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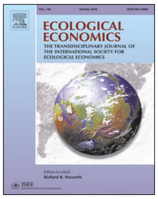

Analysis

Direct and Indirect Costs of Frost in the Australian Wheatbelt

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ABSTRACT

Breeding for improved reproductive frost tolerance could allow greater yield and economic benefits to be achieved by (i) reducing direct frost damage and (ii) allowing earlier sowing to reduce risks of late-season drought and/or heat stresses. We integrated APSIM-Wheat simulations with economic modelling to evaluate economic benefits of virtual genotypes with different levels of frost tolerance for the Australian wheatbelt.

Results highlighted substantial potential national economic benefits, with estimated industry profit increasing by (i) more than 55% for virtual genotypes with improved frost tolerance in silico, by (ii) 115% when sowing date was optimised for virtual frost-tolerant genotypes, and by (iii) an extra 35% (i.e. 150% in total) when using optimal nitrogen application. The total benefit potential was estimated at AUD 1890 million per annum if all these improvements could be combined. Regional benefits varied. In the West, the main benefits arose from improved frost tolerance reducing losses due to direct frost damage and applying additional nitrogen. In the East, earlier sowing allowed by tolerant genotypes resulted in large economic benefit. Overall, the analysis suggests significant economic benefits to the Australian wheat industry, should a source of frost tolerance be found.

1. Introduction

Reproductive frost can cause severe reductions in wheat yield, in countries like Australia (Fuller et al., 2007; Zheng et al., 2015). Wheat seasonal temperature increased by about 0.012 °C yr^{-1} from 1957 to 2010, i.e. an increase of 0.6 °C over the last 50 years for the wheatbelt (Zheng et al., 2016). However, frost has been an increasing problem in wheat, with increasing frequency of frost especially in the southern wheatbelt over the last six decades (Crimp et al., 2016) and consequently potential yield losses across the wheatbelt (Zheng et al., 2015).

With global climate change, the annual mean temperature in Australia is anticipated to increase by between 0.4 and 2.0 °C above 1990 levels by 2030 (Preston and Jones, 2006). While the date of extreme events cannot be predicted, climate models project an increase in the occurrence of hot days, fewer total frost days (Stone et al., 1996; Collins et al., 2000), and earlier occurrence of 'last frost' and 'first heat' events within the wheat growing season (Zheng et al., 2012). However, given the acceleration of crop development due to warmer temperature (Lobell et al., 2015; Zheng et al., 2016), risks of frost are likely to remain a major issue for the wheat industry over the coming decades (Zheng et al., 2015).

Frost is a major constraint to wheat production in Australia, and an appropriate combination of sowing date and variety maturity type is crucial to minimise the risks of stresses such as frost, heat and drought around flowering and during the grain filling period (Zheng et al., 2012; Zheng et al., 2015). In frost-free regions of Australia, early sowing is an appropriate strategies to maximize yield through optimising radiation interception in the winter and avoiding drought stress in the spring grain-filling period (Anderson et al., 1996). In frost-prone regions, later planting is typically required to reduce risks of frost around flowering, but this increases the risk of drought and heat stress during grain filling limiting the extent to which sowing can be delayed (Flohr et al., 2017). Although the date of first sowing is decided in advance by some farmers (dry sowing, with emergence occurring after rain (Fletcher et al., 2015)), in most areas sowing is heavily dependent on the occurrence of a rainfall event (autumn break) (Pook et al., 2009). In Australia, farmers are advised to choose suitable varieties which, when sown after the autumn break at their location, will develop with minimum risks of

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reproductive frost and of other stresses around flowering and during grain filling (Dennett et al., 1999; Zheng et al., 2012; Frederiks et al., 2015; Flohr et al., 2017).

A highly sought alternative to reduce frost impact is to develop varieties with increased levels of frost tolerance. Breeding for improved reproductive frost tolerance may allow greater yield and economic benefits to be achieved, as (i) direct frost damage could be reduced; (ii) crops could potentially be sown earlier to reduce risks of late-season drought and/or heat stresses; and (iii) additional inputs, such as fertiliser, could become more viable.

This study aims to provide insights into the impact of frosts and to quantify the economic benefits of different improved levels of post-heading frost-tolerance. While no genetic source for post-heading frost tolerance has yet been identified, the search remains an active area of research and it is possible to estimate the economic benefits of potential frost tolerant genotypes based on simulation of virtual genotypes with different levels of improved frost tolerance. Estimates of such benefits also provided an estimate of current frost costs, by providing an estimate of income forgone due to the absence of such frost tolerance. Here, crop model simulations were integrated with economic modelling. The APSIM-Wheat crop model (7.6) was adapted to account for frost (Zheng et al., 2015) and used to simulate current and improved frost tolerance of wheat genotypes sown at one day intervals within a fixed sowing window from 1 April to 30 June at 59 sites representing similar cropping area within the Australian wheatbelt (Chenu et al., 2013). The simulations were conducted either for current local fertiliser practices or with additional nitrogen to adapt local practices to better frost-adapted genotypes that can be sown earlier. Importantly, the analysis was done for long-term optimal sowing date defined as the sowing date corresponding to the highest long-term gross margin. This economic model was developed to identify strategies for optimal profits (including optimal sowing dates of frost-tolerance genotypes and optimal additional nitrogen levels) rather than for optimal yield per se. It is good to keep in mind though that to reach optimal yield or economic benefit, a farmer would need to have full prior knowledge of the seasonal weather and market prices in order to optimise variety and management every season. The overall frost impacts were quantified in terms of yield and economic benefits for different levels of postulated breeding achievement relative to current levels of frost tolerance in Australian cultivars. Economic benefits were estimated in terms of cost per hectares (in AUD ha^{-1}) at specific locations, as well as at the agro-ecological, regional and national levels. In addition, the total cost in AUD was calculated for the agro-ecological zones and at the national level.

2. Methodology

2.1. Overview

The analysis integrated crop-model simulations with a gross margin function to achieve optimal profit for different levels of frost tolerance in wheat, based on sowing, nitrogen application and yield performance at 59 representative locations of the 12 agro-ecological zones across the Australian wheatbelt (Fig. 1; Table S1). Note that agro-ecological zones with limited production were not considered, i.e. QLD Atherton, QLD Burdekin, Tas Grain, Vic High Rainfall, WA Mallee and WA Ord. For each location x sowing date combination (sowing at a 1d interval), an average yield was calculated for the 1957–2013 period. The mean yield distribution was obtained for each site by calculating the average yield at each sowing date for the whole sowing window (from 01-April to 30-June). The mean yield distribution or 'yield function' at each site was used to determine the gross margin function (Fig. 2) and identify the optimal sowing day corresponding to the maximum gross margin (profit) for current local cultivars (threshold of 0 °C) and the frost tolerant virtual genotypes (threshold below 0 °C).

Given the uncertainty in the air-temperature threshold for which wheat crops experience post-heading damage, national benefits are also estimated for threshold temperatures of −1 °C and −2 °C.

2.2. Crop Simulations

The development and yield of wheat crops were simulated using the APSIM 7.6 model (Holzworth et al., 2014) with a wheat phenology gene-based module (Zheng et al., 2013), a frost-impact module (Zheng et al., 2015) and a heat-impact module (Bell et al., 2015). Simulations were conducted for 59 representative sites from the East, South-East, South and West of the Australian wheatbelt (Fig. 1, Table S1; Chenu et al., 2013) from 1957 to 2013, using daily climatic data from the SILO patched point data set (Jeffrey et al., 2001) and an atmospheric CO_2 level of 350 ppm. Widely-grown mid-maturing local cultivars were used in simulations for each region; namely Baxter in the East, Janz in the South and South-East and Mace in the West. Genotypic values for the parameters *tt_floral_initiation* (thermal time from floral initiation to flowering), *photop_sens* (photoperiod sensitivity) and *vern_sens* (vernalisation sensitivity) of the gene-based module were 635, 1.1 and 0.6 for Baxter; 675, 0.9 and 0.6 for Janz; 635, 0.9, 0.9 for Mace, respectively (Zheng et al., 2013).

The estimates of yield reductions caused by crop frost damage were generated as described by Zheng et al. (2015). Frost susceptibility of wheat varies with growth stage. Wheat is most frost tolerant in the vegetative stages with susceptibility increasing with plant maturity. In the Australian wheatbelt, the impact of vegetative frost is low due to the low frequency of frost occurrence during this period. The impact of vegetative frost was thus not included in the model (Zheng et al., 2015).

Wheat becomes more susceptible to frost when the spike emerges from the flag leaf sheath (i.e. first awns visible, Zadoks stage Z49; Single, 1964). Sensitivity to frost increases after the awns or spikes start to emerge from the flag leaf (Livingstone and Swinbank, 1950; Single, 1964; Paulsen and Heyne, 1983). In the model, post-heading frost was estimated at the field level and the plant phenology was simulated for average growing stages. However, in reality, spikes of different tiller cohorts emerge both before and after the field average reaches Zadoks stage Z49. To approximate the distributions of exposed heads at susceptible post-heading stages, a multiplier was applied from 1 (i.e. no yield loss) at the late-booting average stage (Z45) followed by a linear decrease to 0.1 (i.e. 90% yield loss) against Zadoks score up to mid-heading (Z55), when almost all tillers would have reached the susceptible post-heading stage (Z49). Maximum susceptibility (i.e. all tillers susceptible) was then maintained until the start of dough development (Z80), with a constant yield multiplier of 0.1 (i.e. 90% yield loss) over the developmental period Z49-Z80 for each day with a minimum temperature below a threshold of 0 °C. After Z80, the yield multiplier was linearly increased over time (from 0.1 to 1) up to the completion of dough development (Z89) after grain development was nearly completed.

The only reliable source of long-term temperature records for the entire Australian wheatbelt are climatic data measured in a Stevenson screen. However, Stevenson-screen measurements are typically several degrees higher than the temperatures of the crop canopy during radiant frost events (Marcellos and Single, 1975; Frederiks et al., 2011, 2012). Wheat crops experience damage post-head emergence at canopy temperatures several degrees below 0 °C (Single, 1985; Frederiks et al., 2012). To determine a Stevenson-screen temperature threshold, Zheng et al. (2015) assessed temperatures from −5 to +2 °C in one degree increments and determined that overall, a threshold temperature of 0 °C best explained major recent incidences of frost damage. Simulations using 0 °C threshold predicted heading dates after the main, mid-winter frost risk period, when sowing dates recommended by industry guidelines were used for known frost-prone areas (Hollaway, 2014; Mathews et al., 2014; Shackley et al., 2014; Wheeler, 2014). Hence, a 0 °C threshold was used in the model base simulations.

Other researchers have suggested lower threshold Stevenson screen