Modelling the impact of frost on wheat production in Australia

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Abstract
Frost can significantly reduce crop yields representing a management challenge for grain producers. In Australia, there has been an increased frequency of frost across much of the southern grain belt between 1960 and 2011, with the current trend of increased frost days in some regions expected to occur until the mid-2030's. In southern Australia, growers need to manage the competing risks of frost around flowering while avoiding heat stress and terminal drought during grain fill. While we can use crop models to help growers understand and manage these competing aims by identifying the risk of climatic events coinciding with key growth stages, we don't generally predict the impact of frost on yield. Although frost damage has been incorporated into a number of crop models through winterkill functions, seedling death or advanced senescence, the non-linear reduction in yield potential associated with reduced grain number due to an anthesis frost is not incorporated into current crop models. Therefore we need to improve model capability to account for frost damage and the subsequent impacts on yield. This paper presents a preliminary frost response function developed from the literature, which aims to capture the effect on grain number (and subsequent yield impacts) of frost events around anthesis. The preliminary frost model was incorporated into the Catchment Analysis Tool (CAT, DEDJTR Victoria) and applied across Victoria. Results from the application of the frost model are presented.

Key words
Crop models, CAT, frost, wheat

Introduction
In Australia, wheat production occurs on over 13 million hectares, producing 19 MT of wheat per year (based on a five year average to 2010/11: ABARE, 2012). Crop production across Australia is being increasingly impacted by climate as the average annual daily mean temperatures have increased progressively since the middle of the 20th Century against a backdrop of natural year to year variability (CSIRO and Bureau of Meteorology, 2012). One of the challenges for crop production is the change in climate extremes, including the increased incidence of frost across the Australian grain belt between 1960 and 2011 (Crimp, 2014). Frost reduces crop production and represents a substantial economic loss to the industry, with direct losses estimated to be at least $120 million per year. Damage to wheat from frost has been observed in all stages of growth from seedlings through to maturity. However, in Mediterranean type climates, frost around anthesis has the greatest potential yield impact, with 10-100% yield loss observed in the literature. Frost around anthesis results in partial or complete sterility of florets and whole spikelets and therefore reduced grain number and yield (Al-Issawi et al., 2012). While we can use crop models to help growers understand and manage the risk of frost coinciding with key growth stages, we don't generally predict the yield impacts. Although frost damage has been incorporated into a number of crop models through winterkill functions, seedling death or advanced senescence, the non-linear reduction in yield potential associated with reduced grain number due to an anthesis frost is not accounted for in current crop models.

The Frost Model
Based on a review of the literature (Barlow *et al*., 2015) a frost model was developed that reduces grain number and therefore yield potential in response to frost around anthesis. The model (Figure 1) includes a calculation of the percentage reduction in grain number in response to a frost event around anthesis; and a statistical distribution of impact over time. The standard method to determine if a frost event has occurred uses a criterion of 2.2°C (measured within a Stevenson Screen at 1.2m above ground level). This temperature is known to cause frost damage in flowering crops, as temperatures at canopy height are invariably lower (2 to 4°C) than those in the Stevenson Screen (Frederiks et al., 2008). In this paper the minimum temperature

(1.2m Stevenson screen) to trigger frost damage was set at either 2°C or 1°C. The reduction in grain number was scaled from 0% loss at the set minimum temperature to 100% loss potential over a 4°C temperature drop, to either -2°C or -3°C depending on the initial temperature (Figure 1a). Once the maximum reduction in grain number is determined, a stochastic distribution of around 50% at anthesis was used to scale the yield reduction. This ensures that the maximum reduction in grain number only occurs at around 50% anthesis, with the losses scaled around 50% anthesis to reflect the variation in the timing of anthesis within a single plant as well as across a paddock and the sensitivity of the plant to frost. These two response functions are multiplicative and used together predict the reduction in yield. This model captures the largest impact from a single frost event during the 14 day anthesis window and does not account for multiple frost events, or frost outside the defined anthesis window.

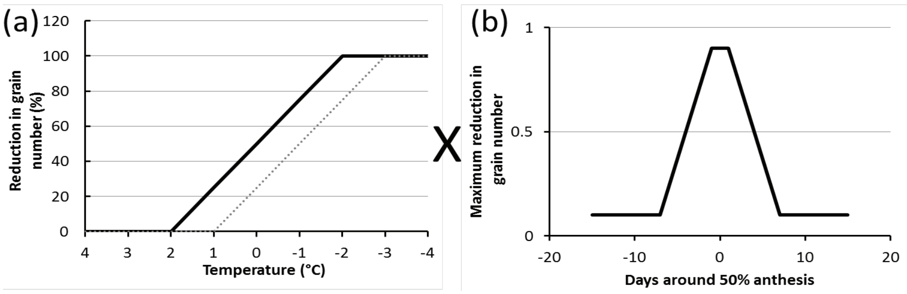

Figure 1. Frost model which describes the reduction in grain number in response to minimum daily temperature (as defined by 1.2m Stevenson Screen), with (a) the reduction in grain number observed at anthesis for two temperature ranges (2 to -2°C & 1 to -3°C), multiplied by (b) the distribution of anthesis around the predicted date of 50% anthesis.

Methods

The Catchment Analysis Tool (Beverly et al., 2005; Weeks et al., 2008) was used to investigate the frequency with which frost coincided with anthesis and the predicted impact on grain yields. The CAT crop model represents biomass accumulation based on extensively used contemporary models (Christy et al., 2013). It includes modules for plant phenology, crop growth and yield, together with dynamics of water and nitrogen in the crop and soil. CAT first simulates phenological progress, above-ground biomass accumulation and then partitioning to grain. Phenological development is driven by temperature and photoperiod. The CAT model was applied across the arable land in Victoria over a 50 year period (1965-2014). Model simulations were conducted on 1 km^2 grid cells of agricultural land within the 200-1000 mm annual rainfall region. For each year and grid cell within this region, the CAT model was triggered to sow wheat at the autumn break (defined by 25mm rain within 10 days) for a mid-season wheat cultivar, with a planting window from April 14 to June 30. To ensure that crops did not fail at planting, soil water was reset at sowing to the upper limit in the surface three layers (~30cm). For each year the number of days in which the minimum temperature was <2°C (or <1°C) was recorded, as well as the predicted yield with and without the frost damage. When frost damage was recorded the minimum temperature on the day that frost occurred was also recorded. There were a number of years in which the wheat crop failed, mainly in response to water stress. These years have been excluded from the analysis.

Results and Discussion

Using a sowing rule around an autumn break of 25mm the average planting date (over 50 years) across Victoria ranged from the 16 April through to 8 June, with the drier regions generally having a later autumn break and therefore planting data. The average anthesis date (50 years) ranged from the 9 August through to 20 November with the later anthesis dates located along the great divide due to colder average temperatures. Across the study region, the wheat crop failed to reach harvest an average of 0.3 years out of 50, with 84% of the study region having no crop failures. The highest frequency of crop failures was observed in the north west of the state where water-stress would be expected to cause premature terminal drought.

Frost around anthesis

Sowing a mid-season wheat cultivar on an autumn break resulted in a large variation in the frequency of frost events within a 14 day window around anthesis. Using a 2°C (Stevenson Screen) threshold frost coincided with anthesis 34 out of the 50 years on average, ranging from 0 to 49 years (Figure 2a). Across the study region an average of 63% of years recorded more than 1 frost event in the 14 day anthesis window, ranging from none through 100% of years (Figure 2b). This high frequency of multiple frost events, suggests that future refinements of the crop model should consider how multiple frost events impact on yields.

When temperatures fall below the temperature threshold within the anthesis window, the frost module was triggered. For every year where a simulated crop was harvested, the predicted yield with and without the frost effect was recorded. Using a 2°C threshold an average reduction in yield of 7% was recorded across the study region (Figure 3a) with the greatest average losses of 14-22% observed in Western Victoria. If the threshold is dropped to 1°C (Figure 3b) there is a noticeable reduction in the yield losses predicted due to frost with an average of 3.2% across the study region.

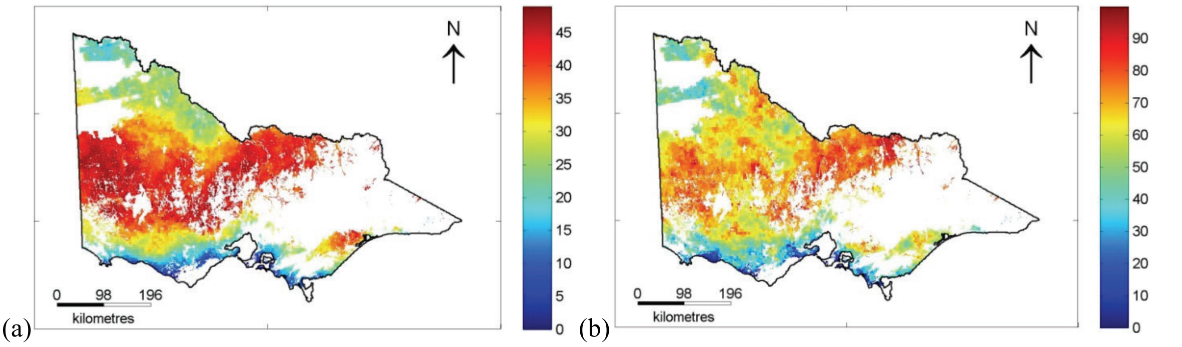

Figure 2. Average frost occurrence within a 14 day anthesis window based on a 2°C threshold for (a) the number of years out to 50 where frost was recorded, and (b) the percentage of years where multiple frost days were recorded.

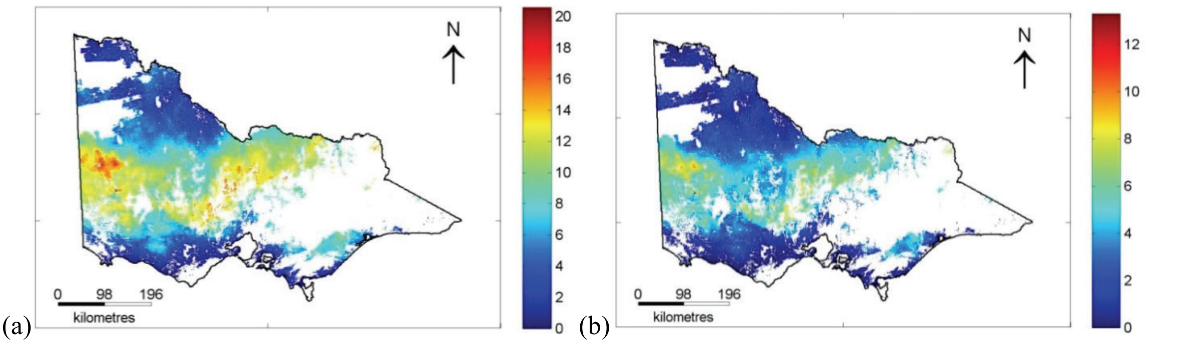

Figure 3. Average reduction in yield (%) due to frost damage (a) with a 2 to -2°C temperature range, and (b) with a 1 to -3°C temperature range.

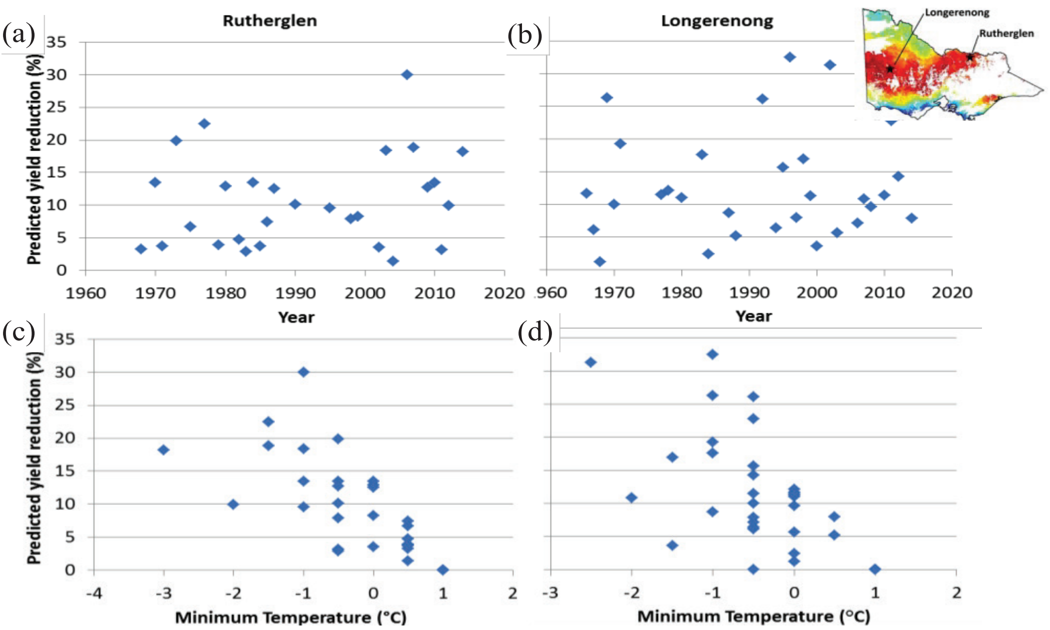

Figure 4. Annual reduction in yield (%) due to frost damage over time in (a) Rutherglen and (b) Longerenong with a 1 to -3°C temperature range. Annual reduction in yield (%) and the associated minimum temperature for (c) Rutherglen and (d) Longerenong.

The application of the CAT model spatially (1km^2 grids), provides an indication of the potential impacts of frost across the grain growing regions. However, frost is dependent on local minimum temperatures which can vary significantly from the nearest climate station, as well as across a paddock or farm. For the temporal response of the model we focused on two locations; Longerenong and Rutherglen. At Rutherglen with a 2 to -2°C temperature range frost was reported in 43 years resulting in an average of 13% reduction in yield. If the threshold is dropped by 1°C, then frost was recorded in 36 years and the average reduction in yield drops to 6%. Similarly for Longerenong with a 2 to -2°C temperature range frost was reported in 46 years resulting in an average of 17% reduction in yield. If the threshold is dropped by 1°C, then frost was recorded in 39 years and the average reduction in yield drops to 9%. There is significant temporal variation in the yield reduction recorded (Figure 4a, b) at both sites with a maximum reduction of 30-33% across the two sites. The minimum temperature resulting in frost losses varied, with damage recorded below the 1°C threshold (Figure 4c,d) highlighting the interaction within the model between timing and temperature. In this application, 90-100% yield losses were not observed, despite the potential for this to occur in the field, this suggests that further consideration is required of the criteria for maximum damage and the need to capture the impact of multiple frost events.

Conclusions and next steps

This paper presents a preliminary analysis of the application of the frost module (Figure 1) to mid-season wheat planted on an autumn break. The spatial response was consistent with expectations and the frequency of frost events coinciding with the anthesis period. Temporal data shows the variation in frost damage between years due to the multiplicative effect of minimum temperature and timing. The next step in developing this frost model is the validation of the response against experimental data. In further refining the model some key questions which still need to be addressed are (1) clarification of the distribution of frost sensitivity around anthesis and how the variation in anthesis within the crop affect whole crop impacts; (2) quantify the cumulative effect of multiple frost events over the anthesis window; and (3) consider how genetic differences in frost tolerance are incorporated within the frost module.

Acknowledgements

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