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Economic assessment of wheat breeding options for potential improved levels of post head-emergence frost tolerance

Shahbaz Mushtaq[a], Duc-Anh An-Vo[a,b,*], Mandy Christopher[c], Bangyou Zheng[d], Karine Chenu[e], Scott C. Chapman[d], Jack T. Christopher[f], Roger C. Stone[a], Troy M. Frederiks[c], G.M. Monirul Alam[a,g]

[a] University of Southern Queensland, International Centre for Applied Climate Sciences, Toowoomba, QLD 4350, Australia
[b] University of Southern Queensland, Computational Engineering and Science Research Centre, Toowoomba, QLD 4350, Australia
[c] Department of Agriculture and Fisheries Queensland, Leslie Research Facility, Toowoomba, QLD 4350, Australia
[d] CSIRO Agriculture Flagship, Queensland Bioscience Precinct,306 Carmody Road, St. Lucia, QLD 4067, Australia
[e] The University of Queensland, Queensland Alliance for Agriculture and Food Innovation (QAAFI), 203 Tor St, Toowoomba, QLD 4350, Australia
[f] The University of Queensland, Queensland Alliance for Agriculture and Food Innovation (QAAFI), Queensland Government Leslie Research Facility, Toowoomba, QLD 4350, Australia
[g] Bangabandhu Sheikh Mujibur Rahman Agricultural University, Bangladesh

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ABSTRACT

Frost, during reproductive developmental stages, especially post head emergence frost (PHEF), can result in catastrophic yield loss for wheat producers. Breeding for improved PHEF tolerance may allow greater yield to be achieved, by (i) reducing direct frost damage and (ii) facilitating earlier crop sowing to reduce the risk of late-season drought and/or heat stress. This paper provides an economic feasibility analysis of breeding options for PHEF tolerant wheat varieties. It compares the economic benefit to growers with the cost of a wheat breeding program aimed at developing PHEF tolerant varieties. The APSIM wheat model, with a frost-impact and a phenology gene-based module, was employed to simulate direct and indirect yield benefits for various levels of improved frost tolerance. The economic model considers optimal profit, based on sowing date and nitrogen use, rather than achieving maximum yield. The total estimated fixed cost of breeding program was AUD 1293 million, including large scale seed production to meet seed demand, with AUD 1.2 million year^{-1} to run breeding program after advanced development and large scale field experiments. The results reveal that PHEF tolerant varieties would lead to a significant increase in economic benefits through reduction in direct damage and an increase in yield through early sowing. The economic benefits to growers of up to AUD 4841 million could be realised from growing PHEF tolerant lines if useful genetic variation can be found. Sensitivity analyses indicated that the benefits are particularly sensitive to increases in fixed costs, seed replacement, discount rate, and to delays in variety release. However, the investment still remains viable for most tested scenarios. Based on comparative economic benefits, if breeders were able to develop PHEF tolerant varieties that could withstand cold temperatures $-4\,^{\circ}$C below the current damage threshold, there is very little further economic value of breeding total frost tolerant varieties.

1. Background

In Australia, spring wheat is typically planted in autumn and harvested in early summer. Significant vegetative frost damage is sporadic in the Australian wheat belt (Frederiks et al., 2004; 2012; Zheng et al., 2015). The risk of crop damage from post head-emergence frost (PHEF) is high in many areas. In these areas, planting is delayed to avoid flowering during the mid-winter peak frost-risk period. PHEF losses in wheat can be catastrophic, with a single frost event having the potential to destroy individual crops by damaging stems and killing whole heads (Frederiks et al., 2012; Zheng et al., 2015). Although wheat yield losses due to frost are irregular, individual growers can suffer heavy losses in some years. Regional PHEF yield losses commonly occur 10% of the time (Frederiks et al., 2004, 2012; Zheng et al., 2015), but financial losses in excess of 85% have also been observed in certain seasons in particular areas of the USA and Australia (Paulsen and Heyne, 1983;

* Corresponding author at: University of Southern Queensland, International Centre for Applied Climate Sciences & Computational Engineering and Science Research Centre, Toowoomba, QLD 4350, Australia.
E-mail address: duc-anh.an-vo@usq.edu.au (D.-A. An-Vo).

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Boer et al., 1993). Therefore in frost prone regions, management of crop flowering date by selecting variety phenology for particular sowing opportunities is necessary to maintain an acceptable frost risk (Frederiks et al., 2004).

In PHEF-prone regions, wheat producers manage frost risk by adopting a conservative sowing time and variety choice. However, while sowing time can be adjusted to reduce the risk of post-heading frosts, all current elite wheat cultivars are sensitive to post-heading frosts. Thus, frost risk management places significant constraints on sowing time flexibility and variety choice (Zheng et al., 2015). In PHEF-prone areas, delayed sowing to manage frost risk often reduces yield potential by exposing crops to increased risks of drought and heat stress late in the crop development cycle (Zheng et al., 2012; Chenu et al., 2013). Breeding for improved PHEF tolerance would allow greater yield to be achieved, as (i) direct frost damage could be reduced and (ii) crops could be sown earlier to reduce the risk of late-season drought and heat stresses. Substantial increases in yield, in the order of 30–50%, has been observed in Australian PHEF-prone regions in seasons when early flowering cereal crops escaped frost damage (Frederiks et al., 2011).

Crop simulation modelling combined with climate analysis indicates that PHEF tolerant varieties would reduce direct frost damage, and would increase yield by allowing early sowing (Zheng et al., 2015). It is useful to evaluate the investment opportunities for various levels of PHEF tolerance. In this study we estimate the economic benefits to growers of reducing PHEF losses if varieties with various levels of improved frost tolerance could be developed using conventional breeding methods. The aim is to examine whether the cost of developing PHEF tolerant wheat varieties could be justified by national economic benefit to growers.

Using a combination of crop simulation modelling and climate analysis, predicted economic losses due to frost damage were compared between current cultivars and hypothetical frost tolerant varieties with tolerance to a range of damage threshold temperatures from −1 °C to −5 °C below those of current cultivars. A hypothetical variety with tolerance to unlimited cold temperatures was also examined. Benefits to the wheat industry are specified as a function of the size of the crop production improvement that can be achieved with improved PHEF tolerance. The economic benefits of a PHEF tolerant breeding program were measured by the aggregated improvement in farm gate returns to growers at the national level from tolerant wheat varieties compared with returns that would have been achieved growing non-PHEF tolerant varieties. Costs are estimated as a sum of both fixed and variable costs involved in the development and operation of breeding programs addressing PHEF tolerance. This information can be used to evaluate whether targeting PHEF tolerance is economically desirable within the Australian cropping context.

2. Methodology

2.1. Cost benefit analysis: an economic model

Economic evaluation of improved PHEF tolerance requires a comparison of the cost of developing and commercialising PHEF tolerant wheat varieties and the potential benefits. As costs and benefits accrue at different points in time, the evaluation is based on comparing the Net Present Value (NPV), which is the present value of the sum of all future benefits and costs associated with PHEF-tolerant variety development after discounting at the chosen discount rate (e.g. usually 5% interest rates). A positive NPV results in profit, while a negative NPV results in a loss (Mushtaq et al., 2007).

The analytical framework enables estimation of the threshold size of crop benefits at which breeding programs producing different levels of PHEF tolerance could be economically justified, including both direct and indirect benefits. It also allows estimation of the threshold rate of yield improvement needed to justify a given amount of breeding expenditure.

Generally, crop variety development programs, consist of a six stage process – discovery, proof of concept, early development, advanced development, pre-launch and market launch (Kalaitzandonakes et al., 2006; Langridge and Gilbert, 2008; Monsanto, 2009). We have modified the Monsanto model (see Monsanto, 2009 for detail) for this economic evaluation. We adopted a four phase approach to the cost-benefit analysis for wheat development by merging the proof of concept and early development phases of the Monsanto scheme into step 1 of the current analysis and the pre-development and large scale seed production phases of the Monsanto scheme into step 4. Thus, the key steps in our analysis are:

1. Discovery (identifying traits or genes);
2. Early development (crossing and testing for frost tolerance expression);
3. Advanced development (field plot trials to test yield potential of adapted material, testing for disease resistance and quality); and
4. Large scale seed production to meet PHEF tolerance seed demand and commercial release.

Mathematically, the Net Present Value (NPV) was calculated as:

$$\mathrm{NPV} = \sum_{t=m+n+1}^{m+n+f} \frac{V_t}{(1+i)^t} - \left[\sum_{t=0}^{n} \frac{C_{s(1-3)t}}{(1+i)^t} + \sum_{t=n+1}^{m+n} \frac{C_{s(4)t}}{(1+i)^t} \right] \quad (1)$$

Where,

$C_{s(1-3)t}$ is the fixed and variable costs of PHEF tolerance breeding options in year 't' for the first three phases;

$C_{s(4)t}$ is the cost of release procedure, pre-launch and market launch, of PHEF tolerance variety in year 't', for last phase;

V_t is the value of economic benefit of adopting PHEF tolerance variety in year 't';

n is the number of years needed for completing the PHEF tolerance breeding program (6 years);

m is the number of years needed for the completion of the release process of PHEF wheat variety (4 years);

f is the useful life of the PHEF variety which is likely to be up to 20 years, and

i is the discount rate (5% unless otherwise specified)

Similarly, the Internal Rate of Return (IRR) was calculated as:

$$\sum_{t=m+n+1}^{m+n+f} \frac{V_t}{(1+\mathrm{IRR})^t} - \left[\sum_{t=0}^{n} \frac{C_{s(1-3)t}}{(1+\mathrm{IRR})^t} + \sum_{t=n+1}^{m+n} \frac{C_{s(4)t}}{(1+\mathrm{IRR})^t} \right] = 0 \quad (2)$$

The IRR is acceptable if it is greater than the minimum expected interest rate (which equals the discount rate)

Also, Benefit Cost Ratio (BCR) was calculated as:

$$\mathrm{BCR} = \frac{\sum_{t=m+n+1}^{m+n+f} \frac{V_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{C_{s(1-3)t}}{(1+i)^t} + \sum_{t=n+1}^{m+n} \frac{C_{s(4)t}}{(1+i)^t}} \quad (3)$$

2.2. Estimation of benefits

Benefits of PHEF tolerant varieties are yield and economic benefits (or impacts) owing to increased frost tolerance by changes in either (i) the frost-damage threshold temperature of the wheat genotype alone (direct impact) or (ii) both the frost-damage threshold temperature and the management strategies such as earlier sowing (direct plus indirect impact). The direct and direct plus indirect yield impacts were estimated for Australian wheat belt by Zheng et al. (2015) using an optimal yield approach. While the yield benefits by optimal yield approach can provide a good indicator of frost impacts, they are not necessarily corresponding to yield benefits by optimal profit approach. In the