



Accounting for soil water improves prediction of lentil phenology for improved frost and heat stress management

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ABSTRACT

Lentils in Australia are primarily grown in temperate and Mediterranean climates, especially in the southern and western regions of the country. As in other parts of the world, lentil yields in these areas are significantly influenced by factors such as frost, heat, and drought, contributing to variable production. Therefore, selecting appropriate lentil varieties and determining optimal sowing times that align with favourable growing conditions is crucial. Accurate predictions of crop development are essential in this context. Current models mainly rely on photoperiod and temperature to predict lentil phenology; however, they often neglect the impact of soil water on flowering and pod set. This study investigated whether incorporating soil water as an additional factor could improve predictions for these critical growth stages. The modified model was tested using 281 data points from various lentil experiments that examined the timing of flowering (61–147 days) and pod set (77–163 days) across different combinations of location, variety, sowing time, and season. The results indicated that including soil water in the prediction model achieved an R^2 value of 0.84 for flowering and 0.83 for pod set. The normalised root mean square error (NRMSE) was 0.07, and Lin's concordance correlation coefficient (LinCCC) was 0.91. The model produced an R^2 of 0.88, an NRMSE of 0.05, and a LinCCC of 0.93 for flowering compared to the default model, which yielded an R^2 of 0.24, an NRMSE of 0.17, and a LinCCC of 0.36 for flowering. A limited sensitivity analysis of the modified model showed that variations in initial soil water and in-season rainfall significantly affected the timing of flowering and pod set. Additionally, we employed a probability framework to assess the crop's vulnerability to the last frost day and early heat stress events during the reproductive stage. This approach provided valuable insights for decision-making to mitigate risks associated with frost and heat stress. Our study suggests that integrating soil water dynamics into lentil phenology models improves the accuracy and precision of predictions regarding the timing of flowering and pod set. These improvements lead to better forecasts, ultimately helping to minimise damage from frost and heat stress during lentil cultivation and can better explain the effect of climate variability.

1. Introduction

Lentil (*Lens culinaris* Medick) is an annual food legume highly valued for its protein- and micronutrient-rich grain (Erskine et al., 2011).

Widely consumed beyond its production areas (Erskine, 2009), the escalating export potential and documented benefits for sustainable farming have elevated lentils to a prominent position as a leading winter pulse in Australia (Materne and Siddique, 2009; Siddique et al., 2013).

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Australia produces > 500,000 t of lentils annually, representing > 13 % of global trade (Kaale et al., 2023).

The advent of the modern lentil industry in Australia, starting in the late 1980s with the introduction of late-flowering, low-yielding phenotypes (Sadras et al., 2021), has seen an annual genetic gain in yield averaging 20 kg ha⁻¹ or 1.23 % in low-yield conditions (Sadras et al., 2021). This gain is attributed, in part, to earlier flowering and podding and a longer pod fill duration. Despite genetic advancements in several traits, including disease resistance (Gebremedhin et al., 2024), lentil yields on Australian farms have averaged only 1.2 t/ha over the past 30 years. In contrast, the global average yield has increased by nearly 20 % over the same period, although it remains < 1 t/ha (FAOSTAT, 2024).

Lentils are primarily grown in rainfed environments and often encounter terminal drought and heat stress (Ghanem et al., 2017). Like chickpea, lentil flowering and pod set are delayed under cool and wet conditions (Rajandran et al., 2022). The prevailing dry conditions and greater tolerance to low temperatures in low-yield environments may facilitate earlier flowering and pod set in lentils and increase water use during the reproductive phase. This observation aligns with earlier findings by Siddique et al. (2001), emphasising that lentil yield correlates with water use after flowering, not the total water use or water use before flowering. Abiotic stresses contributing to the low yield of lentils include post-flowering frost, drought, and high temperatures during pod set, which can be managed through strategic pairing of variety and sowing date (Lake et al., 2021a; Tefera et al., 2024; Wright et al., 2021).

Pairing appropriate varieties with optimal sowing dates is therefore critical to managing the trade-off between faster development, which reduces the risk of drought and heat, and the increased risk of frost (Ghanem et al., 2017; Lake et al., 2021a; Maphosa et al., 2022; Siddique and Loss, 1999). Like other pulses such as chickpea (Chauhan et al., 2023; Li et al., 2022; Richards et al., 2020) and fababean (Stoddard, 1993), lentil phenology is influenced by temperature, day length and soil water, with dry soils accelerating development (Shrestha et al., 2009). Leveraging this plasticity through strategic management of crop phenology can enhance lentil resilience to climate variability. Therefore, understanding and modelling the environmental modulation of phenological development is crucial for developing strategies to improve the resilience of lentil to variable climates.

The critical period for lentil yield spans from flowering to approximately 200 °Cd after flowering (Lake et al., 2021a, 2021b). Aligning this critical period with a favourable environment is crucial for navigating trade-offs between low temperature for fast-developing phenotypes and elevated temperature and drought for their slower-developing counterparts. Accurate flowering and pod set prediction is essential for identifying site-specific combinations of sowing date and variety phenology, reducing the likelihood of abiotic stresses coinciding with the critical period. While experiments combining varieties and sowing dates are commonly used to match phenology with the environment (Lake et al., 2021a; Maphosa et al., 2022, 2023; Richards et al., 2020), this process is time-consuming, expensive, and does not capture inter-seasonal variation adequately (Siddique et al., 1998a).

Photoperiod and temperature drive lentil development, as observed in other pulse crops (Nelson et al., 2010; Roberts et al., 1985; Weller et al., 2012). However, Wright et al. (2021) observed considerable variations in flowering prediction based on these parameters across environments, suggesting that additional factors like water stress may influence flowering. Tefera et al. (2022), who modelled lentil phenology using APSIM, noted a low accuracy of prediction of flowering time, R² = 0.45 in drier and 0.69 in mid-rainfall environments, but did not elaborate if these differences were related to variation in soil water holding capacity, starting soil water and rainfall patterns. Experimental and modelling evidence supports the impact of water supply on chickpea reproductive development (Chauhan et al., 2023, 2019; Johansen et al., 1994; Ramamoorthy et al., 2016; Singh, 1991). A similar effect could also be true for lentils, although it is less widely recognised. Sadras et al. (2021) reported that irrigated lentil took up to 41 % longer to mature

than rainfed lentils, partly due to delayed flowering and pod set and increased expression of crop indeterminacy. Rajandran et al. (2022) noted that numerous lentil floral buds may fail to open on several nodes, a phenomenon common to other winter legumes such as chickpeas and peas.

It is now emerging that soil water may interact with thermal time to influence phenology in several crops (Chauhan et al., 2023, 2019; Undersander and Christiansen, 1986), although such interaction remains unexplored in lentil. This study tested the hypothesis that accounting for soil water content improves flowering and pod set prediction in lentils. We also investigated the implications of improved phenology modelling for predicting frost and heat stress risk during the 'crop's critical period. Unlike previous studies using fixed frost- and heat-stress windows (Anwar et al., 2022; Lake et al., 2021a; Tefera et al., 2024), we adopted a probabilistic framework considering a range of temperatures and the probabilities of the crop experiencing them at flowering (Chauhan and Ryan, 2020). This approach accommodates variety-dependent variation in tolerance to extreme temperatures and the risk attitude of the grower.

2. Methods

2.1. Field experiments

Flowering and pod set data were sourced from experiments conducted at four locations in New South Wales (NSW), one in South Australia (SA), and three locations in Western Australia (WA), covering 32–34.7° S latitudes and 138.7–148° E longitudes (Table 1, Fig. 1). These experiments were conducted primarily to investigate the impact of sowing time and variety on crop development and yield (Lake et al., 2021a; Maphosa et al., 2023; Richards et al., 2020; Siddique et al., 1998a). In NSW, eight lentil cultivars (PBA Ace, PBA Blitz, PBA Bolt, PBA HurricaneXT, PBA HallmarkXT, PBA Greenfield, PBA Jumbo2 and Nipper) were grown at Yanco (four sowings in 2019), Wagga Wagga (four sowings each in 2018 and 2019), Trangie (four irrigated sowings each in 2018 and 2019) and Leeton (four sowings each in 2018 and 2019), following the recommended planting density of 120 plants/m² and sowing depth of approximately 5 cm. The sowing dates ranged from 15 April to 30 May. The trials at all locations were grown either with or without irrigation. Some experiments involved heavy pre-sowing irrigation and some in-season irrigation (e.g. Trangie). Table 1 also presents the amount of irrigation applied to different sowings if irrigated.

In SA, PBA HurricaneXT, PBA Blitz and PBA Jumbo2 were grown at Roseworthy, with 11 sowings from 27 April to 11 July across the 2018 and 2019 seasons using the same agronomy for New South Wale locations. No irrigation was applied.

In WA, Digger was the only cultivar grown at Merredin (12 sowings) from 1994 to 1996, Northam (eight sowings) in 1994 and 1995 and Cunderdin (four sowings) in 1996. Sowing dates ranged from 15 April to 19 July. Planting was done in rows spaced 18 cm apart with seed sufficient to establish 95 plants/m². Sowing was done at 3 cm depth, and crops were raised as rainfed.

Regular monitoring, at least twice a week, was conducted to record 50 % flowering (when approximately half the plants in a plot had at least one open flower, referred to as 'flowering' hereafter) and 50 % pod set (when half the plants in a plot had at least one visible pod, referred to as 'pod set' hereafter). Flowering and pod set were expressed as days after sowing (DAS).

2.2. Modelling flowering and pod set

The original Agricultural Production System Simulator (Classic version 7.10; <https://www.apsim.info/>) module (APSIMc) of the lentil model has had minimal validation to predict flowering, pod set and yield compared to other legume models (Holzworth et al., 2014; Tefera et al., 2024). Tefera et al. (2024) considered lentil cultivars to be photoperiod

Table 1

Location, season, water regime, plant-available water holding capacity (PAWC), initial soil water, sowing date (DAS) and in-crop rainfall (mm) for the lentil experiments reported in this paper.

Location ^a	Season (year) plus rainfed (R) or irrigated (I)	PAWC (mm)	Initial soil water (%)	Sowing date (doy)	In-crop rain (mm)	In-crop irrigation (mm)
Leeton	2018_I	220	20	106, 120, 134 & 148	150, 150, 150 & 169	220 & 24
	2019_R	220	20	107, 120, 134 & 150	310, 316, 329 & 349	210
Trangie	2018_I	141	20	108, 122, 136 & 150	125, 168, 184 & 184	40, 70, 55, 55 & 40
	2019_I	141	20	105, 120, 135 & 150	135, 135, 137 & 137	175, 87, 75, 75 & 75
Yanco	2018_I	202	80	106, 120, 134 & 148	114, 118, 118 & 118	75, 64, 64, & 64
Wagga	2018_I	128	60	107, 118, 133 & 148	259, 260, 287 & 318	15, 5, 11, 8 & 15
Wagga	2019_I	128	60	104, 120, 134 & 150	438, 493, 493 & 493	15, 0, 0 & 0
Roseworthy	2017_R	126	80	138, 151, 165, 179 & 192	287, 266, 266, 262 & 241	
	2018_R	126	80	117, 129, 143, 156, 170 & 185	251, 235, 223, 214, 182 & 180	
Merredin	1994_R	167	80	143, 157, 173 & 185	157, 127, 97 & 78	
	1995_R	167	80	133, 146, 164 & 178	254, 231, 195 & 179	
	1996_R	167	80	107, 136, 169 & 187	244, 244, 249 & 202	
Northam	1994_R	167	80	132, 152, 167 & 189	279, 174, 164 & 93	
	1995_R	167	80	132, 144, 164 & 187	280, 395, 316 & 295	
Cunderdin	1996_R	112	80	137, 174, 187 & 201	319, 271, 241 & 211	

^a Further details of the experiments conducted at Leeton, Trangie, Wagga Wagga, and Yanco in the 2018 and 2019 seasons are available (Richards et al., 2020). Irrigation values in bold occurred before the first sowing. At the start of each planting season at every location, we simulated starting soil water content to 60–80 % of its PAWC. Irrigation values in bold font denote irrigation either pre-sowing or on the day of sowing. If substantial (≥ 40 mm) pre-sowing irrigation, the soil water content adjusted to 20 % the day before the first sowing. The initial water content was reset on a first sowing day for each location.

and vernalisation insensitive in parameterising the lentil cultivar parameters. These authors also did not consider if soil water could impact the flowering time of lentils. However, considering the available literature on the crop (Sadras et al., 2021; Weller et al., 2012), some degree of sensitivity to photoperiod and soil water was required to account for variation in flowering time related to locations, sowing times and seasons. In line with the objective of our study, we decided to modify the model (APSIMw) to achieve this goal by changing the prototype lentil model (APSIMc). Weather data for different experiments, serving as input for the model, were sourced from the Scientific Information for Land Owners patched point (SILO-PPD) dataset, which is the recommended source of agricultural modelling in Australia (Jeffrey et al., 2001). These data were available at <https://www.longpaddock.qld.gov.au/silo> and referred to as SILO weather data hereafter. Additionally, daily weather data were collected at most experimental sites and merged with SILO weather data to improve simulation accuracy for the location. Soil data were obtained from the APSOIL database (<https://www.apsim.info/apsim-model/apsoil/>). In cases where specific soil characterisations were unavailable, data from nearby locations or generic soils were used.

APSIMw, like APSIMc, also used a thermal clock approach to predict flowering and pod set, except that the value of daily thermal time accumulated varied with soil water status to achieve a particular thermal time target sum to attain a particular phenological stage (TTT_{sum}). It should be noted here that the APSIMc model has functionality that incorporates the effect of soil water through the soil water supply and demand ratio (SDR) and slows down crop development when SDR is very low. This functionality has been activated only in maize and peanuts (refer to www.apsim.info). In winter legumes, including chickpeas and lentil, flowering and subsequent crop development are generally accelerated due to the hastening effect of water stress. Therefore, we developed an alternative approach (APSIMw) to slow or hasten the development of lentil in response to variability in soil water. The modified model predicts flowering and pod set by accumulating thermal units after adjusting for soil water levels. This accumulation is aimed at reaching a specific heat sum, known as the target thermal time sum (TTT_{sum}), which is based on the crop's sensitivity to photoperiod. The crop progresses towards flowering and pod set by gathering these thermal units, taking into account the status of the soil water.

Chauhan et al. (2023) extensively detailed this new approach to capture the soil water effect on flowering and pod set. The approach assumes that each cultivar (i) has a unique TTT_{sum} to commence

flowering and pod set, and (ii) soil water moderates thermal time accumulation to reach this target to influence time to flowering and pod set. The moderating effect of soil water on flowering and pod set was implemented through Eqs. (1) and (2) in the manager module of APSIMw:

$$TTT_{sum} = \sum_i TTm_i = \sum_i TT_i \times (a - FASW_i)^I \quad (1)$$

where TT_i ($^{\circ}\text{Cd}$) and $FASW_i$ represented the thermal time and fractional available soil water on day i , respectively. I was an indicator variable which equalled 1 if $FASW_i \geq 0.65$, and the lentil crop stage was ≥ 3 , and 0 otherwise. If $FASW_i$ was less than 0.65 or the lentil growth stage was ≤ 3 , then $TTm_i = TT_i$ as $(a - FASW_i)^0$ equalled 1. By design of this equation, TTm_i was always $\leq TT_i$. TT_i was calculated using a standard set of three cardinal temperatures daily, following the original APSIM model (APSIMc). The cardinal temperatures used in APSIMc in calculating TT_i were base = 0 $^{\circ}\text{C}$, optimum = 30 $^{\circ}\text{C}$, and maximum = 40 $^{\circ}\text{C}$. The constant 'a' in Eq. 1 was manually optimised and set at 1.65, and $FASW \geq 0.65$ represented the fraction of readily available soil water above which only the TT_i was scaled. TTm_i ($^{\circ}\text{Cd}$) was thermal time scaled by $FASW_i$ on the surface 60 cm layer, from the emergence stage onward (lentil growth stage 3). The TTT_{sum} varied in response variation in thermal times required to reach the end of the juvenile phase and photoperiod sensitivity of a genotype. Because of these unique relationships that influence the TTT_{sum} and the varying rate of thermal time accumulation depending upon TT_i , and the extent of its scaling by soil water, as given in Eq. 1, day of the year (doy) to flowering and pod set were expected to be different than the native APSIMc model.

The $FASW_i$ in Eq. 1 was computed in the manager module as the ratio of simulated available soil water and the simulated potential available soil water as given in Eq. 2.

$$FASW_i = \sum_i \frac{(sw_dep(i) - ll15_dep(i))}{(dul_dep(i) - ll15_dep(i))} \quad (2)$$

where $sw_dep(i)$ is the simulated soil water content (mm) on day i , $ll15_dep(i)$ is soil water content (mm) corresponding to a soil water potential of 1.5 MPa, and $dul_dep(i)$ is soil water content (mm) at 0.033 MPa in each layer (i) in the top 60 cm soil surface layers. The parameters for this equation were used in the soil water module, a component of APSIM, capturing the rate of soil water infiltration, movement, evaporation, runoff, drainage, extractable soil water and

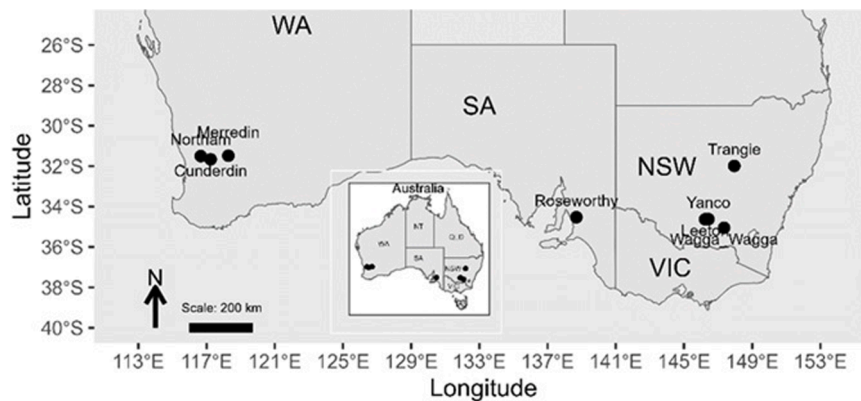


Fig. 1. The eight experimental sites (dark dots) in our study.

total available water. Soil-specific parameters used to calculate the water budget were obtained through systematic soil sampling and characterisation in the APSOIL database (Dalglish et al., 2012).

In our study without data on soil water, the starting FASW was generally set at 80 % on the first day of sowing of each season at an individual location. This figure was arrived at as a planter could plant the crop only when the starting soil water was less than 80 %. For subsequent sowings, the model was allowed to vary soil water dynamically by the soil water module in conjunction with the lentil module (Table 1). In experiments with heavy pre-sowing irrigation, the date at which FASW was reset corresponded to the day before the date of heavy irrigation and was generally set at 20 %. Since the model assumes that radiation use efficiency (RUE) and transpiration efficiency (TE) remain constant from emergence to the late seed fill stage, changes in phenology simulation within the manager module were not expected to affect these fundamental plant processes.

Without pre-existing parameters for different cultivars used in the study that are robust enough to be used in various environments with sensitivity to both soil water and photoperiod (Tefera et al., 2024, 2022), we manually optimised them for a location. When satisfactory simulation with soil water input in APSIMw was obtained ($R^2 = 0.8$), they were applied to all other locations and sowing dates. The parameters are given in Table 2. The TTT_{sum} for flowering and pod set of PBA Ace, PBA Blitz, PBA Bolt, PBA Greenfield, PBA HallmarkXT, PBA HurricaneXT, PBA Jumbo 2 and Nipper grown in NSW were computed by running the model and changing the temperature and photoperiod parameters until high goodness of fit ($R^2 = 0.80$) with observed values for NSW locations was achieved (Maphosa et al., 2023; Richards et al., 2020). The parameters of PBA Blitz, PBA HurricaneXT and PBA Jumbo2 developed for the NSW locations were also applied to predict flowering and pod set in Roseworthy in SA (Lake et al., 2021a). Similarly, the parameters of the cultivar Digger were created using data from a trial conducted at Merredin, WA, in 1994 (Siddique et al., 1998a). There were at least 11 observed data points for each cultivar.

We also evaluated the APSIMc's ability to predict flowering without inputting vernalisation, soil water and photoperiod with three cultivars, PBA Jumbo2, PBA Ace and PBA HallmarkXT grown in New Wales locations. The parameters for these cultivars were optimised for APSIMc without considering the influence of soil water, photoperiod and vernalisation by Tefera et al. (2024). Sowing date, soils, and other agronomic conditions for both sets of simulations were similar, as given in Table 1.

2.3. Sensitivity analysis of soil water effects on flowering time in lentil

The sensitivity of flowering and pod set to the starting soil water and in-season rainfall was studied using two sites with different soils of Cunderdin and Merredin in WA, where soil water was measured

(Siddique et al., 1998b). Both sites were planted on 15 or 16 May 1996 in this comparison. The plant available water-holding capacity in the top 60 cm layer of Cunderdin soil was 62 mm, and the Merredin was 44 mm. In the first set of simulations, the effect of starting soil water input into the model was adjusted from 20 % to 100 % in a 20 % step. In the second set of sensitivity simulations, rainfall input varied from -10 % to $+10$ % in a 5 % step of actual while keeping the starting FASW at 80 %. No pre- or post-sowing irrigation input was included in the model. The simulated data included the number of days for flowering and the pod set.

2.4. Spatial and temporal heat stress and frost risk

The APSIM user interface was configured to reflect standard agronomic conditions, including 120 plants/m², 300 cm row spacing, 5 cm planting depth, and cultivar 'PBA Greenfield', with 60 % starting soil water at each planting for the eight locations considered in this study. Simulations were run for seven fortnightly sowings spanning 15 April to 15 July for the Yanco site. Long-term daily climatic data (1957–2023) for this site were obtained from the SILO website <https://www.longpaddock.qld.gov.au/silo>. The soils used for these simulations matched those used in the model validation. The FASW (at 60 %), nitrogen and organic matter were reset at sowing time for each season. Model outputs were used to compute frost probabilities for minimum temperatures of ≤ -2 , ≤ -1 , ≤ 0 , ≤ 1 , ≤ 2 and ≤ 3 °C and heat stress probabilities for maximum temperatures of ≥ 24 , ≥ 25.5 , ≥ 27 , ≥ 28.5 , ≥ 30 , and ≥ 31.5 °C, as recorded in Stevenson screens at 1.5 m height (Goynne et al., 1996). The mean temperature and rainfall observed during the experimental period are given in Supplementary Table 1. This analysis used weather data from 1957 onwards, identifying temperatures reaching specific thresholds as 'post-flowering frost events' and 'heat stress events' based on the respective criteria.

We determined only the risk of frost and heat stress in terms of probabilities of their occurrence in relation to the stage of crop development. Frost and heat stress impact lentil yield, but we did not simulate yield as quantitative information about their impact on yield was unavailable.

2.5. Model evaluation

We used Excel to calculate various model evaluation metrics, including the coefficient of determination (R^2) from least squares linear regression and normalised root mean square error (NRMSE) for precision. Accuracy was assessed using Lin's concordance correlation coefficient (LinCCC). We compared actual and modelled flowering and pod set for APSIMw using our modified thermal time accumulation scheme and APSIMc using parameters developed by Tefera et al. (2024). Regressions were performed between observed (x) and simulated (y) data.

Table 2

Key parameters used in the model to predict flowering and pod set.

Genotype	Em-EndJ °Cd	Photoperiod h (x1, x2)	EndJ-Fin °Cd (y1, y2) —	Fin-FI	Fl-PS	PS-EGF °Cd —	EGF-M	M-HR	HI (gyld/gbio)/d	
Digger	515	10.4 13.3	446	0	33	150	990	60	1	0.134
PBA Ace	450	11.2 12.0	446	0	33	150	990	60	1	0.134
PBA Blitz	300	11.2 12.2	446	0	33	150	990	60	1	0.134
PBA Bolt	400	10.4 13.3	446	0	33	150	990	60	1	0.134
PBA Greenfield	470	10.4 13.3	446	0	33	150	990	60	1	0.134
PBA HallmarkXT	410	11.0 12.5	446	0	33	150	990	60	1	0.134
PBA HurricaneXT	450	11.0 12.5	446	0	33	150	990	60	1	0.134
PBA Jumbo2	380	11.0 12.3	446	0	33	150	990	60	1	0.134
PBA Nipper	520	11.2 12.2	446	0	33	150	990	60	1	0.134

aThe development phases are **Em_EndJ** = emergence to end-of-juvenile; **EndJ-Fin** = end-of-juvenile to floral-initiation; **Fin-FI** = floral-initiation to flowering; **Fl-SP** = flowering to start-of-pod-set; **PS-EGF** = start-of-pod-set to end-grain-fill; **EGF-M** = end-grain-fill to maturity; **M-HR** = maturity to harvest-ripe; HI = Harvest index; °Cd are thermal time targets for different development phases. The transpiration efficiency of 0.55 g biomass/g H₂O and radiation use efficiency of 0.69 g biomass/MJ were common to all cultivars.

The NRMSE was calculated as follows:

$$NRMSE = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (S_i - O_i)^2}}{\bar{O}} \quad (3)$$

where S_i and O_i are the simulated and the observed values, respectively, \bar{O} is the mean of the observed values, and n is the number of observed values. NRMSE was expressed as a fraction. A lower NRMSE indicates better precision.

LinCCC (Lin, 1989) is defined as follows:

$$x = \frac{2\rho\sigma_x\sigma_y}{\sigma_x^2 + \sigma_y^2 + (\mu_x - \mu_y)} \quad (4)$$

where μ_x and μ_y are the means of two variables (simulated and observed, respectively), σ_x^2 and σ_y^2 are the corresponding variances, and ρ is the correlation coefficient between the two variables. McBride (2005) suggested the following guidelines to infer a model's predictive performance based on LinCCC: $\rho_{cpc} < 0.90$ = poor, $0.90 < \rho_{cpc} < 0.95$ = moderate, $0.95 < \rho_{cpc} < 0.99$ = substantial, and $\rho_{cpc} > 0.99$ = almost perfect prediction.

3. Results

3.1. Observed timing of flowering and pod set in different environments

Actual flowering time ranged from 61–147 days after sowing (DAS) in NSW, 75–116 DAS in South Australia, and 69–119 DAS in WA (Fig. 2a, c, e). Pod set ranged from 82–163 DAS in NSW, 83–126 DAS in SA, and 77–123 DAS in WA (Fig. 2b, d, f).

3.2. Prediction of flowering time

In our analysis of pooled data from eight locations and eight different cultivars, the linear regression analysis yielded an R^2 of 0.84, NRMSE of 0.07, while LinCCC was 0.91 (Fig. 3). These results indicate significant linear regression and a strong alignment with the 1:1 line and relatively small errors (see results for individual locations across three Australian states in Supplementary Fig. 1).

In limited comparison with APSIMc model, which did not scale thermal time accumulation based on soil water status, significantly underperformed across all three analysis metrics compared to APSIMw, which does adjust thermal time accumulation daily according to soil water levels (Fig. 4).

3.3. Prediction of pod set

In the analysis of pooled data from all eight locations, which included eight cultivars, the regression analysis between observed and predicted days to pod set using APSIMw produced an R^2 of 0.83, the NRMSE of 0.07 and the LinCCC of 0.91 (Fig. 5; see results of days to pod set of individual locations across three Australian states in Supplementary Fig. 2).

3.4. Sensitivity of flowering and pod set in two environments to variation in starting water and in-season rainfall

The time to flowering varied with starting water content between 20 % and 60 %, but it stabilised at higher water levels (Fig. 6). The delay in flowering due to starting soil water levels was more pronounced in Cunderdin soil, which had a higher plant-available water-holding capacity than Merredin soil in the top 60 cm layer. When the initial plant-available water was greater than 60 %, the simulated flowering and pod set times were generally more stable and aligned with the observed days to flowering and pod set (no observed pod set data were available for Cunderdin). In contrast, when the initial plant-available water was below 60 %, flowering and pod set times increased somewhat linearly, corresponding to a range of 10 % less rainfall to 10 % more actual rainfall (Fig. 7).

3.5. Risk of post-flowering frost and heat stress in different environments

The probabilities of experiencing the last frost of the season and the first day of heat stress provided insights into the likelihood of the crop being affected by frost and heat stress events (Fig. 8). Based on observed data (not reported here), it was found that the period of reproductive growth from flowering to maturity averaged around sixty days (~690 °Cd). The crop could avoid these stresses if the last frost day and first heat stress day occurred outside this reproductive period. Frost and heat stress were defined by temperatures below 0°C and above 30°C, respectively. The days these stresses occurred at 10 % probability levels were considered safe windows. Other temperatures in the probability charts accounted for genetic variation in susceptibility among different genotypes and the temperature difference between the site where they are measured and the actual field location. This temperature difference could also vary due to differences in elevation and could impact the lethality of extreme temperatures.

4. Discussion

Crop adaptation to environmental stresses is associated with the timing of crop phenological development (Berger et al., 2006; Gaur et al., 2008) and genetic tolerances (Bhardwaj et al., 2024). This creates

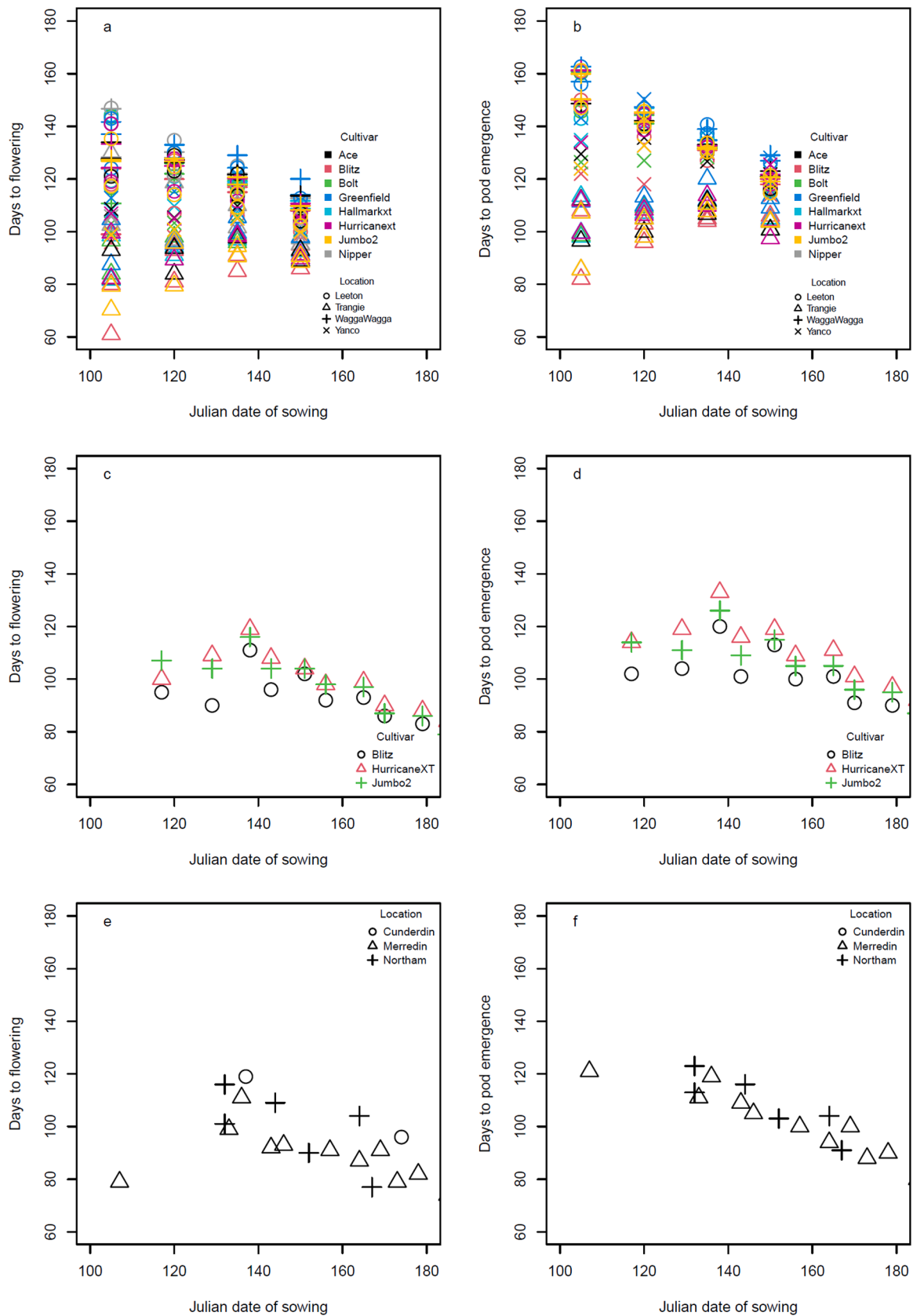


Fig. 2. Observed days to flowering and pod set as affected by sowing time (day of the year) at four locations in New South Wales (a, b), Roseworthy in South Australia (c, d) and three locations in Western Australia (e, f). Cultivars Ace, Blitz, Bolt, Greenfield, HallmarkXT, HurricaneXT and Jumbo2 are indicated in the chart legends and have a PBA prefix. In Western Australia (e, f), Digger was the only cultivar grown.

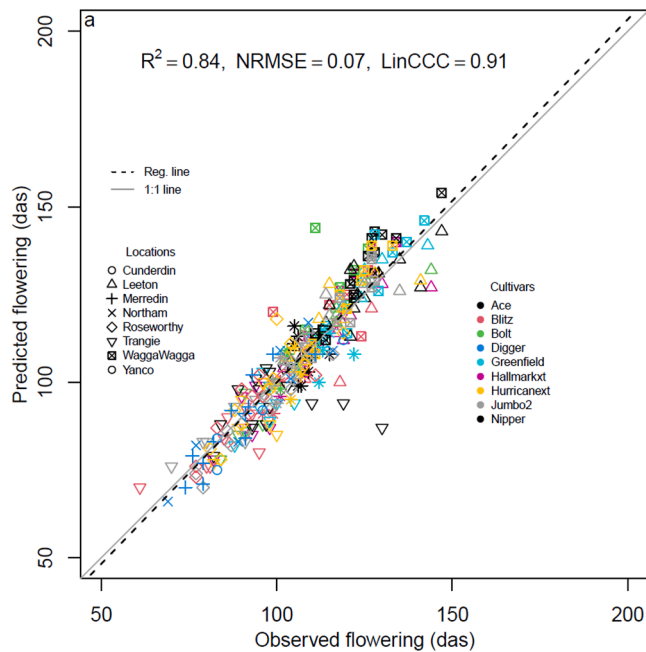


Fig. 3. Observed versus predicted days to flowering (days after sowings) across eight Australian lentil-growing locations. Metrics include the coefficient of determination (R^2), normalised root mean square error (NRMSE), and Lin's concordance correlation coefficient (LinCCC).

a challenging situation in variable climates. Adapting crops will become more complex if climate change further increases climatic variability. In such situations, an easier way would be to accurately predict the onset of sensitive stages and align them to variable and changing climates. Crop models can be helpful tools to develop and test hypotheses and interpret experimental results in diverse sets of situations. Our study showed that the modelling of flowering and pod set in lentils is reasonably accurate only when we take soil water, which often is variable due to climatic variability into consideration. The impact of soil water on phenological development has been investigated in some grasses (Moore et al., 2015). It, however, remains underexplored in many winter crops, including wheat, barley, oat, canola, lupin, field pea, fababeen and lentils.

In this study, we achieved a high accuracy for predicting flowering and pod set by incorporating soil water effects (Figs 3 and 5). Including soil water as an additional factor led to greater accuracy and precision in

predicting flowering over the native model that did not include soil water as a factor influencing flowering (Fig. 4). This highlights the necessity of including soil water to predict flowering in lentils.

Our study demonstrated improved accuracy across diverse environments, even though some uncertainties arose from the weather data collected from weather stations located slightly away from the experimental sites. Additionally, there was variability in the initial soil water conditions (Chauhan et al., 2023). There could still be some other factors that we may not have considered. It's important to note that drier surface soil may develop a crust, potentially reducing predictive accuracy by delaying emergence (Lachlan Lake, SARDI, personal communication). These uncertainties could contribute to discrepancies observed in the flowering time prediction at Roseworthy.

Our study's sensitivity analysis with soil water status suggested that the fraction of starting soil water and in-season rainfall in conjunction with plant available water holding capacity can profoundly affect flowering and pod set. APSIMw appeared reasonably good in capturing the effect of initial soil water and subsequent soil water changes related to in-season rainfall in flowering and pod set. The native APSIM model overlooks these effects. The manager module implemented the rules for accounting for the effect of soil water on flowering and pod sets. As these rules were not fully integrated with other processes, such as radiation use efficiency, nutrient uptake, and water use, which could be considered as a limitation of the study, it could be argued any changes in flowering and pod set may not be aligned to soil water changes through feedback mechanisms. However, this is also true where only photoperiods and temperatures are considered for predicting flowering (Keating et al., 2003). We assume that changes in flowering and pod set incorporated using manager rules may not affect soil water use as plants may continue using soil water unhindered for vegetative development before pods start to emerge but may change the sensitivity of the crop to frosts. This is probably what happens in nature when a crop's delayed flowering and podding leads to self-shading, reduced pod and seed set, low harvest index and ineffective soil water use (Lake and Sadras, 2021). We found that despite the incorporation of these rules in the manager module and operating separately to model's other processes, soil water use predicted by soil water use predicted by the model was within 10 % of actual soil water use for the lentil cultivar Digger (Siddique et al., 1998a).

The phenology component is still crucial to any crop model as some of the plant processes, such as dry matter partitioning into yield, may be affected by the timing of development. However, in the native APSIM model, specific parameters—such as base temperature, nitrogen fixation rates, transpiration, radiation use efficiencies, apportionment of

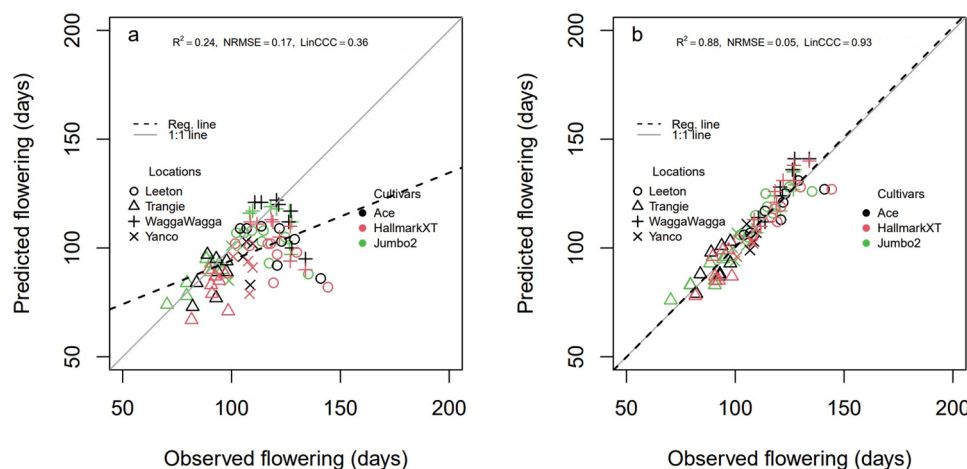


Fig. 4. Observed versus predicted days to flowering simulated by APSIMc, which used parameters from Tefera et al. (2024) without scaling of thermal time accumulation by soil water (a), and APSIMw, which scaled thermal time accumulation based on soil water (b). The metrics used for comparison were R^2 (the coefficient of determination), NRMSE (the normalised root mean square error), and LinCCC (Lin's concordance correlation coefficient).

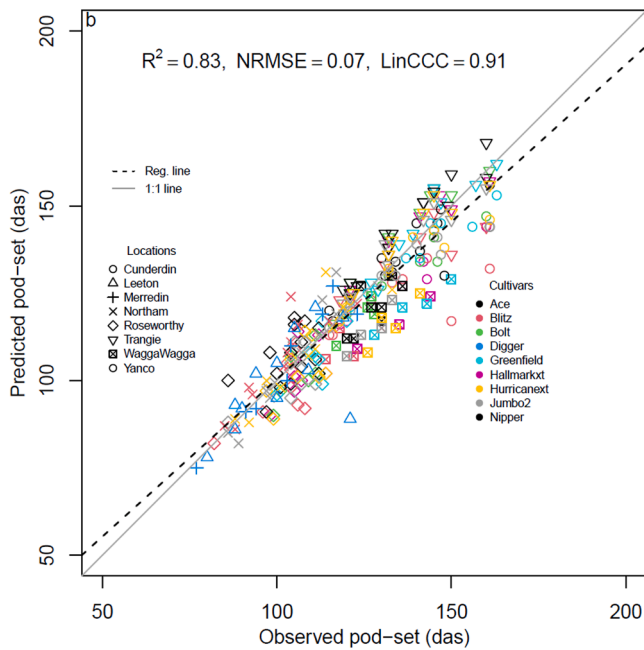


Fig. 5. Observed versus predicted pod set (days after sowings) across eight lentil growing locations. Cultivars Ace, Blitz, Bolt, Greenfield, HallmarkXT, HurricaneXT and Jumbo2 have a PBA prefix. The daily thermal time accumulation was scaled by soil water. R^2 is the coefficient of determination, NRMSE is the normalised root means square, and LinCCC is Lin’s concordance correlation.

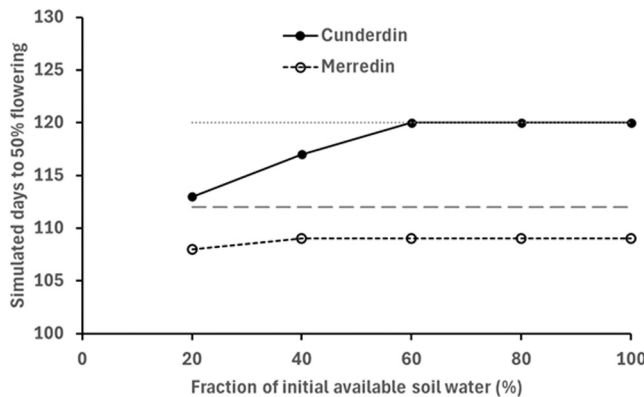


Fig. 6. The simulated effects of different starting plant available soil water fractions at Cunderdin and Merredin with 62 and 44 mm plant available water holding capacity in the top 60 cm soil layer, respectively and their comparison with observed values at each location represented by horizontal straight lines.

carbohydrates to organs, and nutrient uptake—remain unchanged from floral initiation to the completion of the grain-filling stage. Therefore, our results are still relevant in examining whether the current approach of predicting phenology based on photoperiod and temperature can simulate phenology well or must be modified. Future work should integrate the phenology models with the rest of the model to account for any forward or feedback mechanisms, including predicting the occurrence of lodging due to excessive growth and the influence of maturity times on exposure to terminal drought.

Based on our simulations, we can assume that environmental factors, including temperature and soil water status, as for flowering, could also play a crucial role in the pod set of lentils. We could capture these effects by setting an additional thermal time target of 150 °Cd for all genotypes, although minor genotypic differences for flowering related to genotypes have not been ruled out. Capturing these effects could lead to achieving

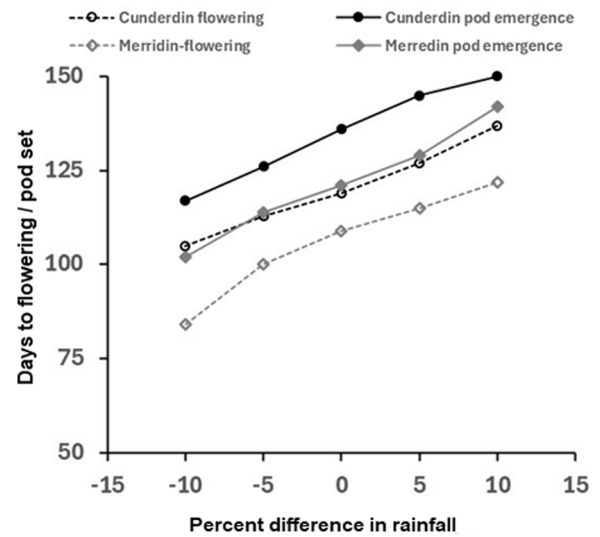


Fig. 7. Sensitivity analysis of flowering and pod set in response to seasonal variation in rainfall amounts (0 = actual observed in the season).

even greater accuracy. This should be investigated further.

Genetic variation in thermal time targets to achieve flowering and pod set, which could be related to the sensitivity of genotypes to the length of juvenile phase and photoperiod sensitivity, may be magnified by the soil water environment. Theoretically, longer and delayed flowering in lentils may allow the crop to benefit from favourable growing conditions, while dry periods in drier environments shorten the growing season. Delays in flowering in wetter soil will lead to a longer time for canopy development and escape from frosts, as noted by Richards et al. (2022). Such delays also increase the number of pod-bearing nodes in lentils, thus increasing grain yield later in the season (Ghanem et al., 2015). The lack of such opportunities related to scanty winter rainfall may be why lentil is poorly adapted in Australia’s northern grain-growing region (Maphosa et al., 2023). Warmer and drier environments may induce early flowering, but occasional frosts could diminish the advantage of earlier flowering. Whether genetic variation exists in this response is unknown, but breeders may indirectly select this trait to identify better-adapted genotypes. However, it is possible to speed up the process by making direct selections for this trait by, for example, examining maximum phenology modulations under a managed stress environment or identifying genes associated with this trait to expedite the selection program.

Our sensitivity analysis suggests that phenological plasticity in lentils could be a crucial mode of short- and long-term adaptation to variable and changing climates in the crop. It could be considered ‘functional plasticity’ and may complement genetic adaptation in tolerance to various stresses (Matesanz et al., 2020). Early flowering may allow the crop to escape terminal drought and heat stress in dry seasons, especially when accompanied by warmer temperatures. Here, adjustment of planting times could overcome these effects. Sadras et al. (2021) reported earlier flowering of lentils in drier southern environments, which is consistent with our model and may increase the length of the reproductive period.

The influence of soil water on the phenological development of lentils, like in other winter crops, could be biologically interesting and significant for modelling, agronomy, and understanding the impacts of climate variability and change on production. Our research on this aspect can help determine whether warming associated with climate change will always result in a shorter phenological cycle or if longer cycles could also occur when accompanied by increased rainfall (Fig. 7). Therefore, our approach can better account for variations in crop development related to longer-term changes in soil water availability.

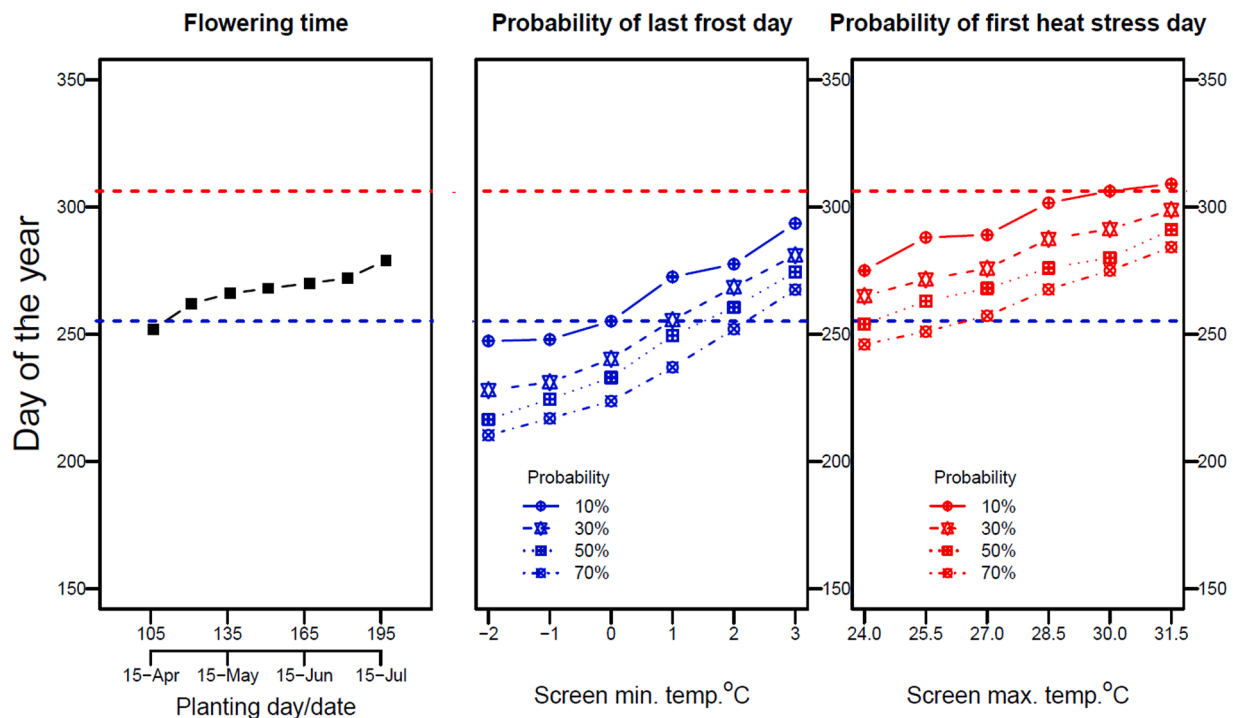


Fig. 8. The simulated flowering day of the year, adjusted for soil water effects, is shown by a solid dark line and solid square symbols in the left panel based on the sowing date. In the middle panel, blue lines with symbols illustrate the probabilities of the crop experiencing frost (temperatures between -2 and 3 °C). In contrast, the right panel features red lines with symbols indicating heat stress (temperatures between 24 and 31.5 °C) from 1957 to 2022. A horizontal blue line without symbols that runs across all three panels, represents days of the year with a 10 % probability of experiencing 0 °C (frost). Similarly, a horizontal red line marks the 10 % probability of experiencing heat stress at 30 °C.

Soil water availability also fluctuates with seasonal conditions and among individual paddocks due to the adoption of particular crop rotations, leading to differences in crop development across neighbouring farms. Our model can capture these effects. Traditional photoperiod-temperature models resulting from paddock-specific agronomic have been unable to capture this variation accurately.

Additionally, we have shown improved modelling of frost risk by incorporating the effects of soil water on phenology. The trade-offs between frost and heat damage are significant and can be modelled more reliably using our approach. From an agronomic perspective, practices can be developed to optimise the interactions between genotype, environment, and management that influence soil water and flowering time within specific contexts. More focused research is therefore required to unravel the potential of this finding.

Once the concept of soil water modulating flowering and pod set in lentils, as in chickpeas, becomes widely accepted as a better phenology model, this will likely be incorporated into the model as a standard feature in the new APSIM nextgen lentil model under development (Holzworth et al., 2018) and spur more research on this aspect. Further research is required to establish this response's physiological basis, which needs to be more precisely understood. Such investigation will be instrumental in improving the prediction of yield and biomass, which currently can not be accurately predicted due to inaccurate prediction of flowering and pod set times and, consequently, maturity times in lentils.

5. Conclusions

This study, through a modelling approach, presents evidence that soil water may be involved in modulating flowering and pod set in lentils and highlights the need for systematic research to understand the impact of soil water on lentil adaptation to variable climates, including its interactions with other phenological drivers like photoperiod and temperature. Further investigation into cultivar-dependent phenological

responses to soil water in lentils and its breeding, including agronomic implications, is warranted. Enhanced predictions of lentil phenology using this approach will contribute to better decision-making when selecting optimal sowing dates and cultivars, thereby helping manage trade-offs related to frost, drought and heat stress to optimise yield, profit and risk. The timing of flowering concerning the probability of encountering frost (≤ 0 °C) or heat stress (≥ 30 °C) is crucial for managing yield risk in lentils.

Priorities for trait-based crop improvement programs would benefit from considering the moderating effect of soil water on lentil development. This research provides valuable insights for refining crop management practices and guiding future breeding strategies to enhance lentil adaptation and performance across diverse environments.

Ethics approval not applicable

Consent to participate is not relevant.

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CRedit authorship contribution statement

David Luckett: Writing – review & editing, Writing – original draft, Data curation. **Ryan Ip:** Writing – review & editing, Methodology. **Lachlan Lake:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Victor Sadras:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Kadambot Siddique:** Writing –

review & editing, Writing – original draft, Methodology, Conceptualization. **Yashvir Chauhan**: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Muhuddin Anwar**: Writing – review & editing, Writing – original draft, Conceptualization. **Mark Richard**: Writing – review & editing, Writing – original draft, Funding acquisition, Data curation.

Declaration of Competing Interest

Authors declare no conflict of interest.

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Authors' contributions

YSC, MRA, MFR, RHLip, VOS, LL, KHMS designed the various experiments whose data has been used in the study. DJL assisted with data preparation, analysis, and visualisation. YSC conceptualised the model analysis and wrote the first draft of the manuscript, which all authors subsequently revised.

Code availability

Not applicable

Consent for publication

Field data was shared under a GRDC generic material transfer agreement between NSW DPI and DAF, Queensland, and this journal article was a planned output.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.eja.2024.127486](https://doi.org/10.1016/j.eja.2024.127486).

Data availability

Data will be made available on request.

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