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 1,890 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.

Keywords: frost, wheat, crop modelling, economic modelling, national assessment, Australia, breeding, ideotype.

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 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 (Livingston 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^{o}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 temperatures for frost damage (e.g. Bell *et al.*, 2015; Flohr *et al.*, 2017). For this reason, we also present economic estimates for threshold temperatures of –1°C or –2°C (FT$_1$ or FT$_2$), for comparison to those with 0°C (FT$_0$).

To estimate the potential economic benefits of genotypes with improved reproductive-frost tolerance, simulations were conducted for current and virtual genotypes with different sensitivities for post-heading frost, using the frost model developed by Zheng *et al*. (2015). As mentioned, current Australian wheat varieties were considered to be affected by post-heading Stevenson screen temperature below 0^{o}C (i.e. frost tolerance of 0^{o}C; FT$_0$). Virtual genotypes were generated with damage threshold temperatures ranging from –1^{o}C to –5^{o}C, i.e. frost tolerance to –1^{o}C to –5^{o}C, respectively (FT$_1$ to FT$_5$). Total frost tolerance (FT$_{tot}$) was also simulated, representing a virtual genotype that is insensitive to frosts of any temperature.

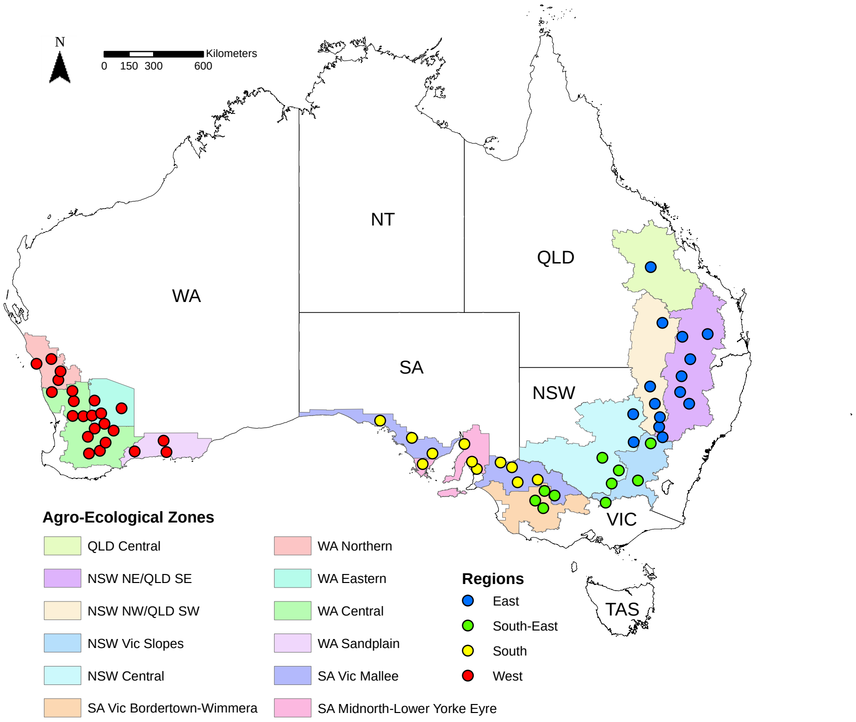

Fig. 1: Australian map with the 59 representative sites used for modelling studies, the four regions of the wheatbelt (Chenu *et al.*, 2013) and the 12 studied GRDC agro-ecological zones

(Stephens, 2011). Note that agro-ecological zones with small production (e.g. QLD Burdekin, Tas Grain, WA Ord) were not studied here and hence not shown in the map. The abbreviations in black correspond to the Australian states of Queensland (QLD), New South Wales (NSW), Victoria (VIC), South Australia (SA), and Western Australia (WA) as well as the Northern Territory (NT).

To characterise the potential of new management practices allowed by improved frost-threshold levels, simulations were conducted for different sowing dates and different fertilisation levels optimised for the different levels of improved frost tolerance. These simulations allowed estimation of ‘indirect frost impact’ (Fig. 2). In simulations, crops were sown every date within a sowing window from 1 April to 30 June. This is a sowing window wider than that used in current local farming practices. Baseline nitrogen fertiliser application (‘Current N’) used in the simulations varied with location and seasonal rainfall to reflect local agronomic practices (Table S1; Chenu *et al*., 2013). Briefly, nitrogen was applied at sowing, at start of stem elongation (Zadoks Score 30, Z30; Zadoks *et al.*, 1974) and/or the stage flag leaf visible (Zadoks Score 37, Z37) depending on the location, rainfall and plant available water content in the soil (Table S1; Chenu *et al*., 2013). To identify potential improvement in management practices when using frost-tolerant genotypes, simulations were also performed with additional potential levels of nitrogen ranging from +20 to +140 kg ha^{-1}, with 20 kg ha^{-1} intervals. The extra nitrogen levels were applied differently depending on the location and season: they were either 1) evenly distributed at Z30 and Z37 if fertilisation occurred both at Z30 and Z37, 2) at Z30 only if no fertilisation occurred at Z37, 3) at Z37 only if no fertilisation occurred at Z30, and 4) at sowing if no additional fertilisation occurred during the crop cycle. Simulations were initialised with soil water contents at sowing set to five levels each representing 20% of long-term conditions encountered for each site (Chenu *et al*., 2013). In the analysis, yield from crops sown at the same site and on the same date were averaged across the five levels of initial soil water, as these five levels had been shown to have approximately equal chance of occurrence (Chenu *et al*., 2013).

2.3 Averaged field direct and indirect economic benefits (in AUD ha^{-1}) at the site, region and nation levels

Gross margin (GM) analysis was employed to estimate the economic benefits of post-head emergence frost tolerance improvements. For each level of improved frost tolerance, economic benefits were assessed when changing either (i) solely the level of frost sensitivity, which is referred to as the 'direct benefit' or (ii) both the level of frost sensitivity and the management (sowing date and/or N fertiliser rate), which is referred to as the 'direct plus indirect benefit' (Fig. 2). A key component of this analysis was the integration of APSIM simulations with a gross margin function to achieve an optimal profit (or optimal gross margin), based on sowing, nitrogen application, frost tolerance level, and yield performance. This approach is considered more for farmers than solely maximising yield *per se*, even though the results only differ when costs vary, i.e. when different amount of nitrogen fertilisation is applied (e.g. change in sowing dates or simulations with extra nitrogen application).

For each site, a generalised long-term mean gross margin (GM) function was used:

$$\mathrm{GM}\left(st,N,FT\right)=f\left[P,Y(st,N,FT)\right]-\sum X_i-X(st,N) \qquad (1)$$

where st is the sowing time from 1 April to 30 June; N is the potential additional nitrogen level from 0 to 140 (kg ha^{-1}) in 20 kg ha^{-1} increments; FT is the frost tolerance level from FT_0 to $\mathrm{FT}_{\mathrm{tot}}$; f is the revenue function and depends on wheat price P (AUD t^{-1}) and wheat mean yield function Y (t ha^{-1}). The yield function here is similar to the concept of production function (An-Vo *et al.*, 2015a; An-Vo *et al.*, 2015b). The wheat prices used in our modelling are average prices over 10 years from 2002/03 to 2011/12 and are specific to each agro-ecological zone (Tables 1, 2 and S2). X_i are average input costs over 10 years from 2002/03 to 2011/12, including costs associated with seed, crop protection, repair and maintenance (R&M), fuel, machinery, insurance, other costs (Table 1) and grower current N application rates for each site ('Current N'). Average 'Current N' was estimated in each crop simulation based on local agronomic practice, with fertilisation amount depending on rainfall and soil moisture constraints at key developmental stages. $X(st,N)$ is the input cost as a function of long-term mean nitrogen applications additional to 'Current N' ('Additional N') and the sowing time. The fertiliser costs associated with the total N amount (i.e. 'Current N' and 'Additional N') are estimated based on the N application and urea price:

$$\text{Fertiliser cost }\left(\text{AUD ha}^{-1}\right)=\frac{\text{N amount }\left(\text{kg ha}^{-1}\right)}{1000}\times\frac{100}{46}\times\text{Urea price }\left(\text{AUD t}^{-1}\right). \quad (2)$$

The urea price was estimated to be the average urea price over 10 years from 2002/03 to 2011/12, i.e. AUD 564 t^{-1} (sourced from ABARES Australian Commodity Statistics).

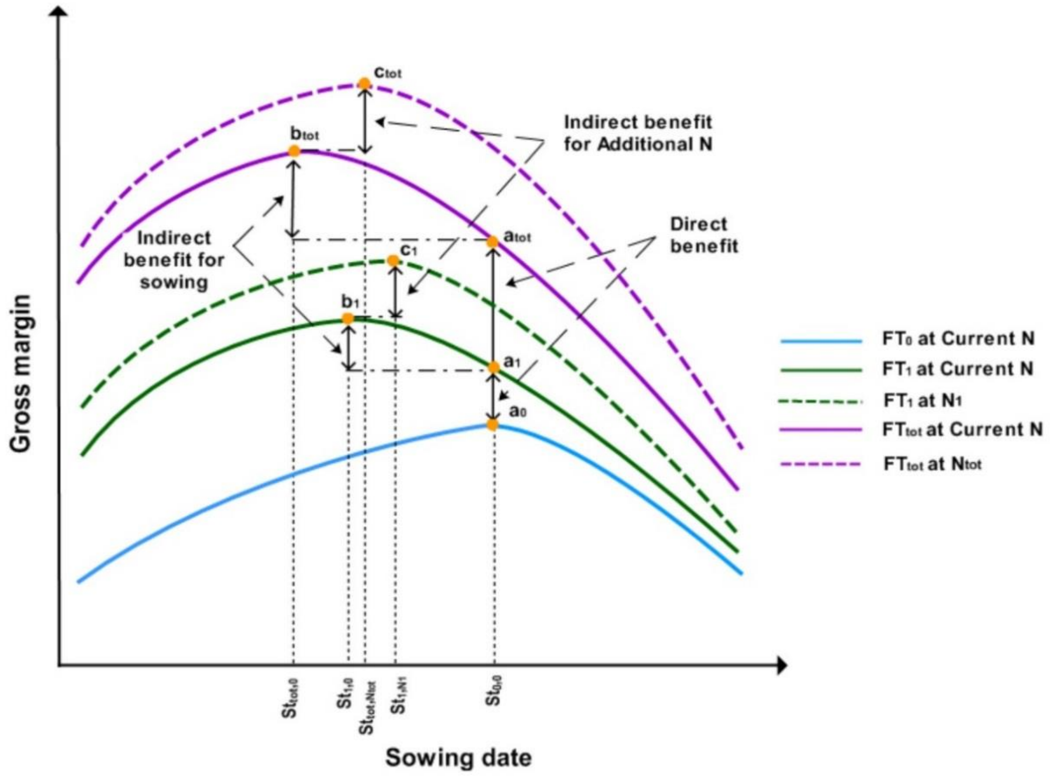

Fig. 2: Conceptual framework for assessing the direct economic benefits of frost improvement and the indirect benefits arising from possible (i) changes in sowing date without or with (ii) additional fertilisation ('Additional N'). Gross margin responses to sowing date (gross margin function) are schematised for long-term average (1957-2013) for current cultivars (FT_0), improved frost tolerant genotype FT_1 (frost tolerance to –1°C) and complete tolerance (FT_{tot}). Note that the gross margin functions with both 'Current N' and optimised 'Additional N' (FT_1 at N_1 and FT_{tot} at N_{tot}) are presented for FT_1 and FT_{tot}. Direct economic benefit corresponding to gross margin differences for the same management practices (i.e. the same sowing date and 'Current N') are represented by $a_1 - a_0$ or $a_{tot} - a_0$, where a_0, a_1 and a_{tot} represent the gross margins obtained for genotypes FT_0, FT_1 and FT_{tot}, respectively, at the optimum sowing of the reference genotype FT_0 ($st_{0,0}$). The indirect economic benefit related to earlier sowing date ('indirect benefit for sowing') correspond to profit gain achieved when adapting the sowing date to each of the considered genotypes, and are represented by $b_1 - a_1$ or $b_{tot} - a_{tot}$; where b_1 and b_{tot} represent the maximum profits that can be obtained at optimal sowing date for FT_1 ($st_{1,0}$), and FT_{tot} ($st_{tot,0}$), respectively. Additional profit gains are similarly estimated by adapting the N fertiliser rate, i.e. $c_1 - b_1$ or $c_{tot} - b_{tot}$, where c_1 and c_{tot} represent the maximum profits that obtained at optimal sowing date for FT_1 (st_{1,N_1}) and FT_{tot} ($st_{tot,N_{tot}}$).

Table 1: Estimated average annual wheat price (AUD t^{-1}) and input costs (AUD ha^{-1}) excluding fertilisers costs for the studied agro-ecological zones across the Australian wheatbelt. Costs are averaged for the 10 year period from 2002/03 to 2011/12 analysed and provided by Neil Clark Business Intelligence (from ABARES data sources). The input costs do not include the fertiliser cost which is estimated based on the amount of fertiliser used in each of our simulations (equation (2)). R&M stands for repair and maintenance.

Agro-ecological zone	Wheat price	Input costs							
		Seed	Crop protection	R&M	Fuel	Machine	Insurance	Other costs[*]	Total
QLD Central	246	29.4	61.3	26.8	34.2	73.5	11.5	48.0	284.6
NSW NE/QLD SE	238	15.4	43.7	20.2	28.3	66.7	12.7	29.4	216.4
NSW NW/QLD SW	237	15.4	38.0	20.2	28.3	66.7	9.3	24.9	202.8
NSW Vic Slopes	235	15.4	45.6	20.2	28.3	66.7	10.3	27.0	213.6
NSW Central	234	15.4	41.8	20.2	28.3	66.7	10.5	24.9	207.8
SA Vic Bordertown-Wimmera	245	21.6	46.0	19.4	27.6	52.7	5.1	9.6	182.0
SA Midnorth-Lower Yorke Eyre	253	16.6	39.6	21.6	26.3	49.7	4.7	65.1	223.6
SA Vic Mallee	249	21.6	46.0	19.4	27.6	52.7	3.2	9.6	180.1
WA Sandplain	263	19.3	56.6	24.8	30.9	56.8	5.3	48.2	241.8
WA Central	264	19.3	56.6	24.8	30.9	56.8	5.8	48.8	243.0
WA Eastern	263	19.3	56.6	24.8	30.9	56.8	5.0	43.8	237.2
WA Northern	263	19.3	56.6	24.8	30.9	56.8	5.4	48.3	242.0

[*] Other cost include:

1. Cartage of grain to local depot because the grain is priced at local depot in calculating income
2. General insurance
3. Professional fees, including agronomy, soil tests, telephone and electricity etc.
4. Motor vehicles (utes, motor bikes etc.)

For each location and each cultivar, an average yield was calculated for the period 1957-2013 for each sowing date. A long-term mean yield function *Y* was constructed based on the average yield for each sowing date within the sowing window, which allowed estimation of the gross margin function using equation (1). The optimum sowing day, resulting in the maximum mean gross margin across years, was identified for the control cultivar (FT_0). 'Direct economic benefit' was assessed by comparing the gross margin of the control (FT_0) with the gross margin of each virtual frost tolerant genotype ($FT_{1\text{–}tot}$) cultivated with the same management practices (Fig. 2), i.e. same N application rate and same optimum sowing date as the control. The long-term mean Direct Benefit (DB in AUD ha^{-1}) for each site, for example for FT_{tot} was obtained as:

$$\mathrm{DB}\left(\mathrm{FT}_{\mathrm{tot}}\right)=\mathrm{GM}\left(st_{0,0},0,\mathrm{FT}_{\mathrm{tot}}\right)-\mathrm{GM}\left(st_{0,0},0,\mathrm{FT}_0\right) \tag{3}$$

where $st_{0,0}$ is the economically-optimal sowing time for a reference cultivar with the current frost tolerance level (FT_0) with Current-N fertiliser rate (i.e. 0 Additional N, Fig. 2), i.e. the sowing time is such that:

$$\mathrm{GM}\left(st_{0,0},0,\mathrm{FT}_0\right)=\max\left\{\mathrm{GM}\left(st,0,\mathrm{FT}_0\right)\right\} \tag{4}$$

For the 'direct plus indirect economic benefit', 'optimum' gross margin of frost-tolerant virtual genotypes ($FT_{1\text{–}tot}$) was calculated by (i) re-estimating the optimum sowing date of each genotype, while considering their respective levels of frost-tolerance, and (ii) without or with optimising the N fertiliser level (Fig. 2). The long-term mean indirect benefits (IB in AUD ha^{-1}) for each site, for example for FT_{tot} (compared to FT_0), are the sum of long-term benefits arising from two management factors, the sowing time and additional nitrogen application. The long-term mean indirect benefit owing to changing the sowing time only (IB_{st} in AUD ha^{-1}) was calculated as:

$$\mathrm{IB}_{st}\left(\mathrm{FT}_{\mathrm{tot}}\right)=\mathrm{GM}\left(st_{\mathrm{tot},0},0,\mathrm{FT}_{\mathrm{tot}}\right)-\mathrm{GM}\left(st_{0,0},0,\mathrm{FT}_{\mathrm{tot}}\right) \tag{5}$$

where $st_{\mathrm{tot},0}$ (Fig. 2) is the optimal sowing time of FT_{tot} with 'Current N' fertiliser rate, i.e. the sowing time such that:

$$\mathrm{GM}\left(st_{\mathrm{tot},0},0,\mathrm{FT}_{\mathrm{tot}}\right)=\max\left\{\mathrm{GM}\left(st,0,\mathrm{FT}_{\mathrm{tot}}\right)\right\} \tag{6}$$

The long-term mean indirect benefit related to new nitrogen applications (IB_N in AUD ha^{-1}) was calculated as:

$$\mathrm{IB}_N\left(\mathrm{FT}_{\mathrm{tot}}\right)=\mathrm{GM}\left(st_{\mathrm{tot},N_{\mathrm{tot}}},N_{\mathrm{tot}},\mathrm{FT}_{\mathrm{tot}}\right)-\mathrm{GM}\left(st_{\mathrm{tot},0},0,\mathrm{FT}_{\mathrm{tot}}\right) \tag{7}$$

where $st_{\mathrm{tot},N_{\mathrm{tot}}}$ (Fig. 2) is the optimal sowing time of $\mathrm{FT_{tot}}$ with optimal additional fertiliser level N_{tot}, i.e.

$$\mathrm{GM}\left(st_{\mathrm{tot},N_{\mathrm{tot}}}, N_{\mathrm{tot}}, \mathrm{FT_{tot}}\right) = \max\left\{\mathrm{GM}\left(st, N, \mathrm{FT_{tot}}\right)\right\}. \qquad (8)$$

Unlike (3) and (5) where only one variable (sowing time) is optimised, in (7) two variables (sowing time and additional nitrogen level) were optimised (Fig. 2). Overall, the long-term mean indirect benefit at a site for $\mathrm{FT_{tot}}$ is calculated as:

$$\mathrm{IB}\left(\mathrm{FT_{tot}}\right) = \mathrm{IB}_{st}\left(\mathrm{FT_{tot}}\right) + \mathrm{IB}_{N}\left(\mathrm{FT_{tot}}\right). \qquad (9)$$

The long-term mean net benefit at the site level (NB_s in AUD ha^{-1}) is a simple aggregation of direct plus indirect benefits:

$$\mathrm{NB}_s(\mathrm{FT_{tot}}) = \mathrm{DB}(\mathrm{FT_{tot}}) + \mathrm{IB}(\mathrm{FT_{tot}}). \qquad (10)$$

2.4 National direct and indirect economic benefits (in AUD)

The economic benefits from the field level (AUD ha^{-1}) were also up-scaled to estimate the gain to the whole industry (in AUD).

First, the net benefit at an agro-ecological zone *z* (NB_z in AUD ha^{-1}) was calculated by:

$$\mathrm{NB}_z\left(\mathrm{FT_{tot}}\right) = \frac{\sum_{s=1}^{n} \mathrm{NB}_s\left(\mathrm{FT_{tot}}\right) \times S_s}{\sum_{s=1}^{n} S_s} = \frac{1}{n}\sum_{s=1}^{n} \mathrm{NB}_s\left(\mathrm{FT_{tot}}\right) \qquad (11)$$

Where *n* is number of sites in an agro-ecological zone and S_s is wheat cropping area represented by each site. Note that each site in our simulation study represented a similar area of wheat cropping (Chenu *et al.*, 2013) so that the equation could be simplified as done in the second part of equation (11).

Finally, total net benefit (TBN, in AUD) of an agro-ecological zone *z* is calculated by:

$$\mathrm{TNB}_z\left(\mathrm{FT_{tot}}\right) = \mathrm{NB}_z\left(\mathrm{FT_{tot}}\right) \times S_z = \frac{1}{n}\sum_{s=1}^{n} \mathrm{NB}_s\left(\mathrm{FT_{tot}}\right) \times S_z \qquad (12)$$

Where S_z is the historical average wheat cropping area of the agro-ecological zone. In our calculation, historical average area for 10 years was used in each agro-ecological zone (Tables 2 and S3).

For each frost tolerance level ($FT_{1\text{-}tot}$), the DB, IB, and NB_s for each site and the NB_z and TNB_z for each agro-ecological zone were estimated using the same steps as those described for FT_{tot} above and in equations (3), (9), (10), (11) and (12), respectively. The summation of TNB_z at all 12 studied agro-ecological zones provided the total net benefit at national level. While economic benefits were primarily estimated for a current frost damage threshold temperature of 0°C (FT_0 as a baseline), national benefits were also estimated for threshold temperatures of -1^{o}C and -2^{o}C as baselines to account for the uncertainty related to estimation of the threshold air temperature (measured in Stevenson screen) under which frost damage occurs.

3. RESULTS

The present approach allows estimation of not only direct and indirect economic benefits but also associated yield benefits, while been different from a *direct* optimal yield approach (Zheng *et al*., 2015). The yield and economic benefits of improved frost tolerance were firstly quantified for the case of current management practices (i.e. no change in sowing date or fertilisation level). These ‘direct’ benefits were defined for tolerant genotypes sown at the same optimum date as for current local cultivars and with current local season-specific fertilization practices (Table S1; Chenu *et al*., 2013). The ‘indirect’ benefits from a change in sowing date, without or with additional nitrogen application levels were then quantified by means of equations (5, 7) to assess the benefit of adapting grower management. Our analysis assumed that no change in price will result from higher volumes of production or any change in grain quality brought about by the postulated changes.

3.1 Frost-tolerant wheat crops cultivated with current fertilizer practices - Yield and economic benefits to farmers

The indirect benefit in this section means the indirect benefit owing to changing the sowing time only (IB_{st}; equation (5)).

3.1.1 Frost tolerance would allow earlier sowing, especially in the East and South-East of the wheatbelt

Improved frost tolerant varieties would allow growers to plant wheat earlier (Table S1) to avoid risks of late-season drought and/or heat stress and hence greater yield could be achieved. The potential to sow earlier generally increases with improved frost tolerance levels. It is noted that the optimal sowing dates in Table S1 are different from those previously reported by Zheng *et al*. (2015), as they relate to gross-margin optimisation and not yield optimisation. In the current study, a wider potential sowing window, from 01-April to 30-June, was also allowed compared to the window from 01-May to 21-June used by Zheng *et al*. (2015). We observed notable potential for early sowing for lines with improved frost tolerance at some sites. For example, with improved frost threshold temperature to -1^{o}C (FT_1) compared to 0^{o}C (FT_0), the optimal sowing dates averaged 35, 30, and 23 days earlier at Walpeup (South), Condobolin (East), and Corrigin (West), respectively. With total frost tolerance (FT_{tot}), the optimal sowing dates averaged 68, 67, and 63 days earlier than the control (FT_0) at Condobolin (East), Glenlee (South-East), and Salmon Gums (West), respectively. However, it should be noted that in the current study we did not examine some potential impediments to the use of the earliest suggested sowing dates, such as high soil temperatures influencing coleoptile emergence, for example (Rebetzke *et al*., 2016).

Nationally, long-term average of 5, 14, 16 and 18 days earlier sowing were found to maximise gross margins for FT_1, FT_2, $FT_{3–4}$ and $FT_{5–tot}$, respectively (Fig. 3a). Hence, most of the potential shift in sowing date (18 days for FT_{tot}) was achieved for a tolerance to -2^{o}C (14 days for FT_2), while further improvement in frost tolerance ($FT_{3\text{-}tot}$) only had a limited impact on the wheat optimal sowing date.

Of the four Australian regions studied (Fig. 1), earlier potential sowing dates were simulated in the East and South-East for all improved frost threshold levels. In these regions, totally removing the frost sensitivity of genotypes (FT_{tot}) resulted in optimal sowing shifted by 34 and

45 days earlier on average for the East and South-East respectively (Fig. 3b,c). This was in stark contrast to most sites in the South and West where little or no change in average optimum sowing dates was simulated (Fig. 3d,e).

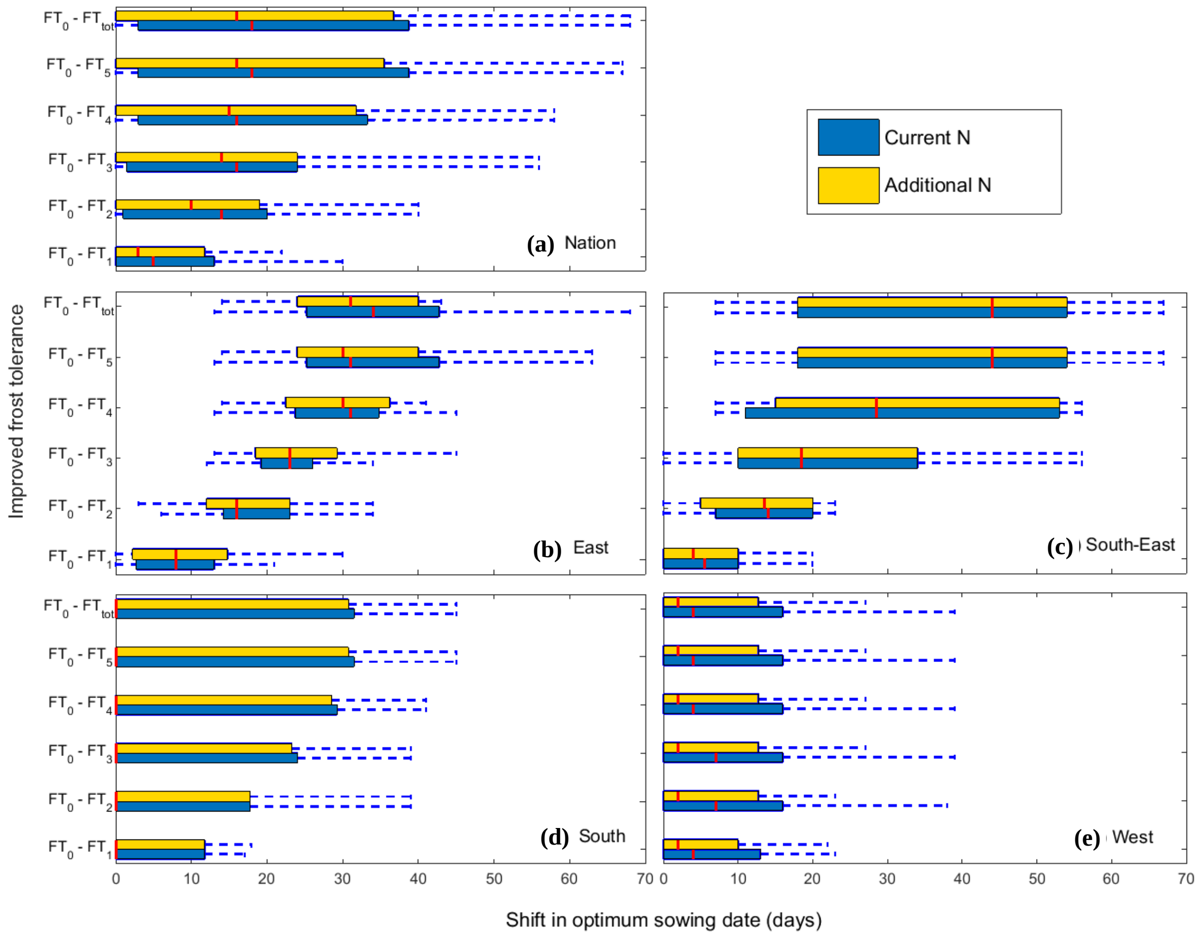

Fig. 3: Change in the long-term optimal sowing dates between the current local cultivars (FT_0) and genotypes with improved frost tolerance. The shifts towards earlier optimum sowing days are given in number of days compared to the optimum sowing dates for the current cultivars. National-level results are presented in (a), while the results at regional level are presented in (b), (c), (d) and (e). Note that there was no change in long-term optimal sowing date with improved frost tolerance levels for half or more of the sites in the South resulting in zero median values (d). The optimal sowing dates were determined based on long-term average gross margin responses to sowing date for the studied period (1957-2013) over an extended potential sowing window (01-April to 30-June) at each site. For each boxplot, the central bar corresponds to the median across sites, the edges of the box are the 25th and 75th percentiles,

and the whiskers extend to the most extreme values (average optimum sowing date for a site within the region).

3.1.2 Small improvements in frost tolerance in the Australian wheatbelt could substantially increase national economic benefits

The quantification of direct and indirect yield and economic benefits requires accurate determination of (i) the losses in yields and gross margins (profits) from direct damage due to the frost events (‘direct benefit’) which represents the difference between yields and gross margins of the frost-tolerant and current genotypes at the optimal sowing date of current genotypes (FT_0); and (ii) the gain in yields and gross margins of the virtual frost-tolerant genotypes for their optimal management practices, including adjusted planting date and nitrogen application based on increased expected yield and gross margin (‘indirect benefit’).

Across the wheatbelt, average yields of 1.91, 2.05, 2.10 and 2.11 t ha^{-1} were simulated for FT_0, FT_1, FT_2 and FT_{3-tot}, respectively, for crops sown at the site sowing date that was optimum for the gross margin of current cultivar (FT_0) (Fig. 4a). This correponds to direct yield benefits of 0.14, 0.19 and 0.20 t ha^{-1} for FT_1, FT_2 and FT_{3-tot}, respectively (Fig. 4b). Hence, most of the frost tolerance impact (70% and 95% of the total tolerance direct yield benefit of 0.20 t ha^{-1}) were achieved by improving frost threshold tempertature to –1 and –2°C, respectively. Nationally, no further direct yield benefit was simulated when improving the frost tolerance to below –3°C (i.e. for FT_{4-tot}). Overall, nation-wide, the direct yield benefit for total frost tolerance (i.e. FT_{tot}) was estimated at 0.20 t ha^{-1} on average, for simulations optimised for profit.

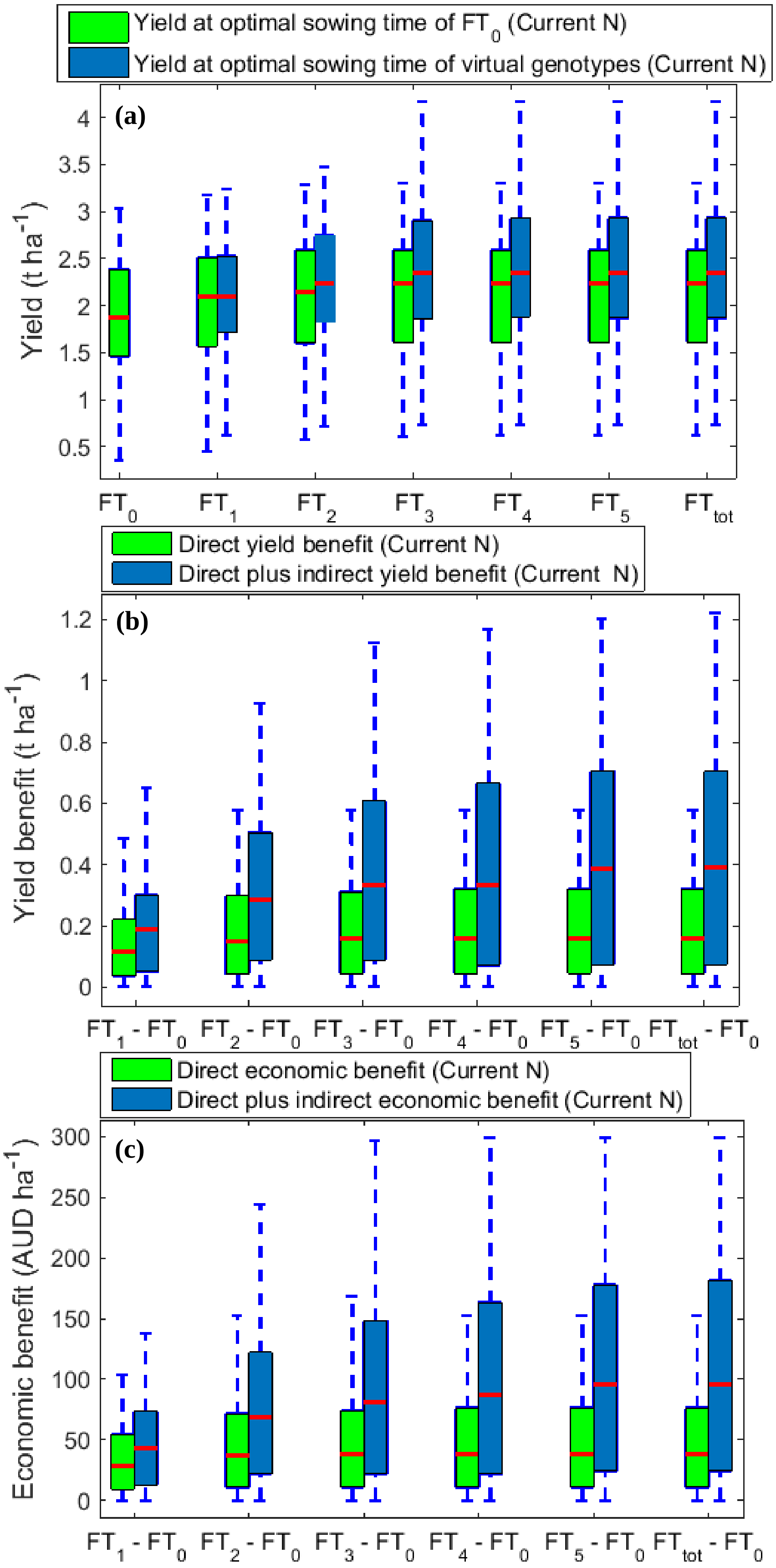

Fig. 4: Yield and economic benefits at national level of virtual genotypes with improved frost tolerance, simulated for 'Current N' application rates. Benefits were assessed by comparing

performances optimised based on gross margin, for genotypes with different levels of frost tolerance ($FT_{1\text{-}tot}$) to their respective current cultivar (FT_0). Boxplots based on average yield values and average gross margins calculated for each site for the studied period (1957-2013) for the optimal long-term sowing dates (i.e. sowing date with the optimal long-term profits included in the sowing window from 01-April to 30-June). In each boxplot, the central bar is the median, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the most extreme values. Similarly results are given for each region in Fig. S1 (for yield), S2 (yield benefit) and 5 (economic benefit).

When adapting the sowing date to allow optimal profit for each genotype (i.e. adding indirect benefit owing to sowing), average yields of 2.10, 2.23, 2.30, 2.33, 2.34 and 2.35 t ha^{-1} were obtained for FT_1, FT_2, FT_3, FT_4, FT_5 and FT_{tot}, respectively (Fig. 4a). The direct plus indirect yield benefits were 0.19, 0.32, 0.39, 0.42, 0.43 and 0.44 t ha^{-1} for FT_1, FT_2, FT_3, FT_4, FT_5 and FT_{tot}, respectively (Fig. 4b). Hence, 43% and 73% of the total direct plus indirect yield benefit (0.44 t ha^{-1}) were achieved by improving frost threshold temperature to –1 and –2°C (i.e. $FT_1 - FT_0$, $FT_2 - FT_0$), respectively. Improvement of frost threshold temperature to below –3°C increased indirect yield benefits but not direct yield benefits at the national level (Fig. 4b). Overall, nation-wide direct plus indirect yield benefit was estimated at an average of 0.44 t ha^{-1}, thus representing a 23% increase for the national simulated yield.

The trends in economic benefits were similar to those of yield benefits (Fig. 4c). For current cultivars sown at optimal sowing dates, average direct economic benefits of AUD 28 and 37 ha^{-1} were obtained for FT_1 and FT_2, respectively; and a similar benefit of AUD 39 ha^{-1} was obtained for FT_3, FT_4, FT_5 and FT_{tot}. Thus, the improvement of frost threshold temperature to only –1 and –2°C could led to 72% and 95% of the total potential marginal direct economic benefit (AUD 39 ha^{-1}). By adapting to the optimal sowing date for each tolerant genotype, average direct plus indirect economic benefits reached AUD 43, 69, 81, 87 and 95 ha^{-1} for FT_1, FT_2, FT_3, FT_4 and $FT_{5\text{–}tot}$, respectively. Improvement of the frost damage threshold temperature to –2°C was estimated at 95% of the total potential direct economic benefits (AUD 39 ha^{-1}) and 73% of the total potential direct plus indirect economic benefits (AUD 95 ha^{-1}).

3.1.3 Regionally, substantial economic benefits of frost-tolerant genotypes are expected in the East and the West

The effects of improved frost threshold levels differed among the regions for yield (Fig. S1-S3) and economic benefits (Fig. 5, 6). The direct benefit of tolerant genotypes was much higher in the East and the West compared to the South-East and South regions (Fig. 5 and S2). Across regions, average direct economic benefits were estimated at:

- AUD 40 and 62 ha^{-1} for the FT_1 and $FT_{2\text{–}tot}$, respectively, in the East;
- AUD 33, 37 and 38 ha^{-1} for the FT_1, FT_2 and $FT_{3\text{–}tot}$, respectively, in the South-East;
- AUD 10 ha^{-1} for all tolerant virtual genotypes in the South;
- AUD 42, 56 and 58 ha^{-1} for the FT_1, $FT_{2\text{–}3}$ and $FT_{4\text{–}tot}$, respectively, in the West.

Thus, the greatest potential direct benefits were achieved in the East at 0.24 t ha^{-1} (Fig. S2) and AUD 62 ha^{-1} by FT_2, and in the West at 0.22 t ha^{-1} (Fig. S2) and AUD 58 ha^{-1} by FT_4.

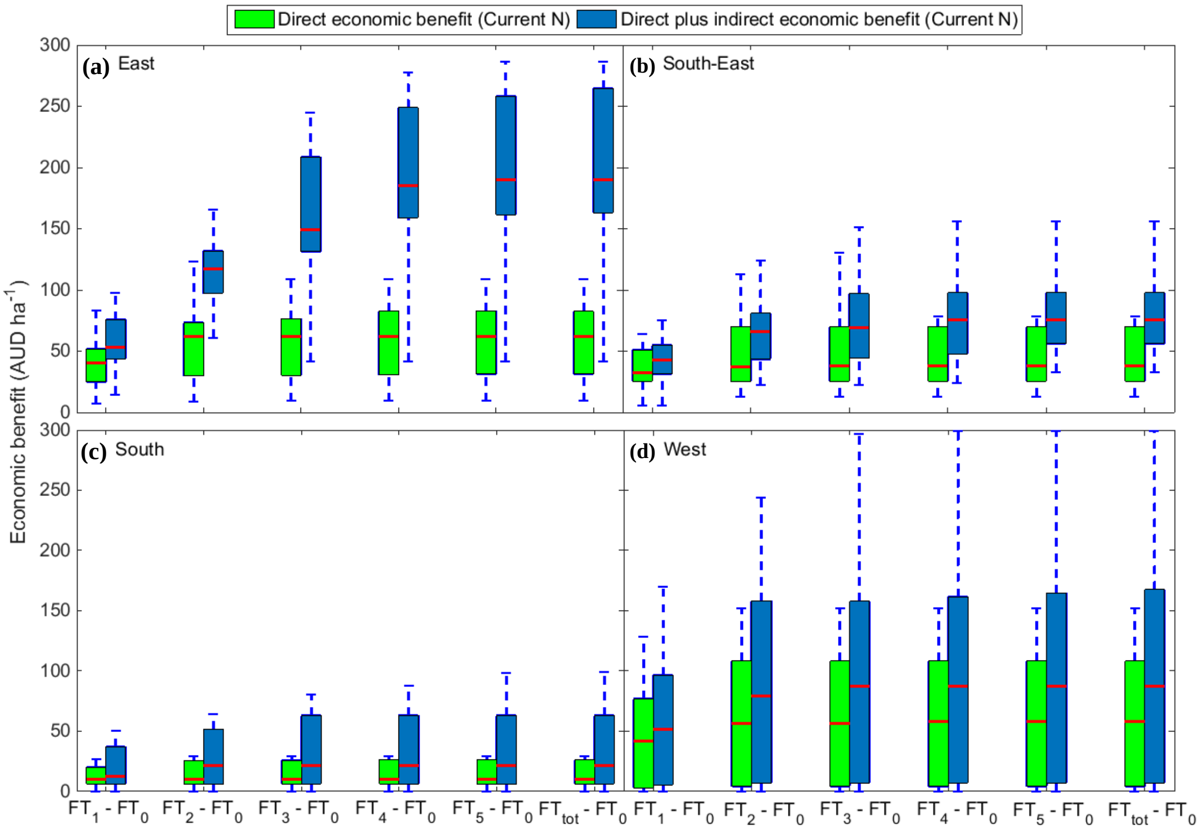

Fig. 5: Economic benefits of virtual genotypes with improved frost tolerance in the four regions with 'Current N' application rates. Benefits were assessed by comparing performances for genotypes with different levels of frost tolerance ($FT_{1\text{-}tot}$) to their respective local current cultivar (FT_0). For each boxplot, the central bar is the median, the edges of the box are the 25th

and 75th percentiles, and the whiskers define the range of values. Results are presented for the nation in Fig. 4.

Extra indirect economic benefit was achieved by changing the sowing date to the optimal sowing days of the improved frost tolerant genotypes. The average direct plus indirect economic benefit (Fig. 5) varied across regions, being on average:

- in the East, AUD 53, 117, 149, 185 and 189 ha^{-1} for FT$_1$, FT$_2$, FT$_3$, FT$_4$ and FT$_{5\text{–tot}}$, respectively;
- in the South-East, AUD 42, 66, 69 and 75 ha^{-1} for the FT$_1$, FT$_2$, FT$_3$ and FT$_{4\text{–tot}}$, respectively;
- in the South, AUD 12 and 22 ha^{-1} for FT$_1$ and FT$_{2\text{–tot}}$, respectively; and
- in the West, AUD 51, 79 and 87 ha^{-1} for FT$_1$, FT$_2$ and FT$_{3\text{–tot}}$, respectively.

The potential of indirect benefit (by managing the sowing date) was thus remarkably high in the East compared to other regions at 0.57 t ha^{-1} (Fig. S2) and AUD 127 ha^{-1}, which represents 67% of the AUD 189 ha^{-1} total (direct plus indirect) economic benefits.

Site-level spatial distribution of direct and direct plus indirect yield benefits (Fig. S1-S3) and economic benefits (Fig. 6) also highlighted that:

(i) The direct benefits of frost tolerant genotypes were dominant in the West (Fig. S1-2d, S3 and 6). Small improvements in frost tolerance of genotypes (FT$_1$) resulted in most of the simulated direct yield and economic benefits in the West (Fig. S3 and 6a,c,e);

(ii) Yield and economic gains owing to the ability to advance sowing dates in the East were greater than those due to simulated improvement of frost damage *per se,* especially with larger improvements in frost threshold temperature (Fig. S1-2a, Fig. S3 and 6b,d,f);

(iii) The advantages of changing the sowing dates for frost tolerant genotypes were smaller in both the South-East and South (Fig. S1-2b,c).

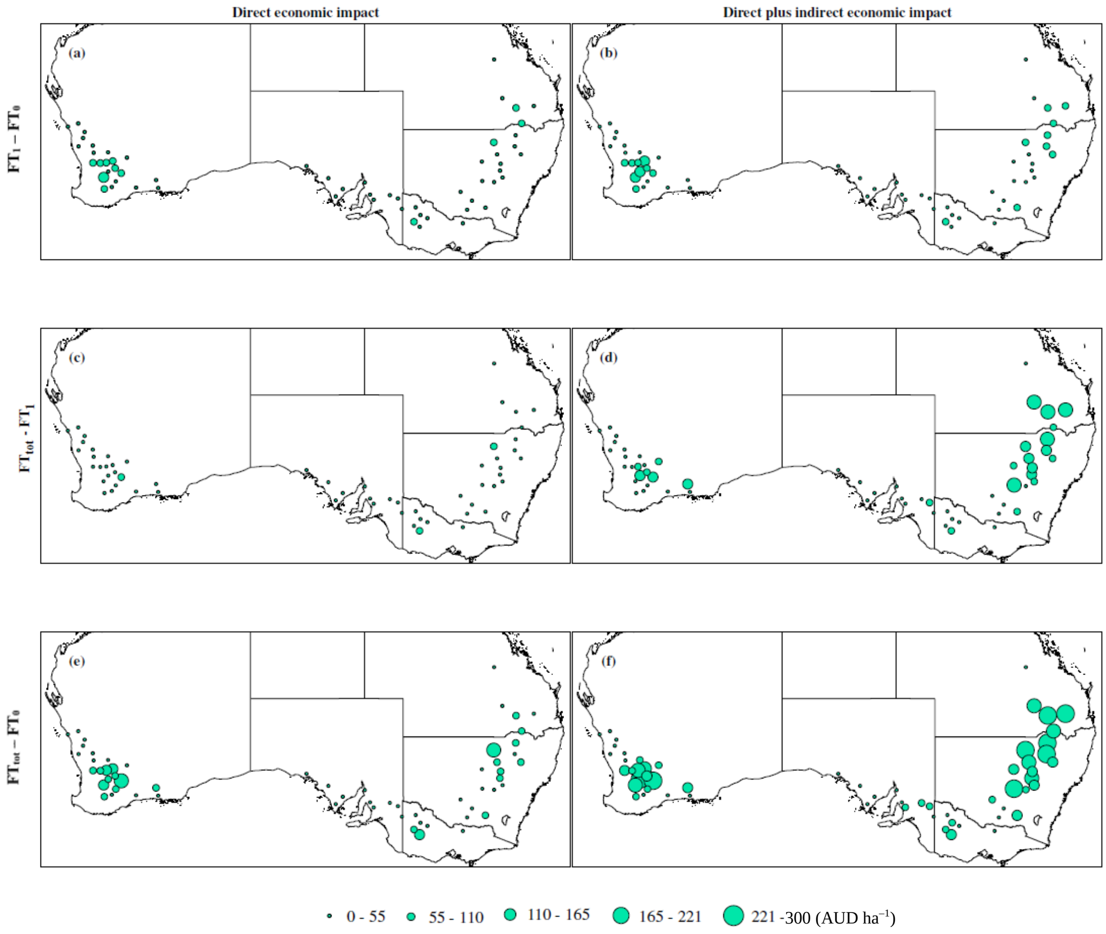

Fig. 6: Direct (left) and direct plus indirect (right) economic benefits per ha with the ‘Current N’ practice when (i) increasing the frost tolerance to –1°C (i.e. FT_1–FT_0; (a and b)), (ii) considering the additional economic gain achieved with a total frost tolerance (i.e. FT_{tot}–FT_1; (c and d)), and (iii) looking at the economic benefit between total tolerance and the current level (FT_{tot}–FT_0; (e and f)). The results for yield benefits are presented in Fig. S3.

3.2. Frost-tolerant wheat crops cultivated with new fertilizer practices could bring additional yield and economic benefits to farmers

In addition to indirect yield and economic benefits related to earlier sowing, the frost tolerant genotypes could also allow extra indirect benefits through increased fertiliser application. The benefits of additional fertiliser were quantified and compared with the results from current fertilisation practices (‘Current N’) described in the previous section.

3.2.1 Effects on early sowing potential

When testing new N fertilisation options to increase the gross margins of frost-tolerant genotypes, optimum sowing dates only slightly changed compared to results from the ‘Current N’ application rate (Fig. 3; Tables S1, S4). Here again, optimal sowing dates were mostly predicted to be in April or early May when totally removing the frost sensitivity (FT_{tot}; Table S4). Additional fertiliser application partially negated early sowing potential, with optimum sowing dates being slightly later than those for ‘Current N’ by 1 to 4 days on average at the national level, depending on the frost tolerance level (Fig. 3a). This effect was most visible for FT_2 and FT_3 in the West (6 days later optimum on average) (Fig. 3e).

3.2.2 National view: managing the nitrogen application would increase the economic benefits from frost-tolerant crops

Applying additional N fertiliser allowed an increase in benefits from frost tolerant genotypes across the wheatbelt. First, optimum additional N slightly increased average profit of current cultivars (FT_0) (Fig. 7a), which is expected as ‘Current N’ were based on current practices by growers who do not always take the risk of applying expensive nitrogen given variability in environmental conditions. More importantly, for frost tolerant genotypes, nation-wide average returns of AUD 60, 96, 118 and 121 ha^{-1} were achieved when applying additional fertiliser for FT_1, FT_2, FT_3 and $FT_{4\text{–}tot}$, respectively (Fig. 7a). These results correspond to an additional profit of AUD 17 (40%), 27 (39%), 37 (46%), 34 (39%) and 26 (27%) ha^{-1} on average, compared with the ‘Current N’ results for FT_1, FT_2, FT_3, FT_4 and $FT_{5\text{–}tot}$, respectively; and a benefit of 38%, 60%, 74% and 76%, compared with the gross margin of current cultivar with the ‘Current N’ (baseline) for FT_1, FT_2, FT_3 and $FT_{4\text{–}tot}$, respectively. While optimal levels of additional nitrogen fertiliser varied depending on the level of frost tolerance (Table S5), the economic benefit of increasing the fertilisation was substantial for all of virtual genotypes examined, and the greatest for FT_3 (Fig. 7a).

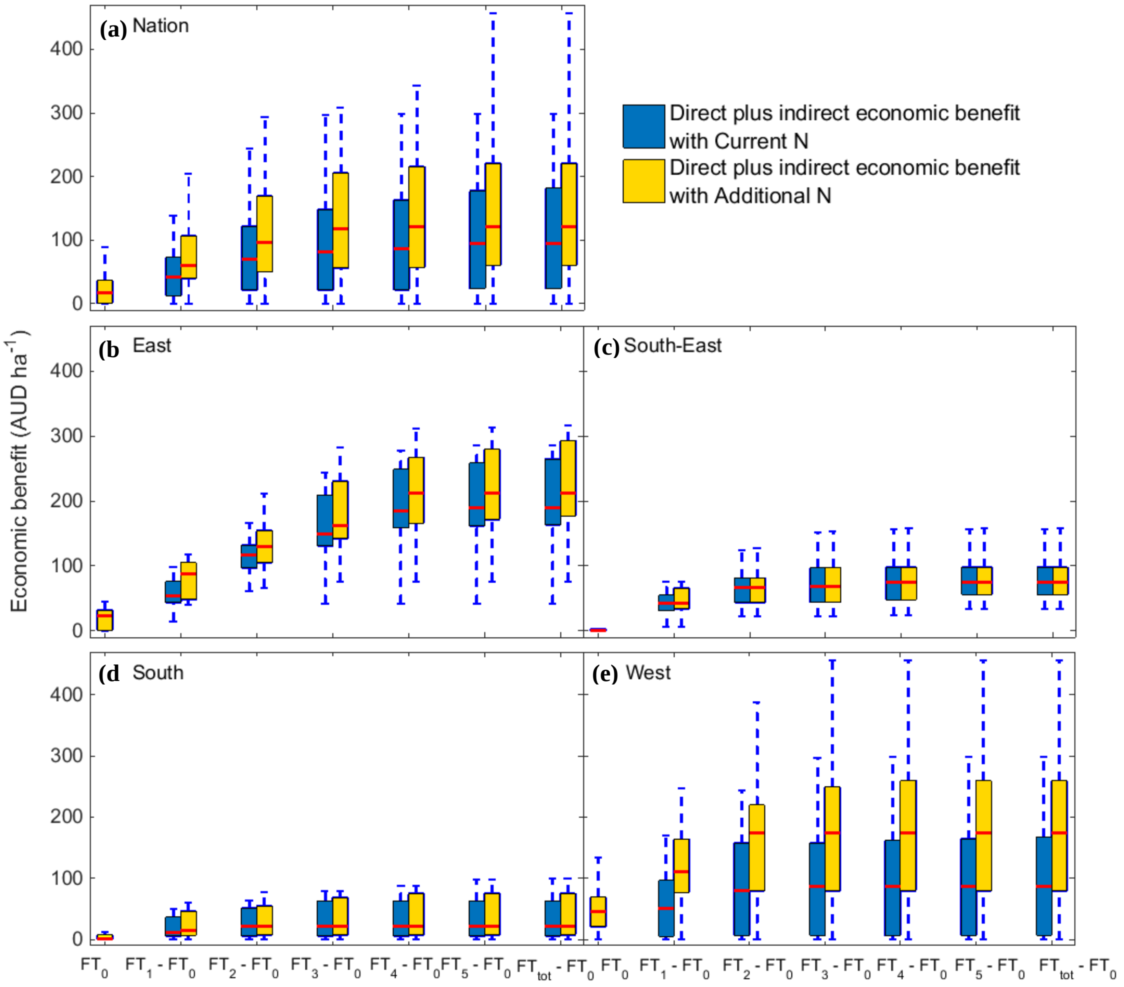

Fig. 7: Economic benefits of the current local cultivars (FT_0) and virtual genotypes with improved frost tolerance ($FT_{1\text{-}tot}$) at the national scale (a) and in the four regions (b,c,d,e) with current ('Current N') and optimised ('Additional N') fertiliser practices. For each boxplot, the central bar is the median, the edges of the box are the 25th and 75th percentiles, and the whiskers define the range of values.

3.2.3 Regional view: effectiveness of additional nitrogen on frost-tolerant crops is expected to vary among the regions

Additional nitrogen fertilisation was most effective in enhancing the economic gains from frost tolerant wheat genotypes in the West (Fig. 7e). In this region, additional fertiliser increased the average profit by AUD 46 ha^{-1} (i.e. 23%) with the current frost susceptible cultivars (FT_0). By improving frost tolerance, adapting the sowing date and using additional nitrogen, the net economic benefits in this region were AUD 111 and 175 ha^{-1} for FT_1 and $FT_{2\text{–}tot}$, respectively. This corresponds to an additional AUD 60 (118%), 96 (122%) and 88 (101%) ha^{-1} on average for FT_1, FT_2 and $FT_{3\text{–}tot}$, respectively, in comparison with the 'Current N' results; and a benefit of 58% and 91% for FT_1 and $FT_{2–tot}$, respectively, in comparison with the gross margin of current cultivars in the 'Current N' (i.e. a baseline). The potential economic benefit of additional fertilisation was thus substantial in the West (Fig. 7). In this region, it was estimated at up to an average of AUD 96 $ha^{–1}$ thus contributing to 55% of the net economic benefit (AUD 175 $ha^{–1}$) if we neglect the small changes in sowing date that occurred when adjusting the nitrogen fertilisation in the 'Additional N' treatment (Figs. 2-3, Tables S1 and S4). The corresponding potential average yield benefit was 0.36 t $ha^{–1}$ (data unshown).

3.3. Economic benefits at the regional and national level – Frost tolerance in wheat could greatly increase returns to industry

Economic benefits were estimated as a national benefit, by up-scaling the average regional benefits for farmers (per ha) by the size of each agro-ecological zone. The baseline revenue and profit values of current Australia wheat production were estimated to be about AUD 5,000 million and 1,200 million per annum, respectively (Table 2). Note that agro-ecological zones with small production (e.g. QLD Burdekin, Tas Grain, WA Ord) were not considered in this study. The nation-wide direct economic benefits were estimated at up to AUD 700 million by totally removing the frost sensitivity of genotypes (FT_{tot}) (Fig. 8a). Direct plus indirect benefits when adapting sowing practices were estimated at up to 1,430 million for those frost-tolerant crops (FT_{tot}), and adapting their nitrogen fertilisation could add another AUD 450 million profit nationally, thus giving a potential total benefit of up to AUD 1,890 million of gains per annum. In other words, the national revenue for wheat when considering total frost tolerance (FT_{tot}) increased by 14% for direct benefit, and by 29% and 38% for direct plus indirect benefits without and with additional nitrogen fertilisation, respectively (Fig. 8d). This corresponded to an increase in profit by more than 55% for direct frost benefit and by 115% and 150% for direct plus indirect economic benefits without and with additional nitrogen use, respectively (Fig. 8g).

Given the uncertainty in the air-temperature threshold for which wheat crops experience post-heading damage, national benefits are also presented for threshold temperatures of –1°C (FT_1 as a baseline; Fig. 8b, e, h) and –2°C (FT_2 as a baseline; Fig. 8c, f, i) for comparison with our reference threshold temperature of 0^{o}C (FT_0 as a baseline; Fig. 8a, d, g). As expected, smaller benefits were estimated for a baseline of FT_1 or FT_2 compared to FT_0, with national benefits of up to AUD 860 million per annum with FT_1 as a baseline, or up to AUD 420 million per annum with FT$_2$ as a baseline (Fig. 8; Tables 3 and S6). With FT$_1$ and FT$_2$ as the baselines, most of the economic benefits were indirect, and could be achieved by adopting earlier sowing practices (Fig. 8; Tables 3 and S6). Overall, the annual economic benefits from frost tolerance were substantial at any of the three damage threshold temperatures examined. Breeding for improved frost threshold temperature in wheat can thus be seen as a highly effective way to increase profit in Australian wheat production.

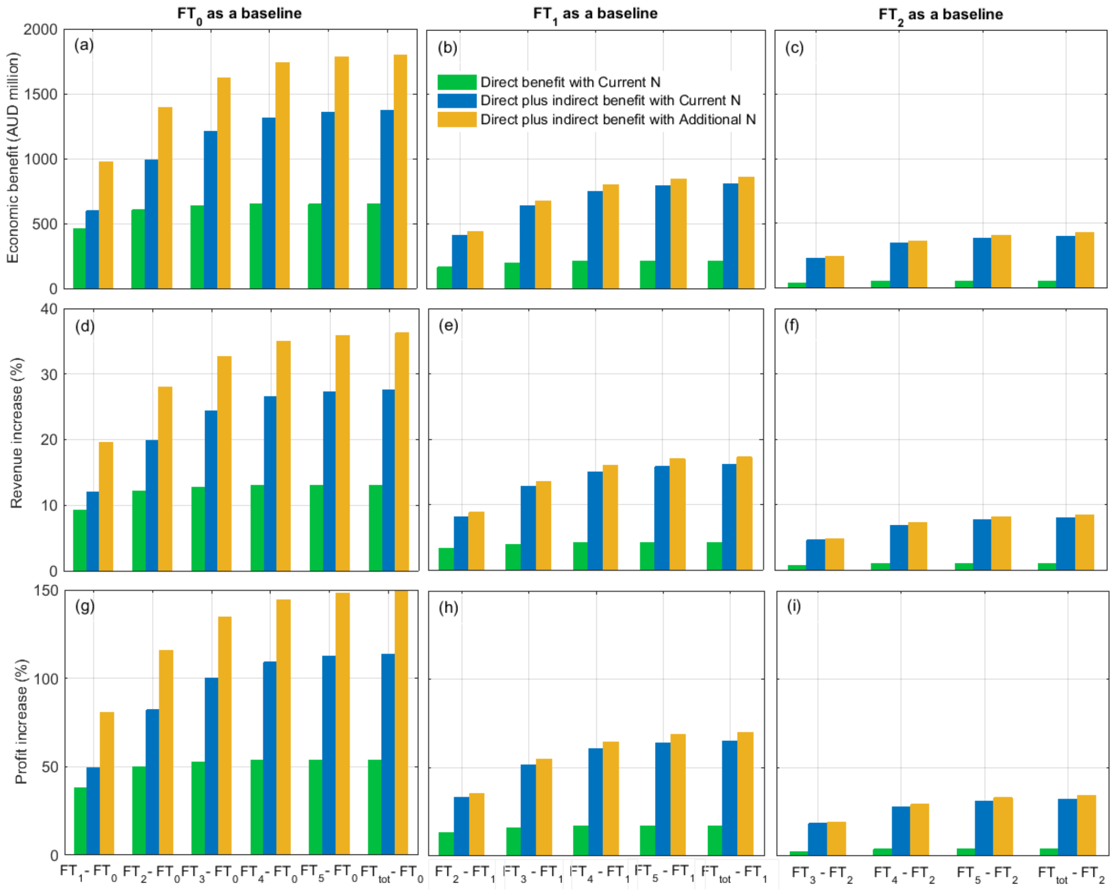

Fig. 8: National economic direct and indirect benefits of improved frost-tolerant virtual wheat genotypes (top row), the associated revenue increase (middle row), and profit increase (bottom row) without and with additional N fertiliser using FT$_0$ (left column), FT$_1$ (middle column), and FT$_2$ (right column) as baseline threshold temperatures, respectively. Direct benefits (green bars) were based on long-term simulations performed with long-term optimised sowing dates of current cultivars (baselines) at each location. Direct plus indirect benefits (i.e. net benefits) without additional N fertilizer (blue bars) were assesed for optimised sowing dates of each considered genotype. Direct plus indirect (net) benefits with additional fertilizer (orange bars) were estimated for optimised sowing dates and fertilisation levels for each genotype. Benefits were assessed by comparing the performances of genotypes with different levels of frost tolerance (FT$_{1\text{-tot}}$) to their respective local current cultivars (for FT$_0$, FT$_1$ and FT$_2$ baselines).

Table 2: Estimated current wheat yield, cropping area, fertiliser cost and economic values (wheat price, revenue and gross margin) for each studied agro-ecological zone. The values of annual revenue and gross margin were estimated by using 10-year historical average values of wheat price (yearly variations presented in Table S2), wheat cultivated area (yearly variations presented in Table S3), input costs excluding fertiliser cost (details per item in Table 1), yield (sources: Neil Clark Business Intelligence, ABS) and fertiliser cost (sources: Neil Clark Business Intelligence, ABARES) for each studied agro-ecological zone.

Agro-ecological zone	Cropping area (ha)	Yield (t ha^{-1})	Costs (without fertiliser) (AUD ha^{-1})	Fertiliser cost (AUD ha^{-1})	Wheat price (AUD t^{-1})	Revenue (AUDm yr^{-1})	Gross margin (AUDm yr^{-1})
QLD Central	155,350	1.6	284.6	85.8	246	62	4
NSW NE/QLD SE	1,157,741	1.9	216.4	65.5	238	522	196
NSW NW/QLD SW	877,887	1.3	202.8	61.6	237	279	47
NSW Vic Slopes	1,189,397	1.7	213.6	71.3	235	478	139
NSW Central	1,252,976	1.3	207.8	69.3	234	395	48
SA Vic Bordertown-Wimmera	610,529	1.9	182.0	63.9	245	279	129
SA Midnorth-Lower Yorke Eyre	798,613	2.1	223.6	68.5	253	419	185
SA Vic Mallee	1,955,152	1.2	180.1	57.0	249	582	118
WA Sandplain	346,687	2.0	241.8	110.6	263	182	59
WA Central	2,340,187	1.7	243.0	107.1	264	1065	246
WA Eastern	1,094,741	1.3	237.2	100.1	263	374	5
WA Northern	868,217	1.6	242.0	110.6	263	367	61
Total	**12,647,477**					**5,004**	**1,237**

Table 3: Total national economic benefits (AUD million) with FT_0, FT_1 and FT_2 as baseline threshold temperatures, respectively.

	Direct benefit with Current N	Direct plus indirect benefit with Current N	Direct plus indirect benefit with optimal Additional N
$FT_{tot} – FT_0$	699	1431	1894
$FT_{tot} – FT_1$	210	807	863
$FT_{tot} – FT_2$	47	399	423

Direct plus indirect economic benefits varied widely across the 12 studied agro-ecological zones (Fig. 9). With a current frost damage threshold temperature of 0°C (FT_0), the greatest benefits occurred in the WA Central zone, reaching annually up to AUD 280 million when considering ‘Current N’ practices, and AUD 470 million when considering long-term optimum fertiliser levels. Frost tolerance was also estimated to have the potential to return more than AUD 200 million annually of direct plus indirect benefits in NSW NE/QLD SE, WA Eastern and NSW NW/QLD SW. By contrast, small economic benefits were estimated in the northern and coastal regions of Western wheatbelt, in one agro-ecological zone in the South and in QLD Central (Fig. 9).

The impact of adapting nitrogen fertilisation for frost-tolerant genotypes were most significant in WA Central with AUD 190 million annual increase in benefit compared to the ‘Current N’ scenario (Fig. 9). Adding nitrogen also greatly benefited other agro-ecological zones, such as WA Eastern with AUD 100 million annual increase in benefit.

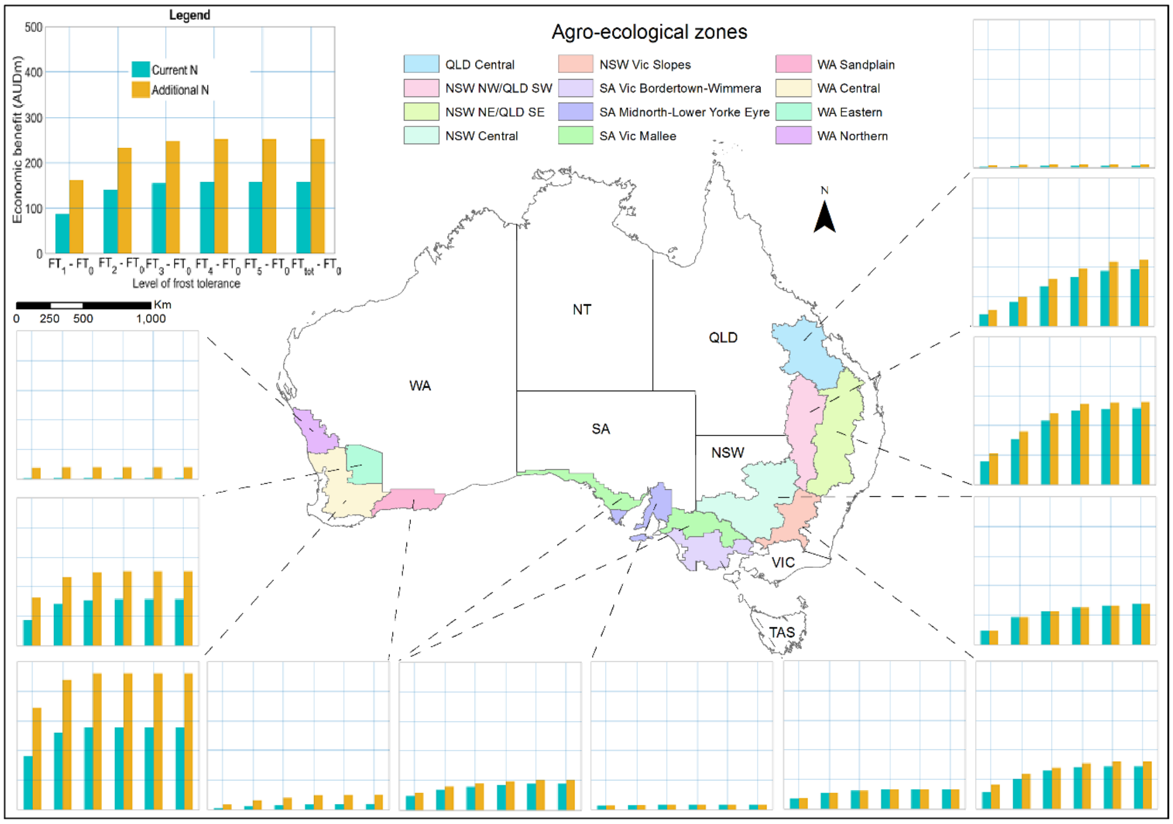

Fig. 9: Direct plus indirect economic benefits in the 12 studied agro-ecological zones. Direct plus indirect economic benefits without (blue) and with (orange) additional nitrogen effect are presented for virtual genotypes with improved frost threshold to –1°C (FT_1), –2°C (FT_2), –3°C (FT_3), –4°C (FT_4), –5°C (FT_5), or total frost tolerance (FT_{tot}). The legend in the top left corner gives the scale for all graphs and colours for columns with the example of data from the 'WA Eastern' agro-ecological zone.

4. Discussion

The present economic analysis provides quantitative estimations of economic impacts of post-head emergence frost damage in Australian wheat cropping systems. Estimates of the economic benefits of frost tolerant virtual genotypes with various levels of tolerance were used to estimate income forgone due to frost. Economic benefits were estimated at the crop, regional, agro-ecological, and national levels, either per hectare or in terms of total benefits in AUD. The analysis quantifies the yield and economic impacts using an optimal profit approach based on long-term optimum sowing date, and estimating the costs and benefits associated with new management practices facilitated by frost tolerant genotypes (earlier sowing dates and/or additional nitrogen fertilisation levels). In addition, the results from this study provided

(i) quantification of the average yield benefits, which could be more than 1 t ha^{-1} at some sites (Fig. S3) which is more than the maximum of 1 t ha^{-1} found when considering a narrower sowing window and no additional nitrogen (Fig. 6 in Zheng *et al*., 2015); and (ii) recommendations for long-term optimal sowing dates without (Table S1) and with (Table S4) additional fertilisation, and long-term optimal additional nitrogen levels (Table S5), should it become possible to introduce a source of frost tolerance into Australian wheat cultivars.

4.1 Impact of frost in the Australian economy

The wheat industry is a major contributor to Australian agricultural production. For instance in the reported year 2012-13, Australia produced almost 23 million tonnes of wheat (ABARE 2013), and more than 80% of this wheat was exported, earning the Australian industry more than AUD 6 billion. Occurrence of extreme climate events, such as frost events, can seriously affect Australian production (Fuller *et al*., 2007). For instance, a late frost (recorded –2ºC at Nhill and Longerenong) on 28 October 1998 impacted the Wimmera region (Victoria state), with yield losses estimated at 60% in wheat and an estimated cost of AUD 200 million across crops in the region (Vallance *et al*., 2009).

The economic analysis suggests that with optimal planting window and optimal nitrogen fertilisation, frost tolerance could benefit the Australian wheat industry by up to AUD 1890 million per annum (Fig. 8a). The estimated benefits could certainly be less when considering potential changes in the market prices due to high volumes of production, change in grain quality affecting wheat price, changes in the gross margin when considering higher harvesting costs (which were not included in the analysis), or changes in the temperature threshold under which current wheat cultivars experience post-heading frost damage (Fig. 8b and c). Our results are, however, comparable with those for other stresses affecting the Australian wheat industry such as heat shocks, estimated to cost AUD 1100 million (source: Agtrans, 2015), the Karnal bunt disease estimated costing AUD 491 million (in 1998 prices; Murray and Brenan, 1998); or cold tolerance affecting rice, which cost an estimated AUD 23 million to the Australian rice industry in 2005 (Singh *et al*., 2005). Note that the cropping area of wheat is about 100 times as much as that of rice in Australia, and that a new cold-tolerant rice variety with 3ºC lower damage threshold was estimated to lead to AUD 142 ha^{-1} in productivity gains (Singh *et al*., 2005). In wheat, the current study estimated at AUD 101 and 134 ha^{-1} the gains from a totally frost-tolerant wheat genotype, which included gains due to early sowing, without and with additional nitrogen, respectively. Thus, estimated gains for improved frost tolerance in wheat were of a similar order of magnitude to those for other major stresses affecting wheat and to those for improved cold tolerance in rice.

4.2 Assumptions related to the simulations

The current study provides an estimate of the extent and economic impact of frosts for wheat in Australia. That said, there are inherent assumptions and some difficulties in estimating certain parameters for any such analysis, which should be considered when interpreting the results. These include challenges in quantifying both the occurrence and the physiological impacts of frost. For example, due to high variation in radiant frosts with local topography, it is difficult to estimate post-heading frost damage at the shire level using data from a small number of sites (Dixit and Chen, 2010, 2011). Frost impacts on crop physiology, including the damage threshold temperature have been based on expert opinion but their incorporation in a crop model has been done without any direct field testing, partly due to difficulty of obtaining frosted-trial data (Zheng *et al.*, 2015; Bell *et al.*, 2015; Barlow *et al.*, 2015). Crop simulations here used historical weather data with minimum temperatures recorded in Stevenson screens and not directly on actual plant temperatures (Frederiks *et al*., 2011) as such data are not available at a national scale. As a result, the baseline temperature of 0^{o}C used in this study may be conservative and may overestimate the occurrence and yield impact of damaging frosts in certain conditions. Nevertheless, the data are presented for a range of frost intensities, making it is possible to interpret the results related to lower baseline temperatures (e.g. FT_1 or FT_2), as done for the national analysis (Fig. 8, Tables 3 and S6).

Economic benefits were based on simulations related to long-term optimum sowing dates (for both current and virtual frost-tolerant genotypes) and/or adjusted fertilizer applications, meaning that the study didn’t account for the range of practices applied within and among farms in a region, in particular in terms of the actual management practices or cultivars used within each region. The simulations performed here did not estimate any losses due to biotic stresses (pests and diseases), nor other extreme events such as heat-stress or storm damage. Furthermore, the yield increase allowed by frost-tolerant crops is expected to change wheat quality, and thus likely wheat prices. No change in price was simulated here, even though wheat price varies widely from season to season (e.g. variation between AUD 198 t^{-1} and AUD 370 t^{-1} over 2002-2012 for QLD Central; Table S2). An increase in yield facilitated by improved frost tolerance could also have an impact on the wheat price globally, given that

Australia is the 4th largest wheat exporter and that other major producers would also benefit from such improvement.

4.3 The potential value of breeding for frost tolerance

To consider the benefits from breeding for different levels of frost tolerance, this study reported results for virtual cultivars with a range of frost-tolerance levels. The benefits of frost tolerance varied greatly across regions. In the West, most of the simulated yield and economic benefits were achieved by reducing the damage threshold temperature of virtual genotypes from 0°C to –1°C in particular in association with optimal additional fertiliser management, without the need to adapt sowing dates (Fig. 5d, 6 and 7e). In the East, substantial yield and economic increases were simulated for improving frost tolerance from 0°C to –1°C, but further significant benefits were achieved from –1°C to –2°C, –2°C to –3°C, and –3°C to –4°C (Fig. 5a and 7b). Importantly, improved genetic frost tolerance allowed earlier sowing and resulted in remarkable yield and economic gain in the East. It is worthwhile to note that the current study may overestimate the benefits, particularly for temperatures close to zero which is particularly important when interpreting the results for the West where a large effect was predicted for a change in the damage threshold from 0°C to –1°C.

5. Conclusions

In this study, more than 85 million simulations from the crop model APSIM-Wheat were integrated with economic modelling to quantify the economic impact of frost (or economic benefits of improved frost tolerance) for Australian wheat production. Assessments were performed for long-term optimum sowing dates, without and/or with additional nitrogen fertiliser to identify potential benefits associated with earlier sowing and/or new nitrogen management practices.

Regionally, the effect of improved frost tolerance and associated changes in management practices varied. In the West, the improved frost tolerance directly enhanced profits, especially when combined with additional fertiliser. In the East, profits were also remarkably increased, including when sowing crops earlier.

Nationally, the improvement of frost tolerance by 2°C allowed most of the frost tolerance (‘total insensitivity’) to be achieved, and resulted in an estimated increase by 50%, 80% and 115% of the current national profits, owing to the direct benefit, direct plus indirect benefit with ‘Current N’, and direct plus indirect benefit with ‘Additional N’, respectively. Overall, frost tolerance was estimated to potentially increase the national economic benefits by AUD 700, 1430, and 1890 million per annum when considering total frost tolerance for direct benefit, and direct plus indirect benefit without and with adjusted fertilisation level, respectively. Given the uncertainty in the threshold temperature (measured in a Stevenson screen) under which current wheat crops are affected by post-heading frost, economics estimates for the reference threshold of 0°C were also performed for threshold of –1°C and –2°C. This resulted in national benefits estimated at up to AUD 860 and 420 million per annum, for baseline thresholds of –1°C and –2°C, respectively. In other words, improving frost tolerance could result in a substantial increase in national income if complete frost tolerance could be developed in wheat.

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Supporting Information

Table S1. Optimal sowing times with current fertilisation practices (‘Current N’) at 59 locations chosen to represent the Australian wheatbelt.

Table S2. Historical values of wheat price (AUD t^{-1}) analysed and provided by Neil Clark Business Intelligence (from ABS data sources).

Table S3. Historical wheat cropping areas in hectares analysed and provided by Neil Clark Business Intelligence (from ABS data sources).

Table S4. Optimal sowing times with additional nitrogen application (‘Additional N’) at 59 locations chosen to represent the Australian wheatbelt.

Table S5. Optimal additional nitrogen levels that could be applied at 59 locations chosen to represent the Australian wheatbelt.

Table S6. Detail analysis of national economic benefits (AUD millions) with $FT_{0,}$ $FT_{1,}$ and FT_2 as baselines, respectively.

Fig. S1. Yields at optimal sowing times for current cultivars (FT_0) and virtual genotypes with improved frost tolerance in the four regions with ‘Current N’.

Fig. S2. Yield benefits of virtual genotypes with improved frost tolerance in the four regions and with ‘Current N’.

Fig. S3. Simulated mean yield advantage with ‘Current N’ when (i) increasing the frost tolerance to -1°C (i.e. FT_1-FT_0; (a,b)); (ii) considering the additional yield gain achieved with total frost tolerance (i.e. FT_{tot}-FT_1; (c,d)); and (iii) looking at the total yield advantage between total tolerance and the current level (FT_{tot}-FT_0; (e,f)).