. 5a). In contrast, the HRZ sites had later, longer optimum flowering windows (Fig. 5b–e). While terminal drought was still a significant potential stressor at Kojonup, and to a lesser extent Bool Lagoon, frost risk was very high at Cressy, and intermediate at Bool Lagoon and Hamilton.

3.5. Responses across Australian arable land

Over the 50 years of simulation, averaged yield response of a cultivar was reported relative to the yield response of 45Y88CL. In Fig. 6, areas where the average yield for a given cultivar is greater than 45Y88CL is shown by either light or dark blue and green. The winter-spring cross with the lowest vernalisation requirement (K50058) demonstrated the benefit of a small increase in the vernalisation requirement of canola across most of the eastern portion of the study area (Fig. 6a). This area covers 64% of the study area and totals 3.72 Mha (Table 4). Seven of the eight field locations reported in this paper (Table 1) achieved superior averaged 50-year yield responses for K50058 over 45Y88CL when sown on an ‘autumn-break’, with the sole exception being Merredin in Western Australia. The area of yield advantage of K50057 was less than K50058, totalling 2.59 Mha, while the area advantage of Hyola® 970CL was 1.57 Mha. These spatial results were based on sowing on the ‘autumn-break’ over 50 years. As shown in Fig. 3, Hyola® 970CL only has a yield advantage over K50058 when planting has occurred in April for sites like Hamilton and Cressy, which are suitable for winter-type canola.

4. Discussion

Our analysis met the aim of determining where in the study area winter-spring crosses (K50058 and K50057) and winter-type canola (Hyola® 970CL) have a yield advantage over spring-type canola (45Y88CL). The photo-thermal phenological model with varying sensitivities to photoperiod and vernalisation was able to describe phenological development of the ten cultivars, with multiple times-of-sowings over four years. The RMSE of less than five days of our model prediction of SOF date compared the site measured data, is similar to other Australian models for spring-type canola (Robertson and Lilley, 2016) and is superior to past model applications of near 10 days RMSE for winter-types (Christy et al., 2013; Lilley et al., 2015). In Australia, simulation of canola phenological development mainly adopts the APSIM-canola approach outlined by Robertson and Lilley (2016) which assumes no interaction between vernalisation and day length. While acknowledging that phenological development in canola is influenced by both vernalisation and photoperiod (Myers et al., 1982; Nanda et al. 1996), APSIM-canola avoids the complication of having to account for possible vernalisation × day length interactions as they are difficult to parameterise (Robertson and Lilley, 2016). The photo-thermal phenological model with varying sensitivities to photoperiod and vernalisation presented in this paper allows for vernalisation × day length interactions and demonstrates an improved ability to predict flowering dates of winter-type canola which has a strong response to vernalisation (Christy et al., 2013; Lilley et al., 2015).

The K50058 cultivar was shown to have a superior yield performance in 64% of the study area which encompassed the entire HRZ cropping area in Australia defined by Zhang et al. (2006) and the low to medium rainfall zones of Victoria and NSW (eastern portion Fig. 6 a). In the remaining 36% of the study area, 45Y88CL was found to have the highest yield potential for the key reason that at these locations when SOF was after mid-July (DOY = 196) water stress over the grain filling period resulted in considerable yield losses (Fig. 5a). At Merredin the only cultivar that achieved SOF by mid-July was 45Y88CL (Fig. 4a). In these regions, the drastic yield reductions resulting from flowering outside the narrow optimum flowering period (Bodner et al., 2015) supports the Australian canola breeding focus on short-season types aimed at escaping water-stress during grain filling in the drier regions

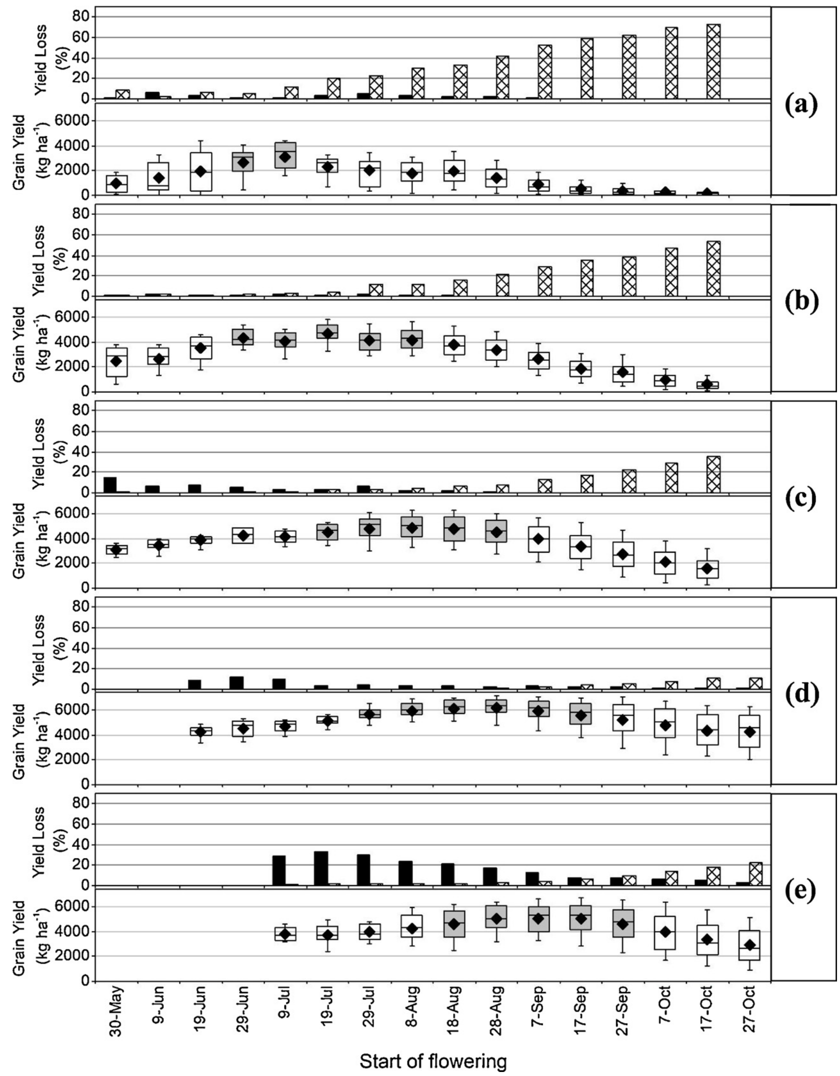

Fig. 5. Simulated grain yield (Box and whisker) and percentage loss of yield potential due to frost (black bars) and water stress during grain filling (hatched bars) from the eight times of sowing, grouped in 10-day start-of-flowering increments, starting from x-axis date at: (a) Merredin; (b) Kojonup; (c) Bool Lagoon; (d) Hamilton; (e) Cressy. The grey boxes show where average simulated yield per group, is within 10% of the maximum predicted average yield, for that site.

of the cropping belt detailed by Salisbury et al. (2016). However, our results show that in most of the southern Australian cropping region the focus on short season spring-type canola is limiting yield potential.

On this basis we advocate the release of well-adapted winter-spring cultivars to enable HRZ growers to meet their yield potentials. Indeed, based on the area sown to canola in 2015 (Australian Bureau of Statistics, 2015), our modelling suggests that winter-spring cultivars could produce an additional 381 M tonnes per year, if planted in areas where K50058 were superior to 45Y88CL. At the 5-year average canola price of \$486 t^{-1}, this could provide an additional AUD 185 M per annum (Table 4). Within southern Australia, the modelled yield response showed that as vernalisation requirement of canola cultivars increased, the areas where such cultivars had a yield advantage tended to be the cooler areas with higher rainfall (Table 1). The value to industry substituting 45Y88CL with K50057 and Hyola® 970CL where they had a yield advantage was found to be AUD 82.8 M and AUD 29.2 M respectively based on the areas sown to canola in 2015.

The spring-winter crosses and winter-types generally performed better when sown earlier than the short-season spring-type canola. The pattern of yield response by different maturity types, represented by the cultivars used in the study at different locations, highlights the complexity of these spatial analyses and the need to develop cultivar specific management packages tailored to different sub-regions within Australia. The location of yield advantage of winter-type canola compared to a spring-type is similar to Christy et al. (2013) who found that within the Australian cropping zone, winter-type canola is restricted to the wetter regions of the high rainfall zone of south-eastern Australia. In terms of SOF dates the phenology of the winter-spring crosses evaluated by this paper demonstrates a completely different phenology than other canola cultivars available in Australia that is in-between spring and winter-type canola. At the higher yielding field experimental sites of Hamilton and Cressy (Fig. 3), Hyola® 970CL out yielded both winter-spring crosses with earlier sowings. At these sites, the cooler winter conditions meant that vernalisation requirements of winter-type canola is easily met and the impact of water stress during grain fill is low (Fig. 5d and e).

The extrapolation of canola yield across landscapes and sowing times using model results validated from a limited number of experimental sites challenges the applicability of results within untested environments especially the early and late sowing dates considered by our simulations. The measured data for phenology and yield used for model validation considered a diverse range in growing season rainfall (138 to 651 mm), temperature and day lengths. The slope of the simulated vs observed validation responses based on this diverse data was near unity with no obvious bias in phenology and yield predictions at the upper and lower bounds of the measured data. However, even with this near

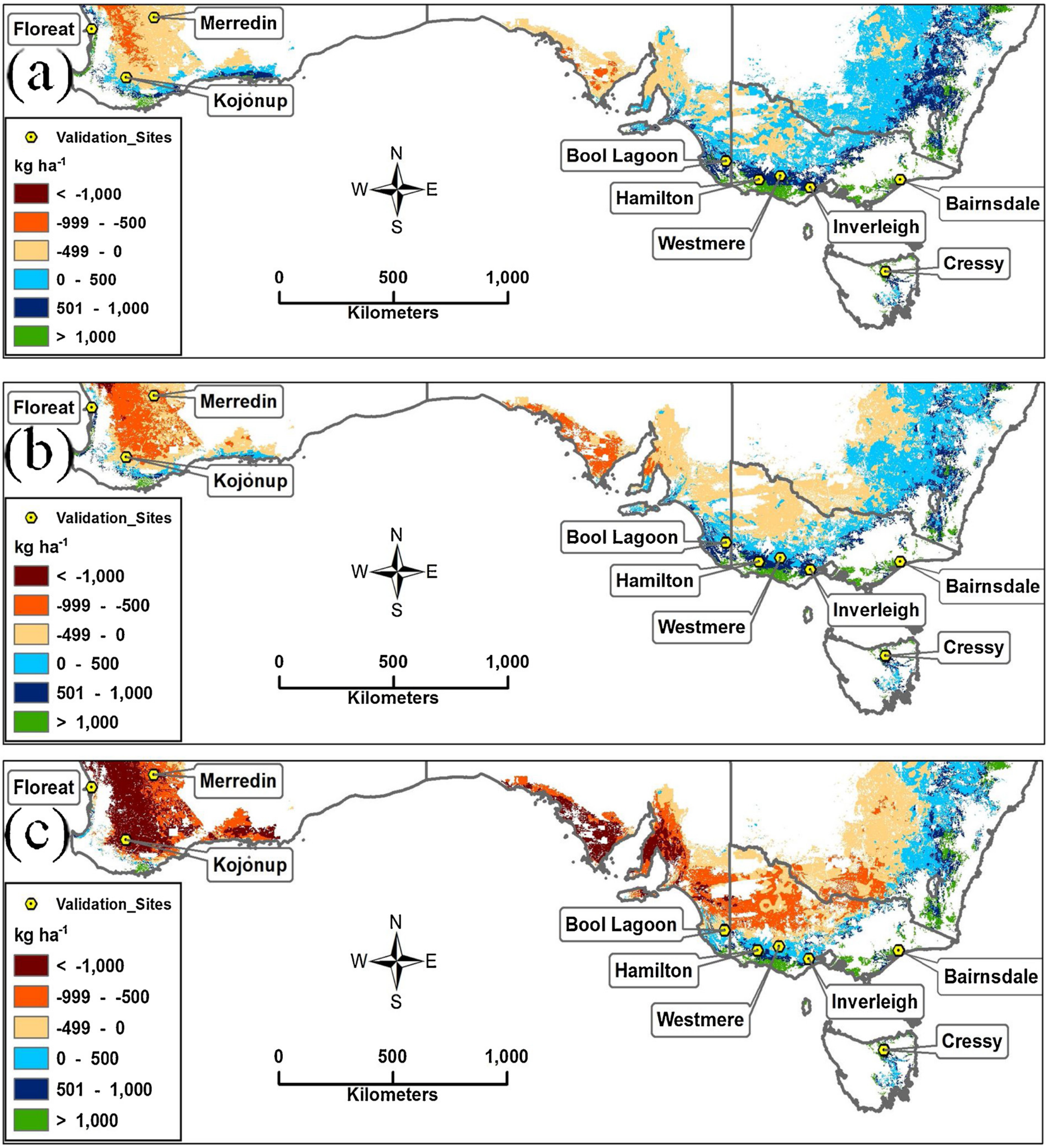

Fig. 6. Canola grain yield (kg ha^{-1}) advantage (over 50 years 1968–2017) of (a) K50058 over 45Y88CL (b) K50057 over 45Y88CL (c) Hyola® 970CL over 45Y88CL.

Table 4
Canola grain yield advantage of K50058, K50057 and Hyola® 970CL over 45Y88CL. Yield advantage is a function of the area sown to canola in 2015 (Australian Bureau of Statistics, 2015) and the areas where a cultivar had a positive 50 year averaged yield advantage over 45Y88CL (Fig. 6).

Cultivar	Yield advantage area (Mha)	% of evaluated area	Increase in Canola Production (t yr^{-1})	Increase Value of Canola Production (AUD M)
K50058	3.72	64%	381,288	185.3
K50057	2.59	45%	170,477	82.8
Hyola® 970CL	1.57	27%	60,033	29.2

unity slope, the extrapolation of modelled results beyond the calibrated bounds of the model, especially the early and late sowing dates for the range of cultivar maturities should be recognised. The consideration of cultivar choice in a sub-region also needs to balance other risks (e.g. heat, frost, false breaks, waterlogging) associated with choice of sowing time (Lisson et al., 2007). Although the modelled results from our analysis would allow consideration of the impacts of these risks at individual site locations, the spatial analysis we conducted has combined these seasonal risks to produce an average yield response. These results should be interpreted as representing general trends within the study region and do not reflect risks faced at individual locations, such as pests, disease, and waterlogging, which will be considered in future work.

The optimised photo-thermal phenological model parameters for the cultivars evaluated in this paper found that all cultivars had a strong sensitivity to photoperiod. This sensitivity was found to be at a value of 0.6 h^{-2} for all spring types and 0.8 h^{-2} for all winter types. The winter-spring cross were found to have a sensitivity of 0.7 h^{-2}. Canola has a strong photoperiod response with flowering (Myers et al., 1982) which was found to be similar across the entire population tested by Nelson et al. (2014). This similarity in photoperiod sensitivity for the spring-type population evaluated by Nelson et al. (2014) was declared an unexpected outcome by the authors, given the contrasting source of germplasm from Australia and Europe. This may indicate that the efforts by Australian breeders to decrease the photoperiod requirement of canola for flowering (Cowling, 2007) has had limited success.

Our results show that there is a strong case for the release of well-adapted winter-spring cultivars with a moderate increase in vernalisation sensitivity, which will have a stable optimal flowering window across a broad range of sowing dates. Given the increased uncertainty around sowing date in Australian rainfed cropping systems, the development of cultivars for which date of flowering is similar, regardless of sowing date, is a recommended and very achievable breeding goal.

Acknowledgements

We acknowledge co-investment from the Grains Research and Development Corporation (DAV00141), the Department of Jobs, Precincts and Regions (Victoria), the Tasmanian Institute of Agriculture, the University of Tasmania and CSIRO. We are thankful and acknowledge Justin Kudnig from Pacific Seeds, now Advanta Seeds www.pacificseeds.com.au for supply and use of the K-line winter-spring crosses used in this paper. We acknowledge the very capable technical assistance of Irma Grimmer, Jamie Smith, Rebecca Fish, Andrea Hurst, Chris Herrmann and Sam Flottmann. Timothy Whitehead is thanked for his contribution in model application including spatial mapping.

References

Australian Bureau of Statistics, 2015. Agricultural commodities, Australia, state/territory and SA2, 2015-16. Last Updated: 31 Oct 2017, Viewed: 30 Jul 2018. http://www.abs.gov.au/AUSSTATS.

Bodner, G., Nakhforoosh, A., Kaul, H.-P., 2015. Management of crop water under drought: a review. Agron. Sustain. Dev. 35, 401–442.

Christy, B., O'Leary, G., Riffkin, P., Acuña, T., Potter, T., Clough, A., 2013. Long-season canola (*Brassica napus* L.) cultivars offer potential to substantially increase grain yield production in south-eastern Australia compared with current spring cultivars. Crop Pasture Sci. 64, 901–913.

Christy, B., Tausz-Posch, S., Tausz, M., Richards, R., Rebetzke, G., Condon, A., Mclean, T., Fitzgerald, G., Bourgault, M., O'Leary, G., 2018. Benefits of increasing transpiration efficiency in wheat under elevated CO2 for rainfed regions. Glob. Change Biol. 24, 1965–1977.

Cowling, W.A., 2007. Genetic diversity in Australian canola and implications for crop breeding for changing future environments. Field Crops Res. 104, 103–111.

Deligios, P.A., Farci, R., Sulas, L., Hoogenboom, G., Ledda, l., 2013. Predicting growth and yield of winter rapeseeed in a Mediterranean environment: model adaption at a field scale. Field Crops Res. 144, 100–112.

Fischer, R., 2011. Wheat physiology: a review of recent developments. Crop Pasture Sci. 62, 95–114.

Habekotté, B., 1997. A model of the phenological development of oilseed rape. Field Crops Res. 54, 127–136.

Kant, S., Thoday-Kennedy, E., Joshi, S., Vakani, J., Hughes, J., Maphosa, L., Sadler, A., Menidis, M., Slater, A., Spangenberg, G., 2017. Automated rainout shelter's design for well-defined water stress field phenotyping of crop plants. Crop Sci. 57, 327–331.

Kirkegaard, J.A., Lilley, J.M., Brill, R.D., Sprague, S.J., Fettell, N.A., Pengilley, G.C., 2016. Re-evaluating sowing time of spring canola (*Brassica napus* L.) in south-eastern Australia—how early is too early? Crop Pasture Sci. 67, 381–396.

Light, K.A., Gororo, N.N., Salisbury, P.A., 2011. Usefulness of winter canola (*Brassica napus*) race-specific resistance genes against blackleg (causal agent *Leptosphaeria maculans*) in southern Australian growing conditions. Crop Pasture Sci. 62, 162–168.

Lilley, J.M., Bell, L.W., Kirkegaard, J.A., 2015. Optimising grain yield and grazing potential of crops across Australia's high-rainfall zone: a simulation analysis. 2. Canola. Crop Pasture Sci. 66, 349–364.

Lisson, S.N., Kirkegaard, J.A., Robertson, M.J., Zwart, A., 2007. What is limiting canola yield in southern New South Wales? A diagnosis of causal factors. Aust. J. Exp. Agric. 47, 1435–1445.

Littleboy, M., Silburn, D.M., Feebairn, D.M., Woodruff, D.R., Hammer, G.L., Leslie, J.K., 1992. Impact of soil erosion on production in cropping systems. I. Development and validation of a simulation model. Aust. J. Soil Res. 757–774.

McMaster, G.S., White, J.W., Hunt, L., Jamieson, P., Dhillon, S., Ortiz-Monasterio, J., 2008. Simulating the influence of vernalization, photoperiod and optimum temperature on wheat developmental rates. Ann. Bot. 102, 561–569.

Myers, L., Christian, K., Kirchner, R., 1982. Flowering responses of 48 lines of oilseed rape (*Brassica* spp.) to vernalization and daylength. Aust. J. Agric. Res. 33, 927–936.

Nelson, M.N., Rajasekaran, R., Smith, A., Chen, S., Beeck, C.P., Siddique, K.H., Cowling, W.A., 2014. Quantitative trait loci for thermal time to flowering and photoperiod responsiveness discovered in summer annual-type Brassica napus L. PLoS One 9, e102611.

Riffkin, P., Potter, T., Kearney, G., 2012. Yield performance of late-maturing winter canola (Brassica napus L.) types in the High Rainfall Zone of southern Australia. Crop Pasture Sci. 63, 17–32.

Ritchie, J.T., 1991. Wheat phasic development. In: Hanks, J., Ritchie, J.T. (Eds.), Modelling Plant and Soil Systems. ASA-CSSA-SSSa, Madison, WI, pp. 31–54.

Robertson, M.J., Lilley, J.M., 2016. Simulation of growth, developemnt and yield of canola (*Brassica napus*) in APSIM. Crop Pasture Sci. 67, 332–344.

Salisbury, P.A., Cowling, W.A., Potter, T.D., 2016. Continuing innovation in Australian canola breeding. Crop Pasture Sci. 67, 266–272.

Sylvester-Bradley, R., Makepeace, R., 1985. Revision of a code for stages of development in oilseed rape (*Brassica napus* L.). Asp. Appl. Biol. 10, 395–400.

Weeks, A., Christy, B., Lowell, K., Beverly, C., 2008. The Catchment analysis tool: demonstrating the benefits of interconnected biophysical models. In: Pettit, C., Cartwright, W., Bishop, I., Lowell, K., Pullar, D., Duncan, D. (Eds.), Landscape Analysis and Visualisation. Springer-Verlag, Berlin, pp. 49–71.

Weir, A., Bragg, P., Porter, J., Rayner, J., 1984. A winter wheat crop simulation model without water or nutrient limitations. J. Agric. Sci. 102, 371–382.

White, J.W., Herndl, M., Hunt, L., Payne, T.S., Hoogenboom, G., 2008. Simulation-based analysis of effects of *Vrn* and *Ppd* loci on flowering in wheat. Crop Sci. 48, 678–687.

Williams, J., Jones, C., Kiniry, J., Spanel, D., 1989. The EPIC crop growth model. Trans. Am. Soc. Agric. Biol. Eng. 32, 497–511.

Yang, Y., Liu, D.L., Anwar, M.R., Zuo, H., Yang, Y., 2014. Impact of future climate change on wheat production in relation to plant-available water capacity in a semiaridenvironment. Theor. Appl. Climatol. 115, 391–410.

Zhang, H., Berger, J.D., Herrmann, C., 2017. Yield stability and adaptability of canola (*Brassica napus* L.) in multiple environment trials. Euphytica 213, 155.

Zhang, H., Turner, N.C., Poole, M.L., Simpson, N., 2006. Crop production in the high rainfall zones of southern Australia - potential, constraints and opportunities. Aust. J. Exp. Agric. 46, 1035–1049.