# Modelling frost and heat risk in the critical period for faba bean and lentil

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## Abstract

Extreme temperatures at critical developmental phases reduce grain yield. Combinations of sowing date and cultivar that favour faster development reduce the likelihood of heat stress but increase the risk of frost at critical phases. Current models are unable to predict pulse yield in response to frost and heat, hence our focus on phenology. We modelled phenological variation with sowing date and cultivar for lentil and faba bean against the climatic patterns of frost and heat in 45 Australian cropping locations. For both crops, modelled mean and standard deviation of time to flowering were close to actuals and mean prediction error was below 5%. The critical period for yield determination was assumed to span from flowering to 200 °Cd after flowering. Curves fitted to the time-course of frost (< 0 °C) and heat (> 34 °C) probabilities between 1957 and 2018 were used to estimate the date of 10 % frost probability and the date of 30 % heat probability as the boundaries of a frost-heat risk window for the critical period. Out of the 45 locations, 12 were frost-free but with risk of heat, 7 were heat-free but with risk of frost, 3 were frost- and heat-free, and 23 featured a window defined by both frost and heat boundaries. Frost variables discriminated locations more strongly than heat variables. Realised warming between 1957 and 2018 advanced the time to 200 °Cd after flowering and shortened the critical period in most locations, particularly in early-sown crops. Comparisons of the probability curves of frost and heat between 1957–1985 and 1986–2018 showed, with few exceptions, an asymmetry between delayed late frost (up to 44 d) and earlier heat onset (up to 11 d), with a narrowing of the frost-heat risk window from 46 to 90 d for the period 1957–1985 to 34–64 d for 1986–2018. We identified a dominant role of frost as (i) the main discriminating factor among geographically distinct locations, (ii) the main source of variation of the frost-heat window, and (iii) a putatively increased risk factor with climate change. Adaptation to frost in the critical period for yield is important for pulses despite warming trends. Increased frost tolerance can directly improve yield and indirectly contribute to reduce risk of heat and drought later in the season.

## Keywords

Climate change, risk, flowering, *Lens culinaris, Vicia faba,* trade-off

## Introduction

Frost and heat risk are major constraints to Australian pulse production. Combinations of sowing date and cultivar that favour earlier flowering reduce the likelihood of water deficit and heat stress at critical crop stages, but increase the risk of frost. For these environments, studies on the trade-off between risk of frost and heat are widespread in wheat (Flohr et al., 2018; Hunt et al., 2019), incipient in canola, and lacking in pulses. Owing to physiological and agronomic differences, risk profiles are crop-specific. The critical window for yield determination in small grain cereals is from approx. 300 $^{o}$Cd before to 100 $^{o}$Cd after flowering with a most sensitive stage shortly before flowering while the most vulnerable stage in pulses is about 200 $^{o}$Cd after flowering (Sadras and Dreccer, 2015). Lentil and faba bean are two important Australian pulse crops and here we focus on phenology because current models are unable to predict pulse yield in response to frost and heat. Our aim was to model phenological variation with sowing date and cultivar for lentil and faba bean against the climatic patterns of frost and heat in Australia.

## Methods

### *Field experiments, model validation and implementation*

Experiments involved the factorial combination of ten cultivars of each crop and six sowing dates (from 1st of April to the 30th July at 15 d intervals) in 8 location-season combinations in South Australia: Minnipa, in 2016, 2017 and 2018, Hart in 2016, Roseworthy in 2017 and 2018 and Bool Lagoon in 2016 and 2017. Faba beans were sown at 60 plants m$^{-2}$ and lentils at 120 plants m$^{-2}$. Phenology was monitored 2-3 times per week to determine the timing for 50% of the plants within the centre-row of each plot reaching flowering. Daily weather data were obtained from the nearest weather station. Thermal time was calculated from daily mean temperature. We used APSIM to model phenology. The model has been locally calibrated, tested and applied for phenological and environmental characterisations in pulses (Chauhan et al., 2019). We use parameters for lentil PBA Hallmark XT, CIPAL 1301 and PBA Blitz which are slow, mid and faster developing respectively, and faba bean PBA Samira, PBA Marne, Fiord which are slow, mid and faster developing, respectively. We compared actual vs modelled time to flowering.

We modelled phenology for 9 sowing dates (from 1$^{st}$ of April to the 30$^{th}$ July at 15 d intervals) using 62-year climate series (1957-2018) in 45 locations (Fig. 1). The critical stage was defined as 200 $^{O}$Cd after flowering, which is in the middle of the critical period for yield determination in faba bean (Lake et al., 2019) and lentil (Lake et al., 2021). The critical stage for each combination of sowing date and cultivar was analysed against the boundaries *frost DOY* and *heat DOY*. For each cultivar type, we derived the earliest sowing for the critical stage to be within the frost-heat *window* in at least 50% of seasons.

*Risk profiles of frost and heat and trends with changing climate*

We characterised 45 locations selected from the NVT. For each location, we retrieved daily minimum and maximum temperature from a 62-year climate series (1957-2018). Both thermal amplitude *Tamp* and average temperature *Tav* were calculated according to definitions in APSIM. A threshold of 0 $^{O}$C was used to define a frost event and 34 $^{O}$C was used for heat (Prasad et al., 2017). Cubic polynomials for frost and piecewise functions for heat were fitted to describe the time-course of probabilities calculated as the square-root transformed frequency of 1 or more event per week. Piecewise models give a more objective characterisation of onset (x-intercept) of heat risk. Fitted curves were used to estimate the date of 10% frost probability *frost DOY* and the date of 30% heat probability *heat DOY* as in previous risk analysis in Australia (Zheng et al., 2015). A *window* (d) was calculated as the difference between *heat DOY* and *frost DOY* in locations where both boundaries were present. We estimated *convergence DOY* as the date when frost and heat curves intersect and *convergence intensity* as the probability at the intersection. The area under the curve *frost integral* was calculated to summarise the intensity and duration of the frost period. Lack of an agronomically unambiguous upper limit for integration precluded the calculation of area under the curve for heat; instead, we calculated *heat onset* as the x-intercept and *heat slope* as the slope of the linear increase in heat probability from piecewise functions. We also explore the effects of climate change on frost and heat risk in the critical period by comparing trends between 1957–1985 and 1986–2018 (for methods see Lake et al. (2021)).

## Results

*Comparison of actual and modelled time to flowering and prediction of frost and heat patterns*

For both crops, modelled mean and standard deviation were close to actuals, mean prediction error was below 5%, and bias correction factor was close to 1. Comparison of actual and modelled time to flowering for lentil returned: $r = 0.89$ ($P < 0.0001$), modelling efficiency = 0.73, and concordance correlation coefficient = 0.88. For faba bean: $r = 0.96$ ($P < 0.0001$), modelling efficiency = 0.84 and concordance correlation coefficient = 0.88. Out of 45 locations, 12 were frost-free but with risk of heat, 7 were heat-free but with risk of frost, 3 were frost and heat-free, and 23 featured a window defined by both frost and heat boundaries (Fig. 1).

A PCA discriminated locations with the first component associated with frost variables explaining 34% of the variation and the second component associated with heat variables in a latitudinal gradient explaining 26% of the variation. Average temperature Tav increased northwards at 0.64 $^{O}$C per degree latitude, and the onset of heat risk advanced 5.9 d per $^{O}$C average temperature. Frost-related variables were unrelated with average temperature. Thermal amplitude (Tamp) increased 0.011 $^{O}$C m$^{-1}$ altitude and 0.013 $^{O}$C km$^{-1}$ from the coast. The heat onset and the duration of the frost-heat window declined whereas the area under the frost curve increased with increasing thermal amplitude. The window between frost and heat spanned from 26 to 117 d, was closely related to the frost boundary frost DOY and independent of the heat boundary heat DOY. Longer windows associated with lower convergence intensity: the probability at the intersection of frost and heat curves was above 25% in locations with windows shorter than 30 d, and decreased to 15% where windows were above 70 d.

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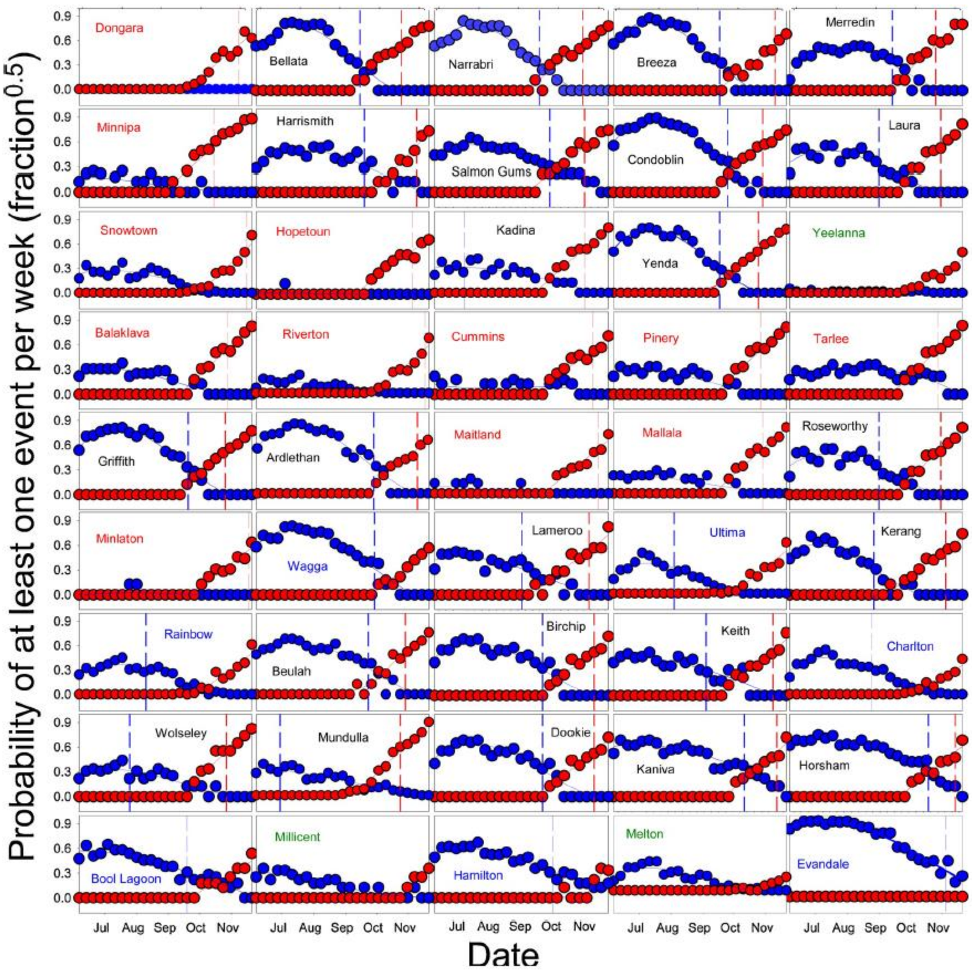

**Figure 1. Time-course of frost (< 0 °C, blue) and heat (> 34 °C, red) probabilities (square-root transformed) in 45 locations of the Australian grain growing region for the period 1957-2018. Vertical lines indicate 10 % (frost) and 30 % (heat). Frost and heat boundaries define windows in 26 locations depicted with black labels; 12 locations were frost-free but with risk of heat (red labels), 4 were heat-free but with risk of frost (blue labels), and 3 were frost- and heat-free (green labels). For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.**

*Sowing date and cultivar combinations for risk management and shifts with climate change*

For each location and crop, we combined sowing date and cultivar representing slow-, mid- and fast-developing cultivars to derive frequency distributions for the timing of the critical stage as illustrated in Fig. 2. For the fast-developing lentil and faba bean cultivars, the earliest sowing for which the critical stage was within the frost-heat window varied between 1st of April and 30th of July. This "safe" sowing date was not different between lentil and faba bean (P > 0.53). The safe sowing date was delayed with later frost DOY at a rate of 1.2 d $d^{-1}$ (for frost DOY > 219) and with the shortening of window at a rate of 1.5 d $d^{-1}$ (for window < 77 d). There was no difference between lentil and faba bean for the relationships (P > 0.33, P > 0.56). The safe sowing date was on average 8.0 ± 1.6 d later for slow-developing lentil and 12.4 ± 1.1 d later for slow-developing faba bean compared with their fast-developing counterparts. For both crops, the safe sowing was 4.1 ± 1.3 d later for mid- than for fast-developing cultivars.

Comparisons of the probability curves of frost and heat between 1957–1985 and 1986–2018 showed, with few exceptions, an asymmetry between delayed late frost (up to 44 d) and earlier heat onset (up to 11 d), with a narrowing of the frost-heat risk window from 46 to 90 d for the period 1957–1985 to 34–64 d for 1986–2018.

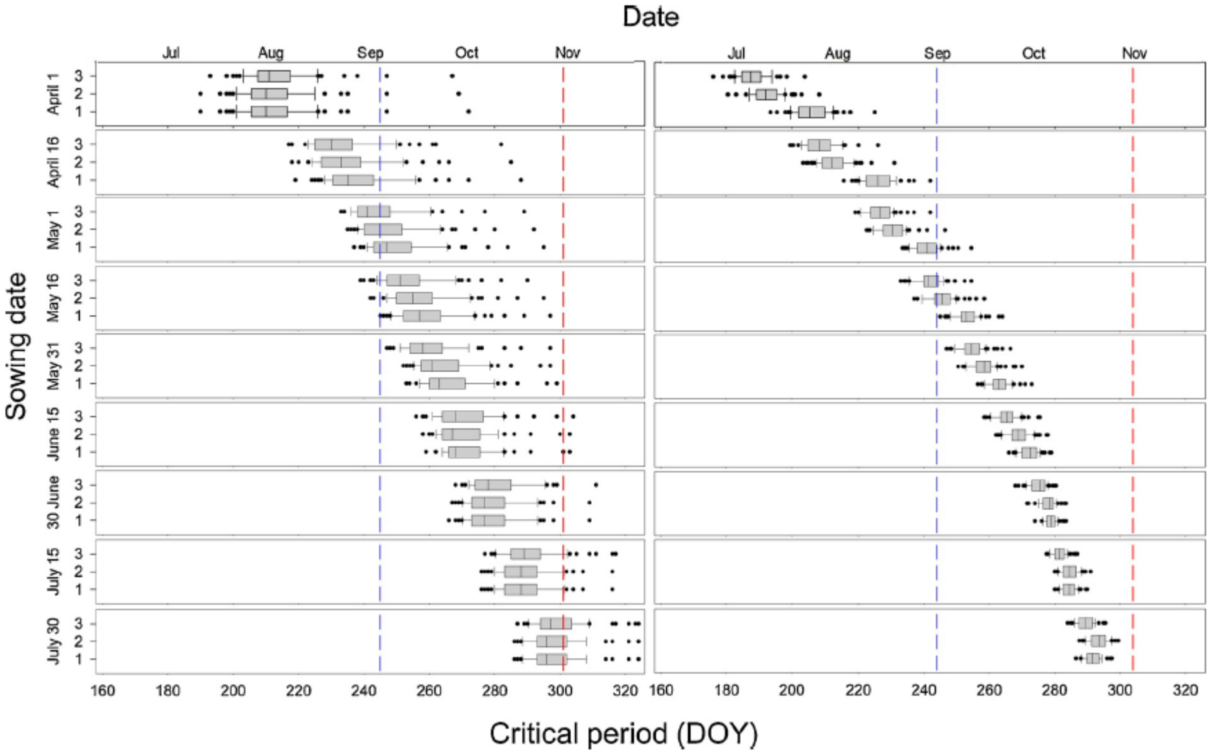

**Figure 2. Example of frequency distribution of critical period of lentil (left) and faba bean (right) for sowing date and cultivar combinations at Laura for climate from 1957 to 2018. Cultivars of contrasting developmental rates are 1 (slow), 2 (mid) and 3 (fast). The blue and red lines are the frost-heat boundaries. The critical period is from flowering to 200 °Cd after flowering.**

## Conclusion

Extreme temperatures are the focus of active research from perspectives including crop physiology, genetics, plant breeding, modelling, risk analysis, and agronomy. We identified a dominant role of frost as (i) the main discriminating factor among geographically distinct locations across latitude, altitude and continentality, (ii) the main source of variation of the frost-heat window, and (iii) as a putatively increased risk factor with climate change. We conclude that adaptation to frost is critical for pulses despite warming trends: increased frost tolerance could directly improve yield and indirectly contribute to reduce risk of heat and drought later in the season.

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