Quantifying the effects of chilling temperatures during the reproductive stages on yield of chickpea

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Abstract

Cold temperatures at critical reproductive stages impacts chickpea yield, limiting its adaptation under diverse agro-climatic regions. Crop growth models provide an opportunity to predict yield performance under diverse climates and identify varieties for target environments. We examined the efficacy of the Agricultural Production Systems Simulator (APSIM) to simulate observed chickpea grain yields, and quantify the impact of low temperature stress on yield. It is difficult to easily define temperature stress, as low temperatures along with the duration of stress are likely to have a considerable effect on pod set and yield. Therefore, we developed seven chilling day-degrees indices to assess the effects of chilling temperatures in chickpeas. There was no significant correlation between chilling indices and observed grain yield suggesting that the current model does not predict the effect of chilling temperatures on yield. This is likely due to a combination of multiple abiotic stresses including frosts and other low temperatures. Using a Regression tree model, we assessed yield responses to chilling indices across 75 trials. Our analysis showed that the most severe chilling index (minimum threshold temperature <10°C) may have contributed to most of the variation in yield variability across the 75 locations. Consequently, this study identifies cool temperature damage as a valuable parameter for improving the chickpea yield prediction ability of the APSIM model.

Key Words

APSIM, Chilling day-degree, floral initiation, CART, *Cicer arietinum*

Introduction

The cultivated area (1,068,000 ha in 2016/2017) under chickpea (*Cicer arietinum* L.) has recently increased in Australia due to higher prices, and profitable options to break disease cycles in rotational cereal crops (GRDC 2011; ABARES 2019). However, most chickpea production in Australia has a high risk of short and intermittent periods of chilling temperatures (average ambient temperature of <15°C) during the reproductive stage. Exposure to this stress typically results in flower and pod abortion and subsequent yield loses, especially in the Mediterranean-type of climate in Southern Australia (Berger *et al*. 2004). In this study, field experimental data were used to validate the Agricultural Production Systems Simulator (APSIM) model for chickpea (Robertson *et al*. 2002). Long-term chickpea simulated yield, as well as observed NVT trial data, across multiple Australian locations were then utilized to elucidate relationships between chickpea yield and a suite of chilling 'day-degree' indices. These results can assist in the prediction and interpretation of chickpea yield under different low-temperature scenarios.

Methods

The APSIM-chickpea model (Robertson *et al*. 2002; Holzworth *et al*. 2014) was parameterized and phenology parameters were calibrated for cultivar PBA HatTrick using field data (2014-2017 inclusive) at Roseworthy in South Australia, Wagga Wagga and Yenda in NSW. Soils and agronomic practices representative of each site were obtained from previous studies (Sadras *et al*. 2016; Xing *et al*. 2017) and from experienced agronomists. The climatic data (patched-point) was obtained from the SILO website (https://legacy.longpaddock.qld.gov.au/silo/ppd/index.php). The performance of the APSIM-chickpea model was evaluated using three measures of "goodness-of-fit": Root Mean Square Error (RMSE), Willmott's Index of Agreement (*d*) (Willmott 1982), and the coefficient of determination (r^2) between observed and simulated yields.

Since using simple daily average temperatures gave only poor correlations with simulated yield (data not shown), we therefore calculated Cumulative chilling 'day-degree' indices using seven different threshold temperatures (Table 1). We chose these temperatures because the literature suggests that post-anthesis temperature below 15^{o}C can cause pod abortion, inhibit pod-set and subsequent yield losses (Croser *et al*. 2003; Berger *et al*. 2004); 16^{o}C was included as a buffer. We then calculated for each day the number of day-degrees below each threshold using the daily minimum temperatures (extreme affects). If the threshold was not exceeded (i.e. lower), then the chilling value was set to zero for that day. These chilling values were then summed across the reproductive stage for each year x location combination for field experimental sites and for the NVT trials (www.nvtonline.com.au) (comprising 75 experiments across 44 sites in 2013 only) where we had observed yield data available. The yield data for the experimental sites was the mean for a single genotype across all replicates; whereas the NVT data was a site-mean-yield of all genotypes in that experiment.

Table 1. Chilling 'day-degree' indices calculated during the phenological growth period from floral initiation to the end of grain-fill. MinT = minimum daily temperature (^{o}C).

Index Name	Threshold temperature (^{o}C)	Calculated as	Units
cdd10	10	=10 – MinT, or zero if MinT > 10	Cumulative day_degrees
cdd11	11	=11 – MinT, or zero if MinT > 11	Cumulative day_degrees
cdd12	12	=12 – MinT, or zero if MinT > 12	Cumulative day_degrees
cdd13	13	=13 – MinT, or zero if MinT > 13	Cumulative day_degrees
cdd14	14	=14 – MinT, or zero if MinT > 14	Cumulative day_degrees
cdd15	15	=15 – MinT, or zero if MinT > 15	Cumulative day_degrees
cdd16	16	=16 – MinT, or zero if MinT > 16	Cumulative day_degrees

To elucidate relationships between chickpea yield and a suite of chilling 'day-degree' indices the Classification and Regression Tree (CART) model (De'ath & Fabricius 2000; Elith *et al*. 2008) was employed. We used the rattle package version 5.2 (Williams 2011) in the R software suite version 3.5.1 (R Core Team 2018) to perform the CART analysis.

Results and discussion

A comparison of APSIM simulated and observed flowering time and yield is shown in Fig. 1. The APSIM-chickpea module explained 75% of the observed variability in flowering time with a RMSE of 11 days (Fig. 1A). The model showed reasonable predictive capacity (r^2=0.66, RMSE = 185 kg/h) for chickpea grain yield (Fig. 1B). These predictions were closer to 1:1 line and with higher r^2 than Kaloki *et al*. (2019). Sources of error using the point sourced data may explain some of the variation between observed and APSIM simulated values as the temperature data used in our simulations are derived from the closest BOM meteorological station (Silo climate) for each of the three locations. Localised frosts or cool temperatures may have delayed emergence and flowering, having a significant effect on the length of some crop developmental stages. The observed yields ranged from 1100 to 2200 kg/ha and the model adequately predicted this range.

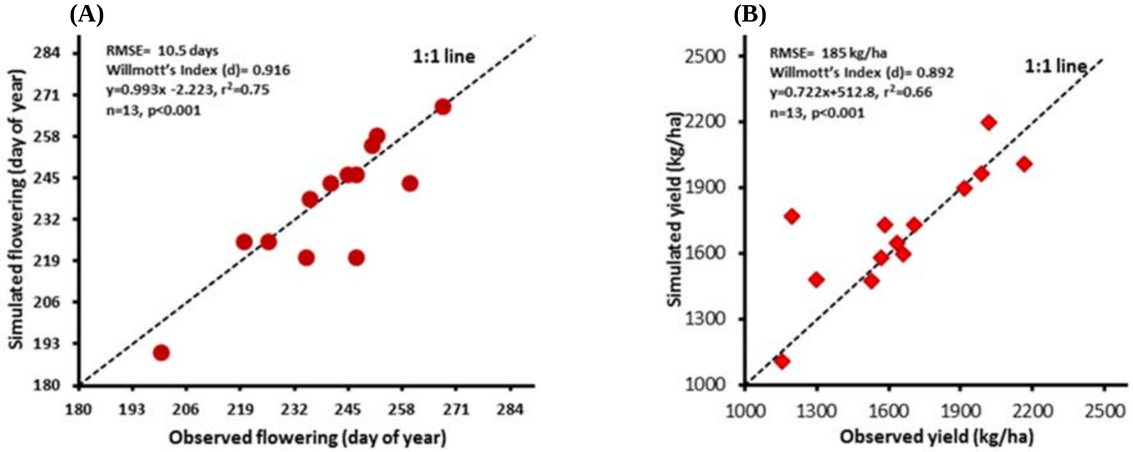

Figure 1. Evaluation of APSIM-chickpea for cultivar PBA HatTrick showing observed v. simulated (A) flowering time and (B) yield at physiological maturity using experimental data from Roseworthy, Wagga Wagga and Yenda. The dashed diagonal line is the 1:1 line and insets are the values of RMSE, *d* and linear regression details.

To identify sensitive chickpea growth periods that might account for variation in simulated yield, we plotted chickpea grain yield against cumulative growing season rainfall (Fig. 2A), which showed a significant, positive (polynomial) relationship (r^2=0.52, p<0.001). In contrast, when we examined the relationship between mean daily minimum and average temperatures (during the floral initiation to pod-fill period or end of grain-fill) with grain yield (data not shown) no significant effects were observed, similar to Lake *et al*. (2016). In addition, we saw no relationship between our chilling indices and observed grain yield (see Fig. 2B for an example using cdd10). It remains a possibility that, since chickpea is an indeterminate plant, chilling damage to floral structures may be compensated for by more flowers and pods as soon as temperatures are above the critical threshold, resulting in yield 'recovery' (Berger *et al*. 2005), a phenomenon that the current APSIM model fails to adequately capture.

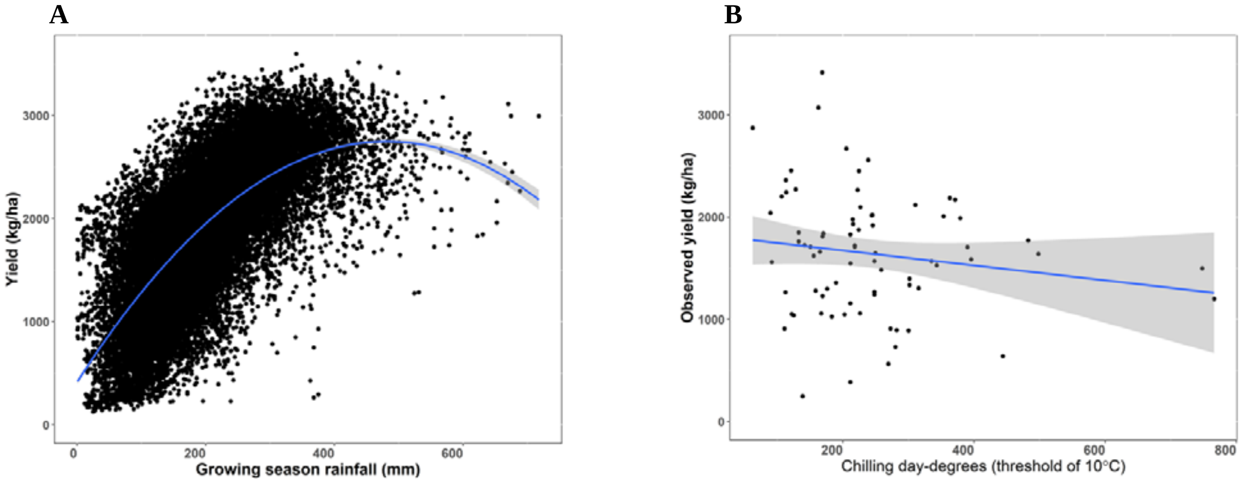

Figure 2. The relationship of growing rainfall (A) and (B) chilling 'day-degree' during the period from floral initiation to the end of grain-fill. The yields in (A) are simulated chickpea yield (129 years) across 22 locations in Australia and the blue line is the linear or polynomial regression line.

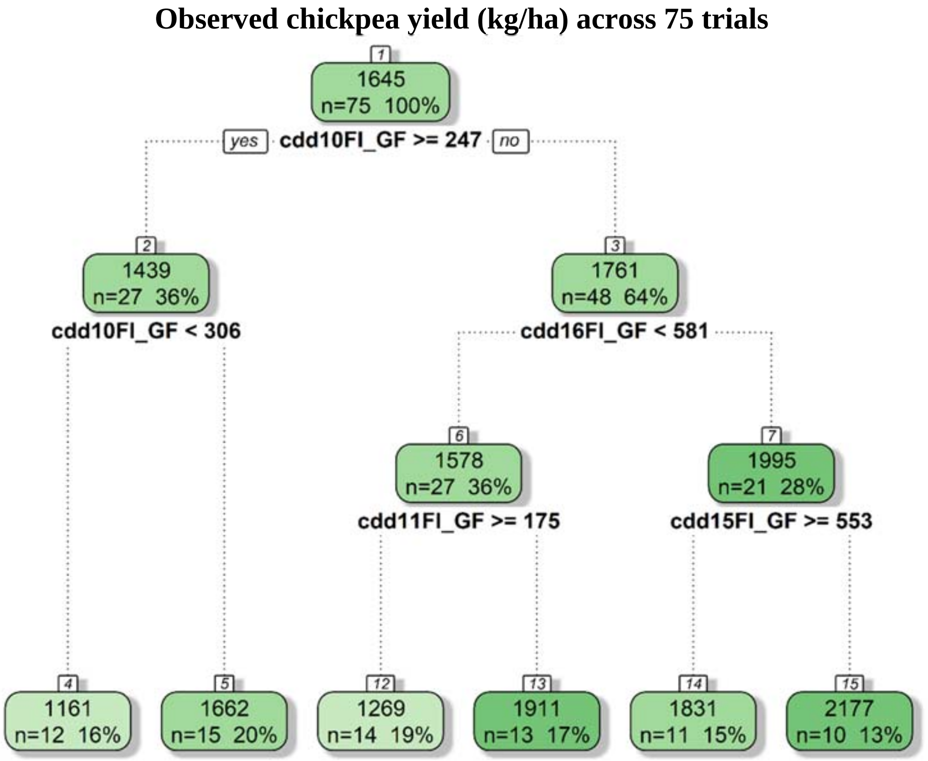

Figure 3. A classification and regression tree (CART) showing the results of the analysis of seven chilling 'day-degree' indices (cdd10 – cdd16, see Table 1) using the NVT trials and field experimental data. Each box contains the mean value of the group (yield in kg/ha) and the percentage of the total sample set (n=75). The bold text below each box shows the variable used for the next binary split, with the left of each split = "yes", and to the right = "no".

The CART tree shows how the full dataset of 75 trials is split four times to produce six final separate groupings for yield (Fig. 3). Most important, chilling index ("cdd10FI_GF"), conditioned the first split by resulting in an 18% yield difference between the two groups (1439 versus 1761 kg/ha) (Fig. 3). Further work is necessary to examine which 'site/sowing time' combinations are responsible for these groupings. After performing multi-year simulations for single sites using APSIM, we will examine the influence of chilling indices on yield using the CART analysis.

Conclusion

The APSIM chickpea model can predict flowering time and chickpea yield with reasonable confidence but there are some limitations in quantifying yield impacts of minimum temperature during flowering to pod set. Phenology and yield outcomes generated by APSIM can be used for further downstream analysis to understand the effects of chilling temperatures on yield. The CART analysis showed that the chilling 'day-degree' indices alone were able to split the observations into six groups with widely different average yields (from 1161 to 2177 kg/ha). Ongoing model validation work, using 2018 experimental field trial data (Wagga and Tamworth) and NVT data from 2014-2018, may further improve model predictions. We plan to further examine phenological parametrization of the APSIM-chickpea model, along with temperature, rainfall, chilling effects, and photoperiod.

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