Improving the relationships used to define frost damage to wheat in crop models

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Abstract

In order to predict the consequences and value of frost adaptation through breeding and agronomy across Australia's cropping region it is essential that a validated frost damage function is incorporated into our crop models. This paper reports on the development of an empirical relationship that predicts the frost induced sterility in wheat at anthesis developed from the analysis of GRDC National Frost Initiative (NFI) data collated from three Australian States. The analysis showed that the extent of frost damage to individual heads was primarily a function of the degree of coldness and its duration. A single function for frost damage to wheat at flowering was derived for all cultivars. While individual frost damage functions were created for each cultivar, with the available data the increased complexity did not appear to improve the damage function. In part this was due to the fact that individual heads were not subjected to the same frost events, with only a few larger frost events for each individual cultivar. This study was a good start in improving the conceptualisation and empirical relationships which could be used in frost models. However, further development is needed to scale the empirical relationship of damage across multiple stages of crop development and from an individual head to a paddock of wheat where plants and individual heads vary in their phenology.

Keywords

Crop model, reproductive growth.

Introduction

Across Australia's cropping regions, frost damage is recognised as a significant challenge for wheat production, with the frequency and severity of events expected to increase under future climate scenarios (Zheng et al. 2015; Crimp et al. 2016). Frost can result in significant wheat yield losses that are estimated at between $100 and $300 million each year in Australia's eastern cropping region alone, with a similar scale of losses reported in South Australia and Western Australia in recent decades.

On-farm management decisions are a complex balancing of risks versus potential production, with key drivers including market and climatic factors. Crop models are an important tool in understanding the frequency and magnitude of yield losses associated with climatic factors such as growing season rainfall, seasonal temperatures, frost and heat waves, and terminal drought. Models help explore more objectively the risks and trade-offs of different on-farm management decisions. However, the literature highlights the limited ability of crop models to account for climatic extremes including frost (Sanchez et al. 2014; Barlow et al. 2015).

The relationships used to describe frost damage in crop models varies considerably, in terms of the period over which frost damage occurs, the level of yield reduction which may occur, and the critical temperatures being used to define frost damage. This variation has significant implications in terms of the predicted frequency and magnitude of frost damage and therefore the management options available to minimise the risks of frost damage.

This paper reports on the development of an empirical relationship that predicts the frost induced sterility in wheat, developed through the analysis of GRDC National Frost Initiative (NFI) data collated from three Australian States. We discuss the available data and new data required to advance and improve the simulation of damage attributed to frost in our crop models.

Methods

The GRDC NFI has been conducting frost benchmarking experiments since 2010, which consist of multiple genotypes sown at multiple sowing times, across a number of sites including Wickepin and Brookton (WA), Loxton (SA) and Narrabri (NSW). The experimental design of these trials has been described in Cullis and Smith (2015). Data were collected from these sites over multiple years through GRDC projects DAW00234, UA00136 and UA00162. Data included the total florets and sterile florets for individual wheat heads which were at anthesis when a frost event occurred and were tagged for later analysis at harvest. Climate data was obtained from the onsite weather stations or the nearest Bureau of Meteorology (BoM) site (Loxton, Narrabri, Wickepin and Brookton).

A frost model for anthesis frost, was proposed and tested with the NFI sterility data and BoM Stevenson Screen temperature data. The model aims to describe the percentage of frost induced sterility observed in individual wheat heads. The model considered a window for frost damage around anthesis (e.g. 200 °Cd before to 300 °Cd after anthesis (cumulative thermal time at Base temperature 0°C)) and uses a threshold minimum temperature (T_{min}) before damage occurs. Once the temperature drops below the threshold value, a daily frost sum is calculated (threshold minus daily minimum temperature). Frost induced sterility (%) is calculated daily, based on the daily frost sum and the timing of the event in the frost window with the sensitivity to frost linearly increasing (0 to 1) before flowering and decreasing (1 to 0) after flowering. Daily frost induced sterility is then summed over the frost window. In fitting the model T_{min} and the size of the frost window (°Cd before and after anthesis) were optimised by maximising the correlation between frost sum and the frost induced sterility data using three approaches:

- Global – T_{min} and the frost window were the same for all genotypes in the NFI database.
- Threshold Only– T_{min} could vary between genotypes, however the frost window was constant.
- Window and Threshold – both T_{min} and the frost window could vary between genotypes.

The analysis was conducted on over 50 genotypes, with a minimum of 15 tag events at flowering. For clarity results from four genotypes are shown graphically in the paper, selected from genotypes with greater than 30 data points. Statistical analysis included the use of correlations and the RMSE. This analysis was conducted on the full data set, with the statistics included for both the full data set as well as the four individual cultivars.

Results and Discussion

The application of this model to the NFI sterility data resulted in a reasonably good fit across the full data set. Strong correlations (>0.66) and RMSE of less than 0.2 between the measured and modelled results were observed for the selected cultivars (Figure 1). However, across the full data set there was a lot of variation in both the correlations and RMSE (Table 1), with model solutions not obtained for all cultivars in the Threshold Only and Window and Threshold models. For the genotypes in Figure 1 the temperature threshold for damage varied from 0.3 to -1.7°C (Stevenson Screen Temperature), as seen in Table 2, while the damage window remained constant. Across the full data set the threshold temperatures ranged from -3 to 1.6 °C and the Threshold windows ranged from 150°C before flowering to 200°C after flowering). Moving from the Global to either the Threshold Only or Threshold and Window approaches resulted in little improvement in either the correlation coefficients or RMSE values, despite the increased complexity of the model. Therefore, based on this analysis we propose that the Global approach appears to be the best. Although with further studies it may be possible to come up relationships which take into account genotypic effects.

Table 1. Correlation coefficients and RMSE for the full data set calculated for the Global, Threshold Only and Window and Threshold models (Win&Thr).

	Correlation			RMSE		
	Global	Threshold	Win&Thr	Global	Threshold	Win&Thr
Mean	0.78	0.77	0.85	0.17	0.17	0.14
Min	0.31	0.12	0.41	0.07	0.07	0.06
Max	0.96	0.96	0.98	0.24	0.24	0.21
n*	56	51	27	56	51	27

*n = number of genotypes where a linear relationship was fitted.

This was a preliminary application of the model, fitted by maximising the correlation coefficients, as such the slope of the relationship, the threshold temperatures (Table 2) and the correlations were biased by the larger sterility and Frost sum values within the dataset and not the total variation. There is also a lot of variation in observed sterility and the lower "Frost sum weighted" values. This noise within the data make it impossible to determine if the different Threshold temperatures (Table 2) and damage windows determined in this analysis are a true genotype difference or an artefact of the data set. This data, which was not collected for model development and validation, was collected through field trials with natural frost events. This results in an uneven distribution of tag events for genotypes across years, sites and time of sowing which could be confounding the results. That is, all cultivars were not subjected to the same frost events at the same stage of development and with the same environmental conditions prior to a frost event, as such other environmental variables may be influencing the frost induced sterility observed. More detailed statistical analysis of the model is currently being conducted, including the investigation of additional environmental variables.

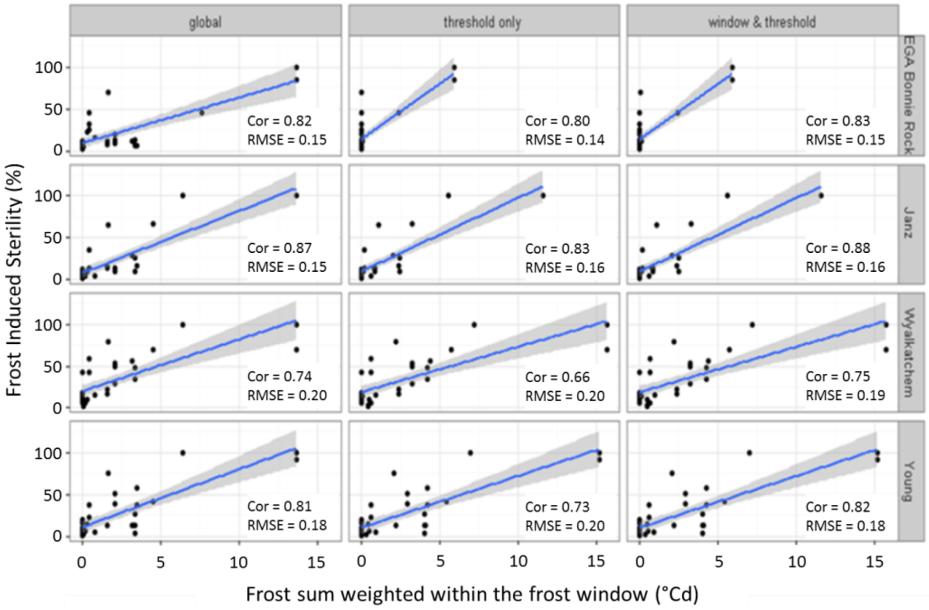

Figure 1. Measured versus modelled frost induced sterility as a function of the frost sum using the three approaches for 4 selected genotypes. The correlation coefficient (Cor) and RMSE are shown.

Table 2. Damage window (°Cd) and threshold temperatures (°C) before and after anthesis (base temperature 0ºC)) used in the calculation of frost damage for the window and threshold approach for four selected genotypes (Figure 1).

	Window	Threshold
EGA Bonnie Rock	-10 to 200	-1.7
Janz	-10 to 200	-0.5
Wyalkatchem	-10 to 200	0.3
Young	-10 to 200	0.2

The frost damage empirical relationships presented were developed using Stevenson Screen Minimum Temperatures, as this data is generally available for model application. However, further investigation and validation of these relationships will consider the effect of canopy temperature as well as temperature duration to determine if the increased complexity in input data significantly improves the proposed damage relationships. While canopy temperature isn't widely available it can be modelled based on the water and energy balance of the crop if this improved the prediction of frost damage.

While the relationships presented in this paper suggest there is the potential to improve the representation of frost induced sterility in crop models, these results are for individual heads at anthesis. Further development of a method is needed to scale the empirical relationship of damage from an individual head at a specific growth stage to a paddock of wheat where plants and individual heads will vary in their phenology. We propose that a distribution of phenology combined with frost damage functions to describe damage from Booting through to Grain filling would be required to scale the relationships from anthesis frost on individual heads to a whole paddock with multiple frost events during reproductive growth.

Next Steps

Throughout a growing season, frost damage to wheat can occur at a range of growth stages varying from Z31 through to Z79 (Zadoks wheat growth stages). Frost does not only damage the wheat heads, but also stems and leaves, which we have not tried to capture within the analysis or frost damage functions. In terms of frost induced sterility (or abortion) of grains the key stages seem to be Z39 through to Z74 as stem elongation (Z31-Z39) and late grain fill (Z74-Z79) appear to be more resistant to damage. Expanding the frost model (Figure 1) to additional growth stages would require sufficient data to define the shape and magnitude of the damage function which will be dependent on individual growth stage. The function also needs to capture the accumulated impact of multiple frost events over different growth stages.

The most important data set still required for model development is single frost events for different temperature extremes and for different growth stages. One of the unknowns in terms of frost damage once reproductive growth has commenced surrounds the potential for and magnitude of acclimation. Obtaining this type of data requires either an ability to protect portions of a field crop from frost (to provide unfrosted controls) or the ability to simulate frost events of different severities in the field.

Conclusion

This paper has presented a frost damage function developed from a sub-set of the National Frost Initiative data. The analysis showed that the extent of frost damage to individual heads was primarily a function of the degree of coldness and its duration. A single function for frost damage to wheat at flowering was derived while individual frost damage functions were created for each cultivar, with the available data, the increased complexity did not appear to improve the damage function.

The results to date have highlighted that while frost is complicated to measure and model, there is potential to improve the representation of frost damage within crop models. The challenging next step is to describe the frost function not only for anthesis but from early booting (Z39) through to early grain fill (Z73) for individual heads. This would then need to be extended based on a distribution of crop development to a paddock scale.

We conclude that in order to predict the consequences and value of frost adaptation through breeding and agronomy across Australia’s cropping region it is essential that we have an operational and validated frost model. This study has improved the conceptualisation and empirical relationships, especially around anthesis, which could be used in frost models, however further investment is required to develop and validate a more robust frost model across the different growth stages.

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