Effect of soil water on flowering and pod-set in chickpea: implications for modelling and managing frost and heat stress

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Take home messages

- Frost and heat stress risks to chickpea yield can be minimised by better matching flowering time to the growing environment.
- Flowering and pod-set in chickpea are influenced by temperature, photoperiod, and soil water.
- Plants growing without water stress have a longer vegetative period and delayed pod-set, while water stress reduces the time to flowering and pod-set.
- The delaying and hastening effects of soil water on chickpea flowering and pod-set have been successfully modelled.
- There are significant practical implications of the soil water effects on flowering and pod-set in minimising yield losses due to frost and heat stress in chickpea.

Introduction
Factors such as frost and heat stress can affect chickpea yields in different chickpea-growing environments in Australia. Each frost event reduces chickpea yield by approximately 5% (Chauhan and Ryan 2020). It is essential to align the timing of flowering and pod-set more accurately with the growing environment to minimise these risks. Prediction tools can help achieve this. Currently, such tools rely on factors like photoperiod and temperature to predict flowering timing. These predictions need to be more accurate to effectively manage chickpea growth and minimise the impact of frost and heat stress.

Changes in timing of flowering and pod-set, whether due to soil water holding capacity or in-season rainfall, can also influence flowering and pod formation in chickpeas. A comprehensive model that considers the effects of soil water, photoperiod, and temperature has been developed to improve the prediction of these events. This work is presented here.

Methods
The research on the prediction of flowering and pod-set in chickpea presented here focuses on model development, validation, and application (see Chauhan *et al.,* 2019 for more details).

Model development

Chickpea cultivar PBA Boundary⦶ was grown in three environments, including Kingaroy, Jondaryan, and Hermitage, from 2015 to 2019 as part of GRDC project DAQ 00193 and five other Queensland locations as part of GRDC project DAN00121.

To predict flowering and pod-set, two approaches were used, namely:

1. Predictions based on the Agricultural Production Systems Simulator (APSIM) Classic version 7.10 (APSIM) model development with no temperature threshold for the pod-set.
2. APSIMw **–** a modified version of the APSIM model that moderates thermal time accumulation as a function of soil water.

To incorporate the effect of soil water on flowering and pod-set, the following equations were used in the manager module of the model:

$$\mathbf{TTm = TT * (1.65 - FASW)\ (only\ when\ FASW \geq 0.65,\ else\ TTm = TT)}$$

In the above equation, TT (thermal time) is the daily thermal time, and TTm (modified thermal time) is scaled by fractional available soil water (FASW) in the surface 60 cm layer from the crop emergence stage (stage 3 in APSIM). This equation when included in the model ensures that chickpea development slows when soil water is greater than 65% of its total availability and speeds up when it is less than this threshold. TT is derived using a set of cardinal temperatures with a base of 0 °C, optimum of 30 °C, and ceiling of 40 °C. TT equals mean ambient temperature up to 30 °C. FASW – the fractional available soil water used in the above equation was computed using another equation:

$$\mathbf{FASW = \Sigma\ (sw\_dep(i) - ll15\_dep(i))\ /\ \Sigma\ (dul\_dep\ (i) - ll15\_dep(i))}$$

sw_dep(i) is soil water, ll15_dep(i) is the soil water corresponding to a soil water potential of 1.5 Mpa, and dul_dep(i) is the soil water at field capacity in each layer (i) in the top 60 cm soil surface layers. FASW equals 1 when soil water is at the field capacity.

The thermal time target required by the crop for flowering was computed by photoperiod temperature interaction, and its daily accumulation was dynamically scaled using soil water.

Model validation

Data used was collected at flowering and pod-set in chickpea experiments at various locations, seasons, and sowing dates in southeastern Australia on cultivar PBA Boundary⦶ (Figure 3, also see Chauhan *et al.,* 2023). The locations ranged from 26.6 to 34.6 °S and 138.7 to 151.8° E. ‘Flowering’ refers to when at least 50% of plants had an open flower, while ‘pod-set’ refers to when at least 50% had a visible pod.

Model application

The improved model was used to determine the occurrence of post-flowering frost and heat events by predicting the flowering time. Frost frequency was calculated by counting the number of days where the minimum temperature was less than or equal to 0°C. Heat stress frequency was determined by counting the number of days where the maximum temperature was ≥32°C. Prediction of probabilities of frosts and heat stress was done in relation to planting time for Goondiwindi.

Results

The model for flowering incorporating the scaling effect of soil water on thermal time was developed using data collected on a chickpea cultivar PBA Boundary⦶ grown in three environments, including Kingaroy in the South Burnett, Jondaryan on the Darling Downs, and Hermitage on the Southern Downs in GRDC project DAQ 00193 as part of APSIM (Chauhan *et al.,* 2019). It was later applied to other locations in Queensland, and composite Figure 1 presents these results along with APSIM predictions without soil moisture effects. The model's predictive accuracy for flowering was much greater than when only thermal sum modified by photoperiod was used for predicting flowering. The amount of soil water modulates phenology considerably, which may affect how many frosts crops will experience in the critical period for yield (Figure 2).

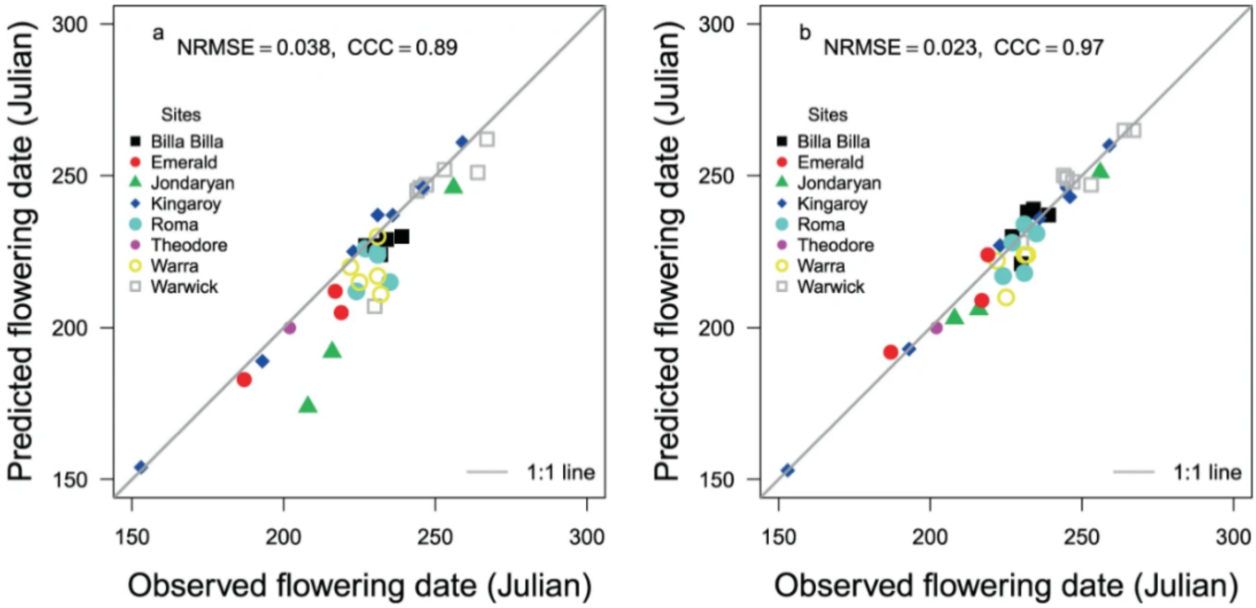

Figure 1. The predictive accuracy of flowering time for 37 chickpea sowings (a) is based only on temperature and photoperiod, and (b) is based on the additional effect of soil water. NRSME is normalised root mean square error. The grey line is y = x. CCC = Lin's concordance correlation coefficient (Redrawn from Chauhan *et al.,* 2019).

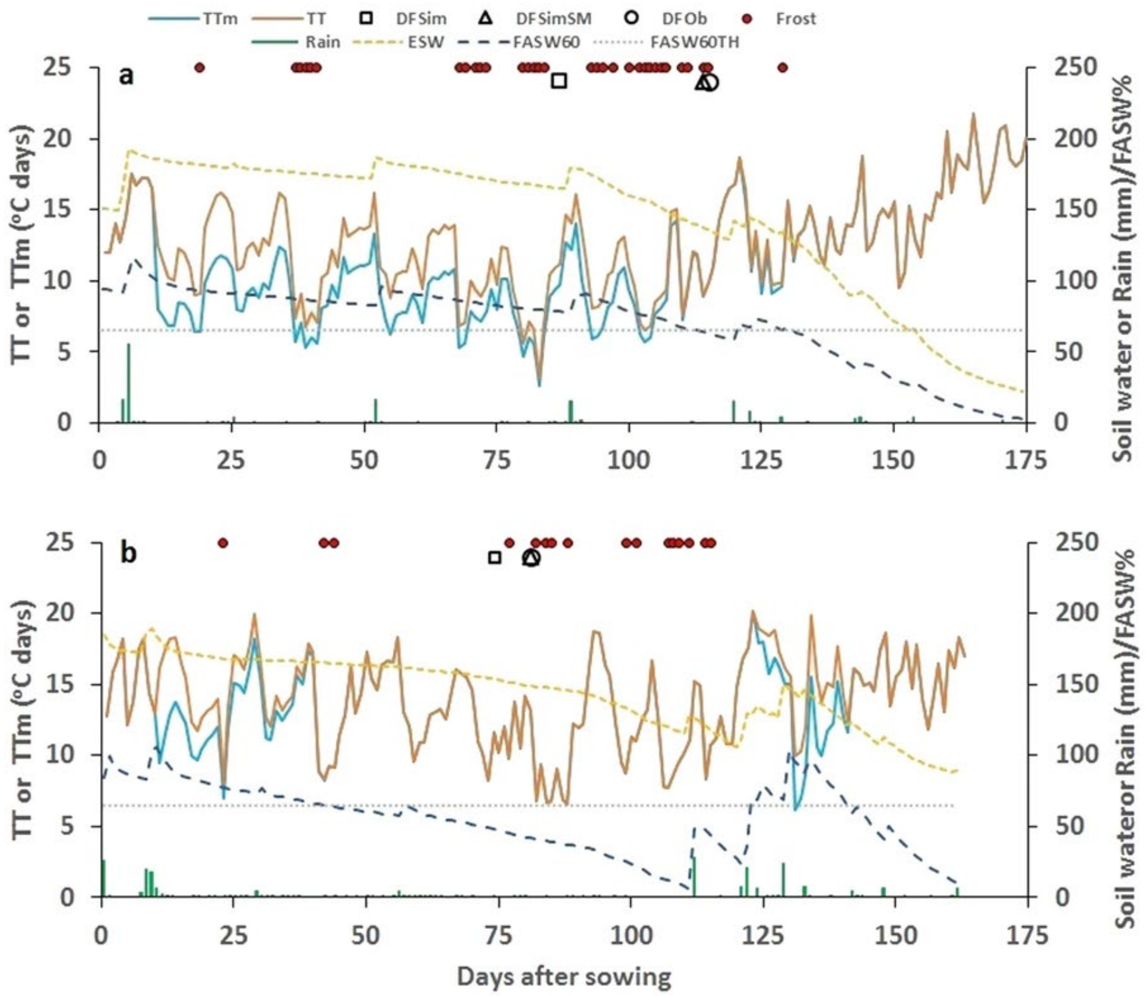

Figure 2. Dynamics of extractable soil water (ESW), rain, daily thermal time (TT), modified thermal time (TTm), flowering time predicted with soil water (DFSimSM), and without soil water input (DFSim), observed days to flowering (DFO), and frost events at Warwick (a) and Kingaroy (b) in Queensland in 2015. Kingaroy also received 25 mm irrigation (shown as rain) at sowing and 113 days after sowing. FASW60 is fractional available soil water (FASW) of 60 cm layer (%) and FASW60TH = FASW threshold (%) (Redrawn from Chauhan *et al.,* 2019). Modification of thermal time occurred only when soil water was above the threshold level of 65% availability.

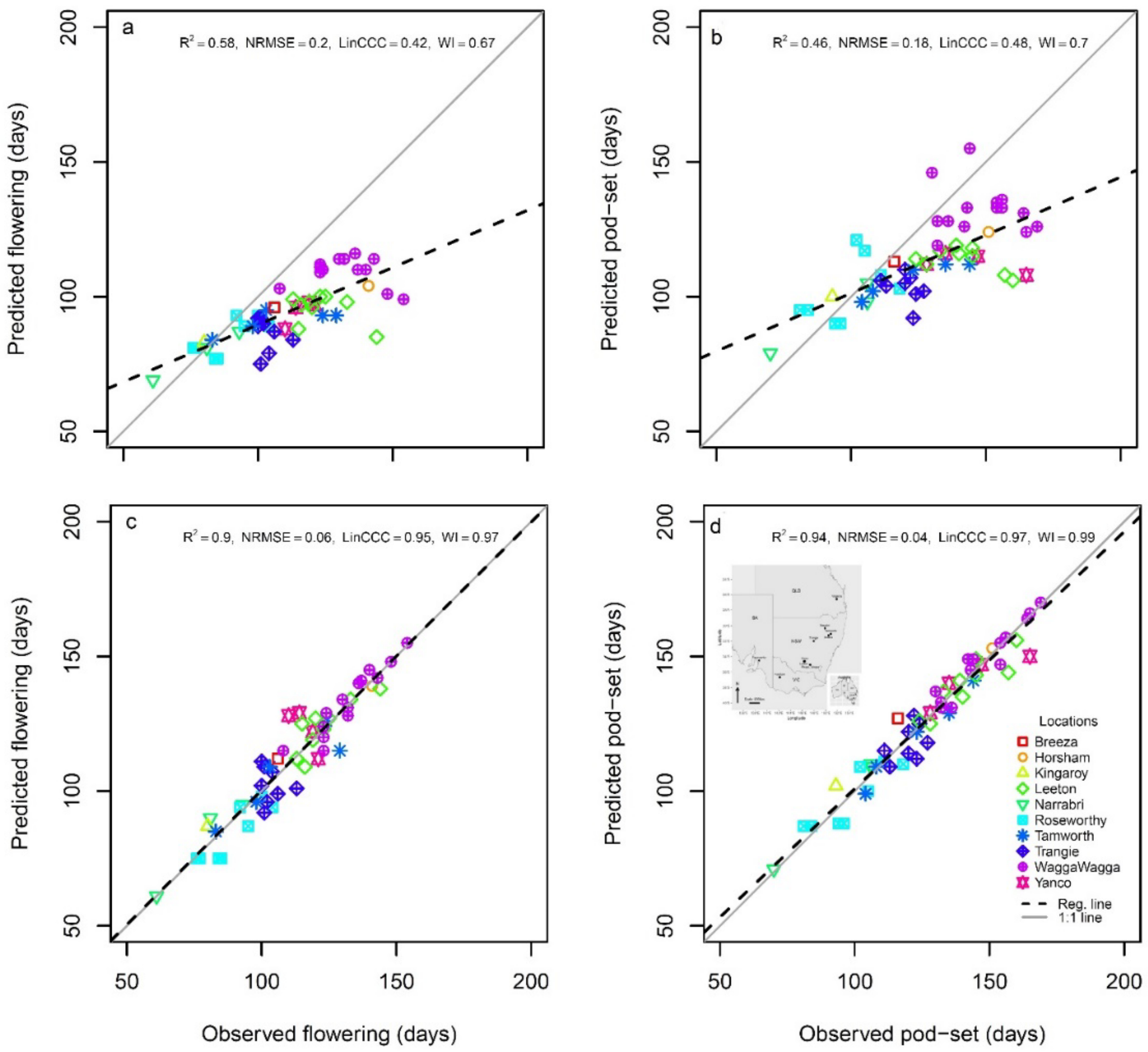

Figure 3. Prediction (n = 54) of flowering (a & c) and pod-set (b & d) by APSIM Classic and soil water model for cultivar PBA Boundary⁽ᵇ⁾ sown in different sowings across ten locations (see inset in chart d). The coefficient of determination of the linear relationship, normalised root means square error (NRMSE), 'Lin's concordance correlation coefficient (LinCCC), and Willmott's index (WI) are shown on the top of each chart. Redrawn from Chauhan *et al.,* (2023).

Collaboration with scientists of the NSW DPI and SARDI, who collected flowering and pod-set data in various GRDC projects, permitted validating the flowering model and adding further ability to predict pod-set (Figure 3). Experiments in which this data was collected were grown in 10 diverse environments with the ambient mean maximum temperature varying between 15.8 and 22.7 °C, and the minimum ambient temperature between 1.3 and 9.4 °C. The predicted vs observed regression line was closer to the 1:1 line for APSIMw than for APSIM (Figure 3a-c). Model precision quantified with R2 and the measurement error, ranked APSIMw > APSIM (Figure 3a-c). LinCCC and Willmot index parameters were lower for APSIM compared to LinCCC of > 0.95 and the Willmot index of 0.98 for APSIM (Figure 3).

Pod-set was also able to be predicted by adding 200 °Cd to the target of flowering. The regression line related to the predicted and observed time of the pod-set was closer to the 1:1 line for APSIMx and APSIMw than for APSIM (Fig. 3b-d). The precision (R2, NRMSE) ranked APSIMw > APSIM. The performance parameters of the LinCCC and Willmot index were lower for APSIM (Figure 3b) compared to LinCCC, which was 0.97 (Figure 3d).

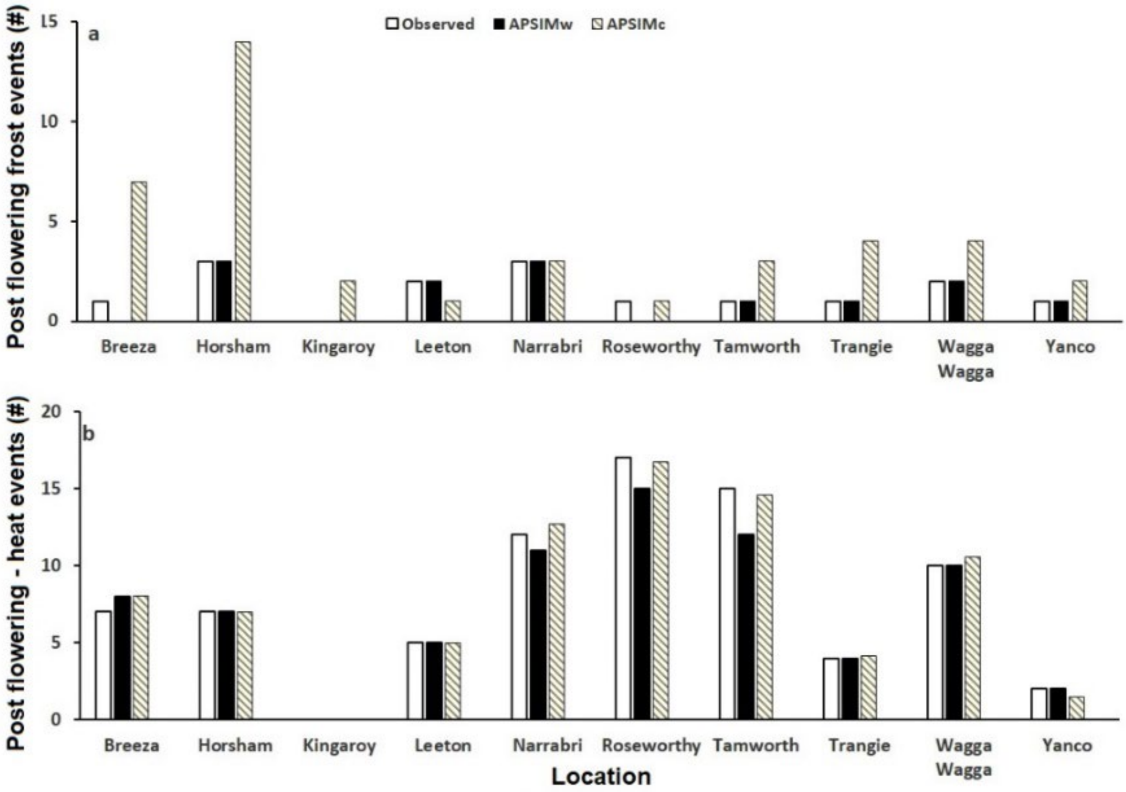

Figure 4. Evaluation of observed frequencies and predictions made by soil water (APSIMw), APSIM Classic model (a) frost and (b) heat stress events after flowering. Redrawn from Chauhan *et al.,* (2023).

The APSIMw predicted post-flowering frosts (Figure 4a) and heat events (Figure 4b) with reasonable accuracy, particularly in more stressful environments. Frost events after flowering calculated using default phenology APSIM models were overestimated, but heat stress events were similar. Figure 5 shows how sowing time influences the probabilities of the crop experiencing frost and heat events.

The model was also validated for flowering, pod-set and flowering to pod-set interval using data published (results not shown) in a GRDC update paper (Pattison *et al.,* 2018). The ability to predict their data enabled us to explain their observations, and identify the factors that lead to such variation.

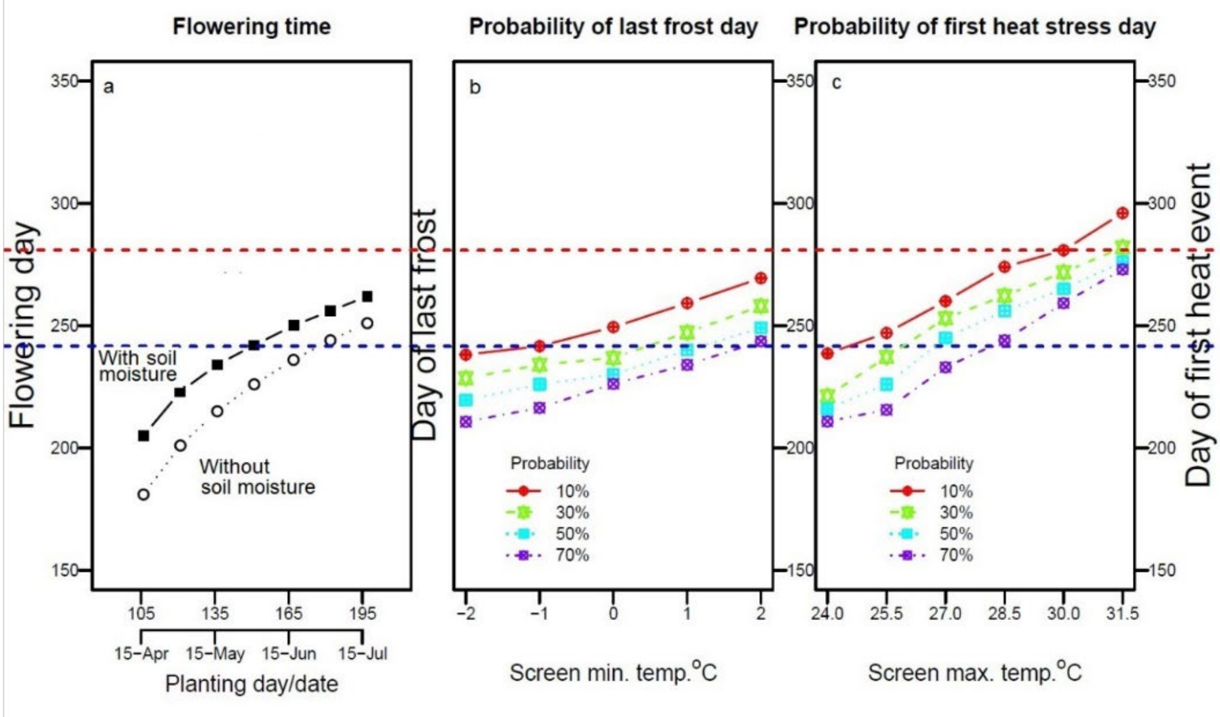

Figure 5. Simulated Julian day of flowering after accounting for soil water effects (a), represented by a dark solid line and solid symbols, as a function of the sowing date in the left panel (15 April = day 105; 15 July = day 195) for PBA Boundary⦶ at Goondiwindi. The lines in the middle and the right panel represent corresponding frost and heat stress probabilities for low (–2 to 2 °C) and high (24 to 31.5 °C) screen temperatures from 1957 to 2022. The days between the horizontal straight dashed lines without symbols indicate the frost- and heat-stress-free periods, respectively. A 60-day gap (as chosen visually) between the bottom (indicating frost) and top (indicating heat stress) lines was necessary to select a planting date, avoiding frost and heat stress from flowering to maturity.

Discussion

Time to flowering and podding in chickpea has traditionally been modelled using temperature and photoperiod. Some researchers, however, noted a stronger relationship between the amount of rainfall and the flowering time of chickpeas (Vadez *et al.,* 2013). This is because the amount of soil water seems to modify the average temperature perceived by the crop, resulting in hastening or delaying flowering time (Singh 1991). The effect of soil water on flowering and pod-set can be substantial, up to two months. The exact relationship can explain why there is a delay in pod-set in some situations. However, this effect of soil water has been ignored in flowering prediction models of chickpea, probably due to difficulty in capturing the dynamic impact of soil water on thermal time accumulation on a routine basis.

In a modelling framework, the relationship between soil water and the rate at which plants accumulate heat units, i.e., day degrees has now been incorporated. This relationship was quantified while trying to interpret the phenological responses of chickpeas grown in three environments, including Warwick, Jondaryan, and Kingaroy, as part of a project to investigate frost's effect on chickpea yield. The prediction of flowering time was appreciably improved by incorporating the dynamic impact of soil water on flowering time in this study (Chauhan *et al.,* 2019; Chauhan *et al.,* 2023). This concept was successfully extended to predict pod-set as well. As an independent validation, we could also predict flowering and pod-set in a study by Pattison *et al.,* (2018), conducted at Narrabri. The prediction of pod-set in these studies was achieved without the temperature threshold of 15 °C postulated previously in several studies on chickpea

(Croser *et al.,* 2003). This validation suggests that the use of this threshold of 15 °C may not be required in the model to predict the pod-set date. Further, considering podding in response to soil water may be more promising than focusing on low-temperature responses.

The importance of accurately predicting phenology became more evident when we analysed the occurrences of post-flowering frost and heat with and without soil water input. The number of post-flowering frosts calculated was three times higher than that predicted with APSIM, as this model significantly underestimated the time to flowering. Predicting flowering and pod-set without considering soil water effects would suggest delaying sowing to reduce the frequency of yield-reducing frosts. However, significant delays in sowing could result in lower yields than when frost frequencies are predicted more accurately.

While degree-day requirement is identified as a cultivar specific parameter, soil water's effect on chickpea phenology has implications in minimising the impact of stress by optimising genotype x environment x management interactions and a better understanding of how yield develops. Wetter soil, for instance, can delay flowering and increase plant size, including pod-bearing nodes, potentially leading to a higher yield. It can also make overgrown plants more susceptible to foliar diseases, including Ascochyta blight and Botrytis. In a limited water environment, earlier flowering may be an adaptive trait. These findings underscore the critical role of managing soil water levels in optimising chickpea development and yield outcomes.

How high soil water affects chickpea progress towards flowering and pod-set remains to be determined. We believe high soil water has the same effect as short days in slowing down chickpea development or drought in hastening crop development as would long days. This knowledge can help optimise the crop's growth and yield.

Conclusions

It is important to enhance our ability to predict when chickpea plants will flower and set pods to prevent stress during this critical stage of development. This research has shown that soil water levels have a significant impact on the flowering and pod-setting process in chickpea plants. Therefore, it is crucial to consider the dynamic changes in soil water using this model to anticipate these important events. By using this model, we can determine the optimal time for planting to minimize the risks of frost and heat stress and to maximize growth for a high yield.

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