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

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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 1,293 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 4,841 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°C below the current damage threshold, there is very little further economic value of breeding total frost tolerant varieties.

Keywords: Economic assessment, Benefit Cost Analysis, Frost, Crop modelling, Wheat, APSIM Australia

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; 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^{o}C to –5^{o}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:

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

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:

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

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:

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

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 present work, we employed an optimal profit approach typically required by farmers which allows estimation of not only the yield benefits but also the ultimate economic benefits.

2.2.1 Crop modelling for improved yield benefit assessment

Wheat yield and Zadoks decimal phenological stages (Zadoks et al., 1974) were simulated using the APSIM 7.6 model (Holzworth et al., 2014) with a wheat phenology gene-based module (Zheng et al., 2013) and a frost impact module (Zheng et al., 2015). A brief summary of crop simulation procedures is presented here while details are given in Zheng at al. (2015); An-Vo et al. (2016, submitted).

For crop simulation, current elite Australian wheat varieties were considered to be affected by post-heading Stevenson screen temperature below a 0°C threshold (Zheng et al., 2015). To estimate the potential benefit of genotypes with improved tolerance, wheat crop simulations were conducted for the current (0°C, FT_0) and a range of damage threshold temperatures from –1°C to –5°C (FT_1 to FT_5) representing wheat genotypes with different levels of improved PHEF tolerance. Total frost tolerance (FT_{tot}) was also simulated, representing a virtual genotype that is insensitive to frosts of any temperature. For this study, crop simulations were conducted at 1 day intervals, commencing within a fixed sowing window based on current recommendations from 1 April to 30 June for 59 selected sites (Table S1) across the wheat belt representing 12 agro-ecological zones (Figure 1).

Baseline nitrogen fertiliser application values used in the simulations varied with location and seasonal rainfall to reflect local farming practices (Table 1 of 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 fertiliser ranging from +20 to +140 kg ha^{-1}, with 20 kg ha^{-1} intervals, for the current and virtual frost-tolerant genotypes.

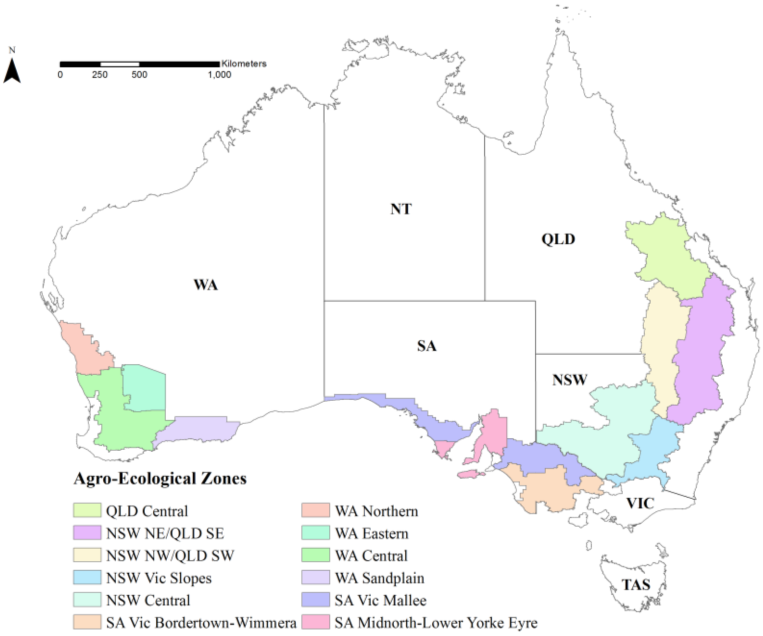

Figure 1. Most of the Australian cereals cropping area was represented by the 12 major agro-ecological cropping zones in this study.

2.2.2 Conceptualisation of direct and indirect economic benefits

The conceptual framework considers economic benefits 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 and additional nitrogen fertilizer (direct plus indirect impact). Figure 2 shows the conceptual framework for assessing the direct and indirect economic benefits of improved frost tolerance. It is anticipated that improved PHEF tolerant varieties would allow greater economic benefits to be achieved by growers via reducing direct frost damage and allowing flexibility to plant earlier (and possibly adding more nitrogen).

Gross margin analysis was employed to estimate the economic benefits of PHEF frost threshold resilience improvements. A gross margin distribution curve for PHEF tolerant varieties can be shown for FT_1 and FT_{tot}, where FT_{tot} is totally frost tolerant and FT_1 is frost tolerant to –1°C (Figure 2). Point ‘a_0’ in the current FT_0 gross margin distribution shows the optimal gross margin that can be obtained by sowing at the optimal sowing time and using an optimal nitrogen level, taking into account frost risk. The gross margin would be increased with improved PHEF tolerant varieties (for example FT_{tot} in Figure 2) without changing management by retaining the sowing time used for baseline FT_0 as indicated by point ‘a_{tot}’ shows. The gross margin difference between point ‘a_0’ and point ‘a_{tot}’ is the direct economic benefit owing to total frost tolerance (FT_{tot}). It is noted that the optimal nitrogen level for the FT_{tot} might be different from that for the FT_0 (Figure 2) and hence there would be nitrogen effects in the direct economic benefit by the present estimation. However, this nitrogen effects were shown to be small (An-Vo et al., 2016 submitted) and can be ignored.

With changes in management by varying the optimal sowing time and nitrogen level, the additional indirect economic benefits can be calculated by the gross margin difference between point ‘b_{tot}’ and point ‘a_{tot}’. The total economic benefit can be calculated by the difference between point ‘a_0’ and point ‘b_{tot}’.

In the present analyses, the ‘baseline’ economic return refers to the economic return of current varieties (FT_0), when sown at the optimum sowing date and using the optimal nitrogen application rates unless otherwise stated.

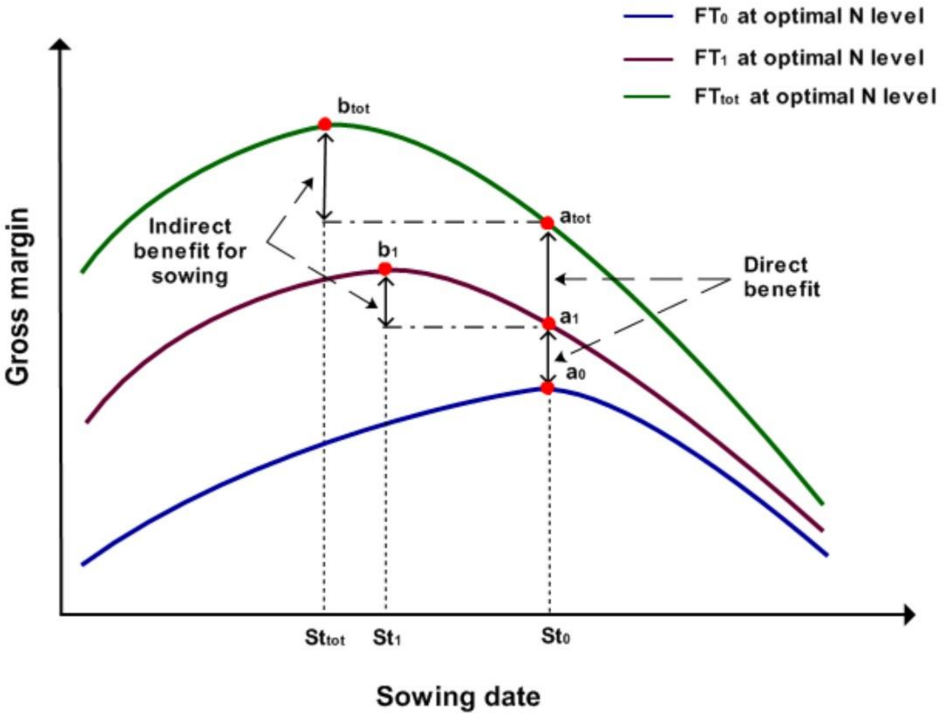

Figure 2. Conceptual framework for assessing the direct benefit and indirect benefit on profit improvement. Gross margin responses to sowing date (gross margin function) at optimised nitrogen application level are depicted for current cultivars (FT_0), an improved frost tolerant genotype (FT_1) and fully tolerant genotype (FT_{tot}). Direct economic benefit corresponds to the gross margin difference for the current management practices used for FT_0 are represented by $a_1 – a_0$ or $a_{tot} – a_0$, where a_0, a_1 and a_{tot} represent the long-term-average gross margin that can be obtained for genotypes FT_0, FT_1, and FT_{tot}, respectively, at the optimum sowing date for the reference genotype FT_0. Indirect economic benefit related to earlier sowing date corresponds to the estimated profit gain achieved when adapting an earlier sowing date optimised for each of the considered genotypes with improved tolerance. These are represented by $b_1 – a_1$ or $b_{tot} – a_{tot}$, where b_1 and b_{tot} represent the maximum long-term-average profit that can be obtained at optimal sowing time for genotypes FT_1 and FT_{tot}, respectively (adapted from An-Vo et al., 2016 submitted).

2.2.3 Economic assessment of direct and indirect yield benefits: An optimal profit approach

A key component of the analysis was the integration of APSIM simulations with a gross margin function to achieve an optimal profit, based on sowing dates, additional nitrogen application and yield performance. The present approach, which allows estimation of direct and indirect economic benefits associated with the direct and indirect yield benefits, is considered more useful for farmers than a maximum yield approach, presented by Zheng et al. (2015), which may not necessarily lead yield to maximum income for the farmer.

For each location x sowing date combination (sowing simulated at a 1d intervals), an average yield was calculated for the 1957-2013 period – a total of 85 million simulations were performed. 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 (Figure 2) and to identify the optimal sowing day corresponding to the maximum gross margin (profit) for current local cultivars (threshold of 0^{o}C) and for frost tolerant virtual genotypes (threshold below 0^{o}C).

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

$$GM(st,N,FT) = f\left[P,Y\left(st,N,FT\right)\right] - X - X(st,N) \quad (4)$$

Where st is sowing time from 1 April to 30 June; N is nitrogen additional to the current application for the current cultivar (FT_0) from 0 to 140 (kg ha^{-1}) in 20 kg ha^{-1} increments;

FT is frost tolerance level from FT_0 to $\mathrm{FT}_{\mathrm{tot}}$; f is the revenue function; P is wheat price (AUD t^{-1}); Y is the wheat mean yield function obtained from the APSIM simulation (t ha^{-1}). The yield function of sowing time here is similar in concept to the production function (yield function of water use) as described in An-Vo et al. (2015a and 2015b); X is a sum of average input costs (without additional nitrogen cost), including costs associated with seed, fertiliser, crop protection, repair and maintenance (R & M), fuel, machinery, insurance and other costs and varying with agro-ecological zones (Table 1 of An-Vo et al., 2016 submitted); and $X(st, N)$ is the input cost as a function of long-term mean additional nitrogen applications and the sowing time.

For each level of frost tolerance ($\mathrm{FT}_{1\text{–}5}$ and $\mathrm{FT}_{\mathrm{tot}}$), two types of impact (benefit) were estimated (Figure 2): (i) a direct impact reflecting the direct frost damage with no change in management; and (ii) a direct plus indirect impact reflecting both the direct frost damage and the indirect effects from adaptation of sowing date. The Direct Benefits (DB) at site level in AUD ha^{-1}, for example between $\mathrm{FT}_{\mathrm{tot}}$ and FT_0, can be obtained by:

$$\mathrm{DB}_s\left(\mathrm{FT}_{\mathrm{tot}}\right) = \max\left\{\mathrm{GM}\left(st_0, N, \mathrm{FT}_{\mathrm{tot}}\right)\right\} - \max\left\{\mathrm{GM}\left(st, N, \mathrm{FT}_0\right)\right\} \tag{5}$$

where st_0 (Figure 2) is the optimal sowing time for a reference cultivar with the current frost tolerance level (FT_0) and an optimised additional N level, i.e. the sowing time is such that:

$$\mathrm{GM}\left(st_0, N, \mathrm{FT}_0\right) = \max\left\{\mathrm{GM}\left(st, N, \mathrm{FT}_0\right)\right\} \tag{6}$$

The optimisation strategy in (6) was implemented in two steps. For each site x genotype combination, we firstly identified an optimal level of nitrogen application for which the corresponding long-term mean gross margin function then was optimised to identify the optimal sowing time (Figure 2).

Similarly, the Indirect Benefits (IB) at site level in AUD ha^{-1}, for example between FT_{tot} and FT_0, can be obtained by:

$$\mathrm{IB}_s(\mathrm{FT}_{\mathrm{tot}}) = \max\left\{\mathrm{GM}\left(st, N, \mathrm{FT}_{\mathrm{tot}}\right)\right\} - \max\left\{\mathrm{GM}(st_0, N, \mathrm{FT}_{\mathrm{tot}})\right\} \quad (7)$$

Net Benefits (NB) at site level in AUD ha^{-1} is a simple aggregation of direct plus indirect benefits:

$$\mathrm{NB}_s\left(\mathrm{FT}_{\mathrm{tot}}\right) = \mathrm{DB}_s\left(\mathrm{FT}_{\mathrm{tot}}\right) + \mathrm{IB}_s\left(\mathrm{FT}_{\mathrm{tot}}\right) \quad (8)$$

At an agro-ecological zone level, we can estimate the corresponding Direct Benefits (DB_z), Indirect Benefits (IB_z) and Net Benefits (NB_z) in AUD ha^{-1} by

$$\mathrm{DB}_z = \frac{1}{n}\sum_{s=1}^{n} \mathrm{DB}_s\left(\mathrm{FT}_{\mathrm{tot}}\right) \quad (9)$$

$$\mathrm{IB}_z = \frac{1}{n}\sum_{s=1}^{n} \mathrm{IB}_s\left(\mathrm{FT}_{\mathrm{tot}}\right) \quad (10)$$

$$\mathrm{NB}_z = \frac{1}{n}\sum_{s=1}^{n} \mathrm{NB}_s\left(\mathrm{FT}_{\mathrm{tot}}\right) \tag{11}$$

Where n is the number of sites in an agro-ecological zone. Finally, Total Net Benefits (TBN) at an agro-ecological zone in AUD is calculated by:

$$\mathrm{TNB}_z\left(\mathrm{FT}_{\mathrm{tot}}\right) = \mathrm{NB}_z \times S_z \tag{12}$$

where S_z is the historical average area of wheat crop from the zone (Table 2 of An-Vo et al., 2016 submitted).

For each frost tolerance level ($\mathrm{FT}_{1\text{-tot}}$), the DB_s, IB_s, and NB_s for each site and the DB_z, IB_z, NB_z, and TNB_z for each agro-ecological zone were estimated using the same steps as those described for $\mathrm{FT}_{\mathrm{tot}}$ above and in equations (5), (7-8), and (9-12), respectively. The summation of TNB_z at all 12 studied agro-ecological zones provided the total net benefit at national level.

2.3 Estimation of potential improved post-head-emergence frost (PHEF) tolerance wheat seed demand

Most farmers grow and store a proportion of their own seed for use in the following year (Heffer, 2001), but also purchase new good quality seed of existing or new varieties, with improved traits for their conditions. Farmers have a wide choice of wheat varieties, depending on the climatic conditions and a range of marketing options (DEPI Victoria, 2012). Grain growers are generally a risk-averse group (Bond and Wonder, 1980; Ghadim and Pannell, 2003); therefore it is likely that if improved frost tolerance could be achieved with little or no yield, disease or quality penalty, then the PHEF tolerance trait would offer an attractive choice for growers in frost prone regions when deciding on the adoption of a new variety.

The demand for seed of a new wheat variety is difficult to estimate and depends on the adoption rate, which in turn is influenced by several technical, institutional, economical and sociological factors (FAO, 2002). To estimate the likely PHEF tolerant wheat seed demand across all Agro Ecological Zones (AEZs) of the Australian wheat belt, three key elements were considered (likely adoption rates, seeding rates and historical wheat area), assuming no change in the technical, institutional, economical and sociological factors.

- The Australian wheat belt was divided into low (5% of regional seed demand), medium (M, 30% of regional seed demand) and high (H, 60% of the regional seed demand) seed demand zones based on the potential frost damage and expected benefits from adopting frost resistant varieties (see Zhang et al., 2015; An-Vo et al., 2016 submitted). Based on these criteria and local knowledge, a potential PHEF tolerant wheat seed demand was estimated by an expert for each of the AEZs. Based on these criteria 5%, 30% and 60% seed demand rates were assigned to low, medium and high frost damage impact AEZs (Figure 3).

- Different seeding rates are advised for different regions in Australia to allow for different environmental conditions. For example, seeding rates of about 40-60 kg ha^{-1} are suggested in lower rainfall zones (up to 400mm annual rainfall) and about 80-90 kg ha^{-1} in the higher rainfall zones (DEPI Victoria, 2012; DPI NSW, 2015; GRDC

2015). To estimate the overall PHEF tolerance seed demand, based on local recommendations, an average of 60 kg ha^{-1} is considered for this study.

- An average of 35 years of historical data for wheat planted area, obtained from Australian Bureau of Statistics (ABS) across all AEZs, was used for potential wheat area estimates (see Figure 3).

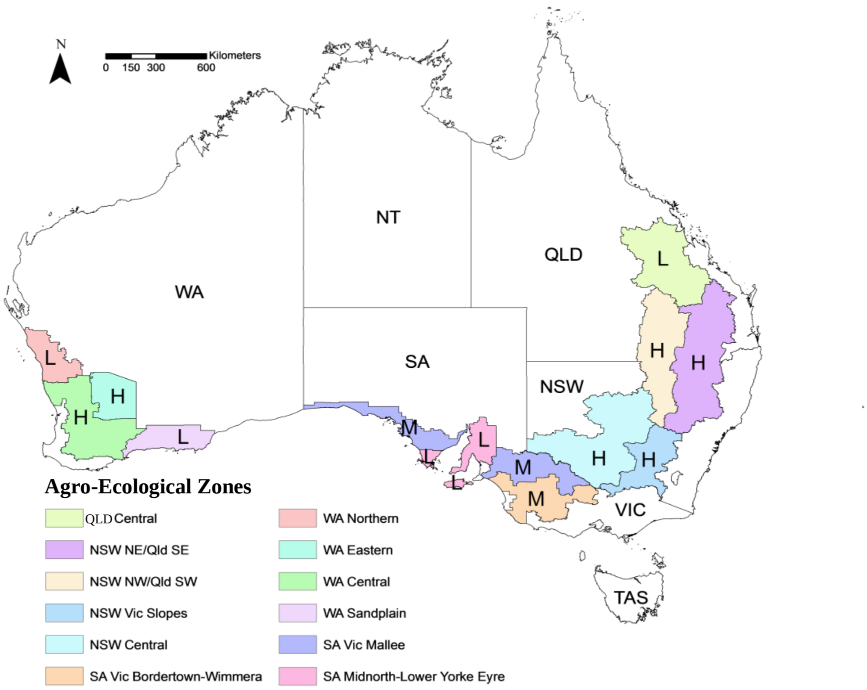

Figure 3. Most of the Australian cereals cropping area was represented by the 12 major agro-ecological cropping zones in this study. Estimated regional potential for PHEF tolerance wheat seed demand, based on the potential frost damage and expected benefits from adopting frost resistant varieties, is indicated as zones of: low PHEF seed demand (L, 5% of regional seed demand), medium PHEF seed demand (M, 30% of regional seed demand) zones and high PHEF seed demand (H, 60% of regional seed demand). The Australian Northern Grains Region includes QLD Central, NSW North West (NW) – QLD South West (SW) and NSW North East (NE) – QLD South East (SE). The Southern Region includes NSW Central, NSW

Vic Slopes, SA Midnorth-Lower Yorke Eyre, SA Vic Bordertown – Wimmera and SA Vic Mallee. The Western Region includes WA Northern, WA Eastern, WA Central and WA Sandplain.

2.4 Estimation of cost: Assumptions and parameters

The major costs of PHEF tolerance breeding options, during the four stages (see section 2.1), depend on factors such as (i) capital costs including laboratory facilities, salaries for breeders, scientists and support staff, operational costs, small scale glasshouses and pot test facilities for early development, and large scale field testing; and (ii) meeting registration requirements, including IP, pre-launch and market launch, and commercial seed production to meet expected demand for PHEF tolerant wheat seed. For all four stages of the tested PHEF tolerance breeding program, both fixed and variable costs were considered. Due to difficulties in obtaining robust data on costs, the estimates of costs were mainly obtained through market rates, where possible, published literature and discussions with experts in the area of wheat breeding (see appendix Table S2 in supplementary material). The following assumptions were considered when deriving cost estimates:

- Cost estimates assume no changes in the cost of labour used in PHEF tolerance breeding over the period of the analysis.

- Advanced large scale field trails for yield testing of PHEF tolerant varieties and commercial seed production was assumed to be managed by contractors at a fixed price (AUD 1,000 ha^{-1} yr^{-1}) (estimate based on pers comm with the field trial experts at Kalyx; https://www.kalyx.com.au/).

2.5 Other key assumptions

Other key assumptions for the economic analysis include:

- The relevant price for estimating benefits is the average farm gate price during last 10 years over all AEZs, adjusted for CPI (AUD 230 t^{-1}). Moreover, we assumed that changes in wheat production from new PHEF varieties are sufficiently small that they will not cause a fall in the world wheat price. Prices may in fact rise or fall but we assumed that this will not be due to the development of PHEF tolerant wheat.

- Following Brennan and Bialowas (2001), who found that varieties are grown for approximately 17 years after release, our analysis assumes PHEF variety market life of 20 years except where otherwise stated. For comparison, analysis was also performed to determine the economic benefit for varieties in use for 10 and 15years.

- In wheat breeding, there is a lag between the discovery and testing of traits and or genes of interest and the release of an improved variety. Lag periods averaging between 9 and 12 years have been reported (Brennan et al., 2004; GRDC, 2007; 2011). For this study the adoption on farms is assumed to begin 10 years after the initial discovery. Sensitivity analysis was also conducted to estimate the impact of changes in the lag period between discovery and adoption of 6 and 12 years.

- The possibility of concurrent improvements in grain quality during the development of PHEF tolerant wheat varieties has been ignored in the current study. Wheat quality improvements have been reported with the introduction of new varieties over time (Brennan and Bialowas, 2001; Barlow et al., 2013). Brennan and Bialowas (2001) indicated that varietal change had led to an improvement in bread-making quality of wheat by 1.77% per year in the southern shires and 0.94% per year in the northern shires (where quality was higher at the start of the analysis period). However, there is no reason to anticipate that breeding for PHEF tolerance would necessarily lead to changes in quality.

- An S-shaped sigmoid cumulative adoption curve was assumed. For PHEF tolerant wheat seed demand, the demand will begin slowly, accelerate rapidly owing to evidence of potential benefits and then slow after 4 years as demand for PHEF tolerant wheat seed will be realised, after large scale production.

- An interest rate of 5% was employed in the economic modelling. However, interest rates of 3% and 10% were also examined in the sensitivity analysis.

- It is likely that introduction of a PHEF tolerant wheat variety will lead to an expansion of wheat production in Australia, although this expansion may be counteracted by other factors (i.e. climate change). However, the modelling does not take into account any expansion of wheat cropping into frost-prone areas where wheat is not widely grown currently.

- In addition to the purchase price of seed, Australian growers pay plant breeders a small royalty on each tonne of grain of a registered variety delivered to grain handlers whether or not the seed was purchased new each year. This provides a return to breeders when on farm seed is retained for sowing. We have assumed that end point royalties paid on delivery of PHEF tolerant varieties would be similar to those for non-tolerant varieties and so should not have a net effect on farmer income.

3. COST BENEFIT ANALYSIS: RESULTS AND DISCUSSION

3.1 Estimation of direct and indirect yield benefits

At present, reducing frost impact on wheat yield in PHEF-prone regions of Australia is achieved by adapting the sowing time to ensure that heading occurs after the main, mid-winter frost risk period has passed (Zheng et al., 2012 and 2015). However, on the other hand, later sowing increases the risk of terminal drought and heat stress during grain filling, and consequently risk to reduce yields (Chenu et al., 2013; Richards et al., 2014; Zheng et al., 2015).

The simulated results suggest that, after removing the sensitivity of a genotype (FT_{tot}) but retaining the current sowing times and fertilizer inputs to estimate the direct impact, an average yield increase of 0.27, 0.14, and 0.28 t ha^{-1} was achieved in the Northern, Southern, and Western regions, respectively (Figure 4). The highest increase in yield (0.51 t ha^{-1}) was achieved in the WA Eastern AEZ (Figure 4). However, after optimizing the sowing times for tolerant varieties and optimal nitrogen application rates – direct plus indirect impact –

additional yield benefits of 0.45, 0.14, and 0.19 t ha^{-1} were realised in the Northern, Southern, and Western regions, respectively (Figure 4).

The yield increase resulting from different degrees of PHEF tolerance varied across the Australian wheat belt. In the Western region, most of the predicted benefits were gained by reducing the frost damage threshold from 0°C to just –2°C with no change in management (Figures 4 and S1). On the other hand, at certain AEZs in the Northern and Southern regions, yield was substantially further improved by frost tolerance to –3°C or –4°C, and extra yield improvement arose from the opportunity to exploit earlier sowing times and longer growing seasons (direct plus indirect impact, Figure S1). The greatest AEZ wide average yield impact was simulated in the NSW NW/QLD SW (1.15 t ha^{-1}, representing a 68% increase) for total frost tolerance with adjusted sowing date (Figure 4). Noted also that the reductions of yield benefits at improved frost tolerant levels typically appeared at the QLD Central AEZ is a result of the present optimal profit approach. Management practices leading to an optimal profit might not result in an optimal yield (see Figure S2 for an example at Emerald). Similarly, at the national scale, mean yield across 85 million simulations increased by 7.7% for a –1°C frost tolerance (FT_1) up to 10.8% for total frost tolerance (FT_{tot}) for mid-maturing cultivars (direct impact) planted at the current locally optimum sowing date. The results also indicate that improved frost tolerance beyond –4°C resulted in little if any further yield gains in terms of direct frost impact. However, when the optimum sowing dates of the new genotypes were adjusted to reduce or avoid end-of season stresses such as heat and drought, yield increased by between 10.3% for –1°C frost tolerance and 20.3% for total tolerance (direct plus indirect impact). Therefore, adapting management practices (sowing times) resulted in an additional yield advantage of 2.6 to 9.5% for –1°C and total tolerance, respectively.

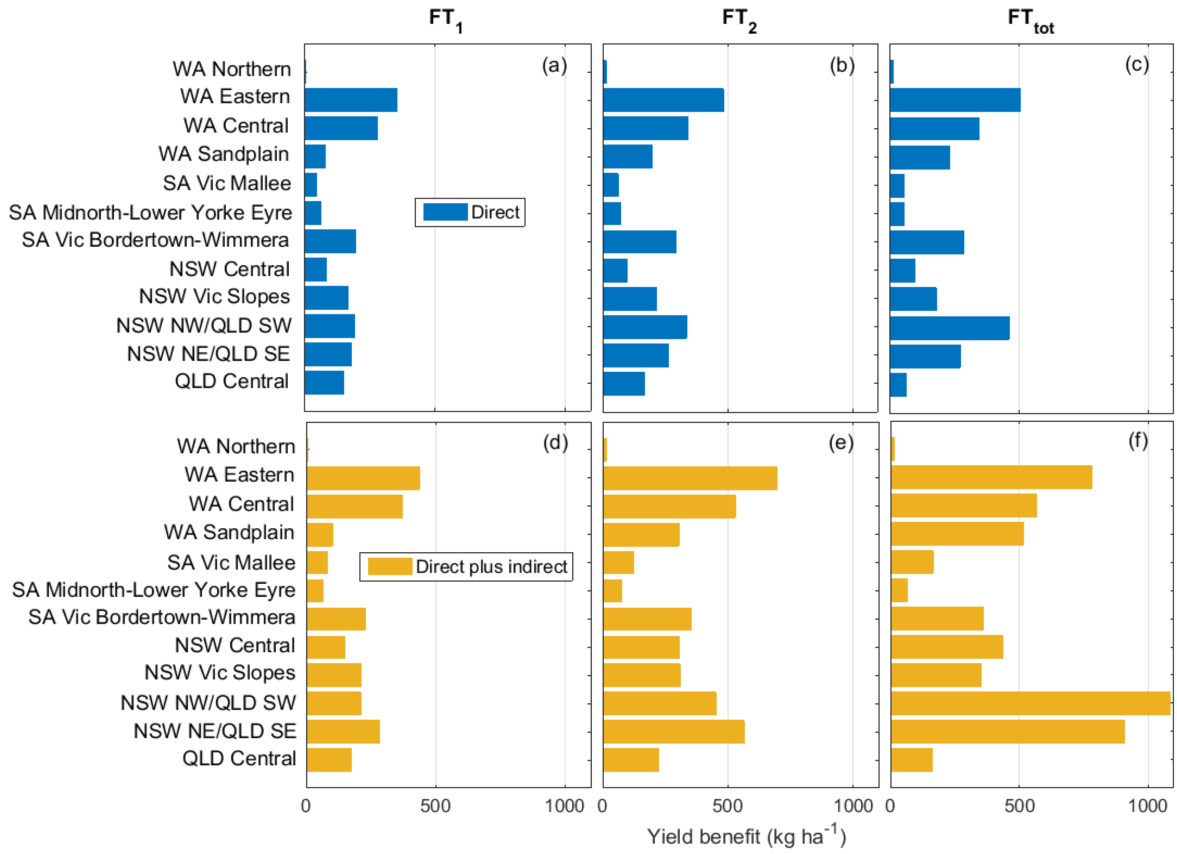

Figure 4. Average direct (blue colour bars) and average direct plus indirect (gold colour bars) yield benefits (kg ha^{-1}) of improved PHEF tolerance to –1°C (FT_1), –2°C (FT_2) and total tolerance (FT_{tot}) based on optimal profit and optimal nitrogen use for the agro-ecological zones. Additional results for improved PHEF tolerance to –3°C (FT_3), –4°C (FT_4), and –5°C (FT_5) are presented in Figure S1. The Northern Region includes QLD Central, NSW North West (NW) – QLD South West (SW) and NSW North East (NE) – QLD South East (SE) AEZs. The Southern Region includes NSW Central, NSW Vic Slopes, SA Midnorth-Lower Yorke Eyre, SA Vic Bordertown – Wimmera and SA Vic Mallee. The Western Region includes WA Northern, WA Eastern, WA Central and WA Sandplain.

3.2 Estimation of regional direct and indirect economic benefits

In Australia, frost events result in major economic loss through direct yield losses and indirect losses through driving a conservative sowing strategy (Frederiks et al., 2011 and 2012; Zheng et al., 2015). The present optimal profit approach allows estimation of the direct and indirect economic benefits of PHEF tolerant varieties. The economic assessment is based on the last 30 years of historical farm financial data obtained through the ABS and ABARE. All the financial costs and prices data were converted to 2012 values using the Consumer Price Index (CPI). Estimates of regional direct and indirect economic benefits are provided in Figures 5 and S3.

With regard to potential direct and direct plus indirect economic benefits, the economic results suggest average direct economic benefits of AUD 59, 38, and 60 ha^{-1} can be achieved in the Northern, Southern, and Western regions, respectively (Figure 5). The highest average direct economic benefit (AUD 114 ha^{-1}) was estimated in the WA Eastern AEZ. However, after considering indirect benefits due to earlier optimal sowing dates, average direct plus indirect economic benefits of AUD 167, 79, and 111 ha^{-1} could be achieved in the Northern, Southern, and Western regions, respectively (Figure 5).

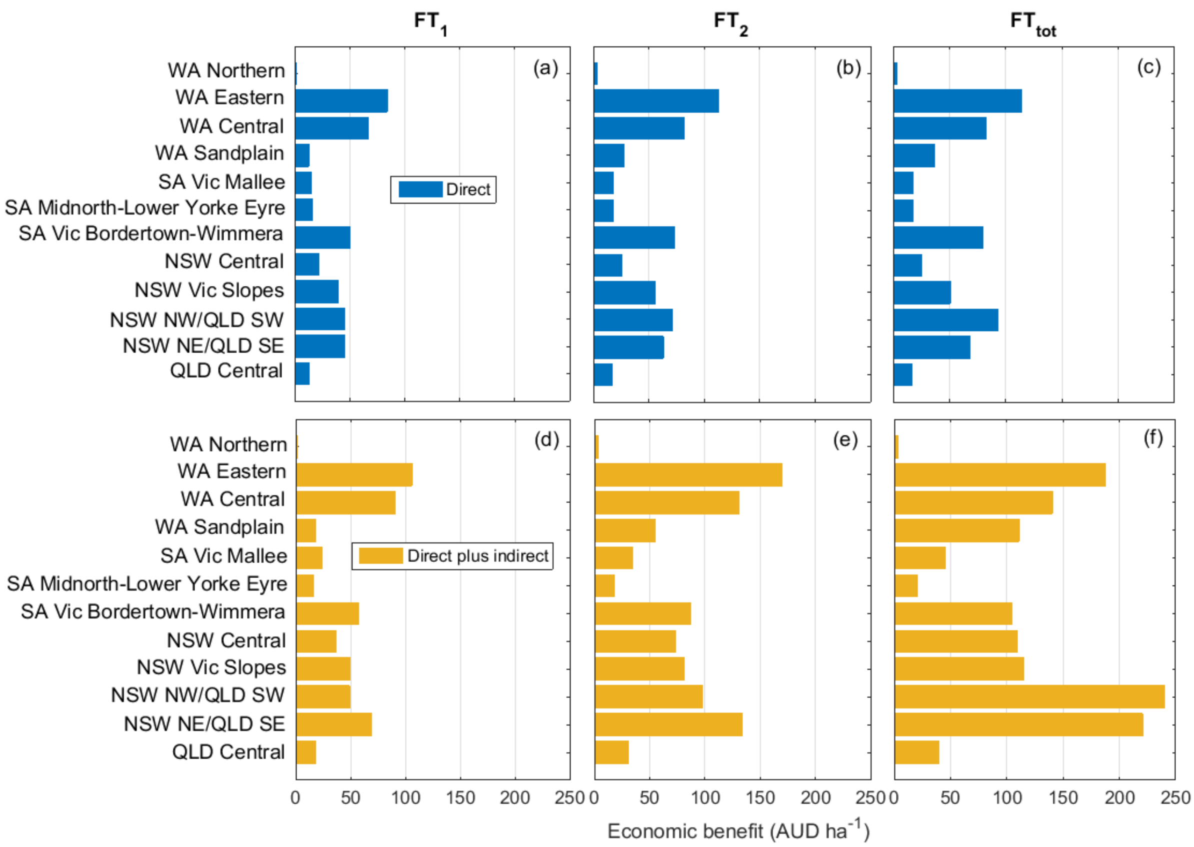

Figure 5. Average economic benefits (AUD ha^{-1}) at agro-ecological zones of improved PHEF tolerance to –1°C (FT_1), –2°C (FT_2) and total tolerance (FT_{tot}) both direct (blue colour bars) and direct plus indirect (gold colour bars) based on optimal profit and optimal nitrogen use. Additional results for improved PHEF tolerance to –3°C (FT_3), –4°C (FT_4), and –5°C (FT_5) are presented in Figure S3. Northern Region includes QLD Central, NSW North West – QLD South West and NSW North East – QLD South East. Southern Region includes NSW Central, NSW VIC Slopes, SA Midnorth-Lower Yorke Eyre, SA Vic Bordertown – Wimmera and SA Vic Mallee. Western Region includes WA Northern, WA Eastern, WA Central and WA Sandplain.

With regard to economic benefits for various levels of PHEF virtual tolerant genotypes, the nationally average direct plus indirect benefits increased from FT_1 (AUD 45 ha^{-1}) to FT_{tot}

(AUD 112 ha^{-1}). However, there was not much difference between FT_4 (AUD 107 ha^{-1}), FT_5 (AUD 110 ha^{-1}) and FT_{tot} (AUD 112 ha^{-1}). Regionally, in the Western zones, especially WA Central and WA Eastern AEZs, considerably higher direct than indirect economic benefits were indicated when compared with other regions. In contrast to WA Central and WA Eastern AEZs, the Northern WA AEZ exhibited almost no direct benefits and indirect benefits. This is likely due to the generally low frost risk in this zone (Frederiks et al., 2011 and 2012; Zheng et al. 2015).

Aggregating the direct and indirect economic benefits, by means of using average historical wheat production areas of the AEZs, the results are presented in Figures 6 and S4. For example by planting an FT_4 genotype (tolerant to –4ºC) at the regional level an average economic benefit of AUD 436 million $year^{-1}$, AUD 420 million $year^{-1}$, and AUD 575 million $year^{-1}$ are predicted in the Northern, Southern, and Western regions, respectively (Figure S4). Therefore, at the national level, for example by planting FT_4 at the optimal sowing time, a total economic benefit of AUD 1,431 million $year^{-1}$ could potentially be achieved (by aggregation of regional results on Figure S4).

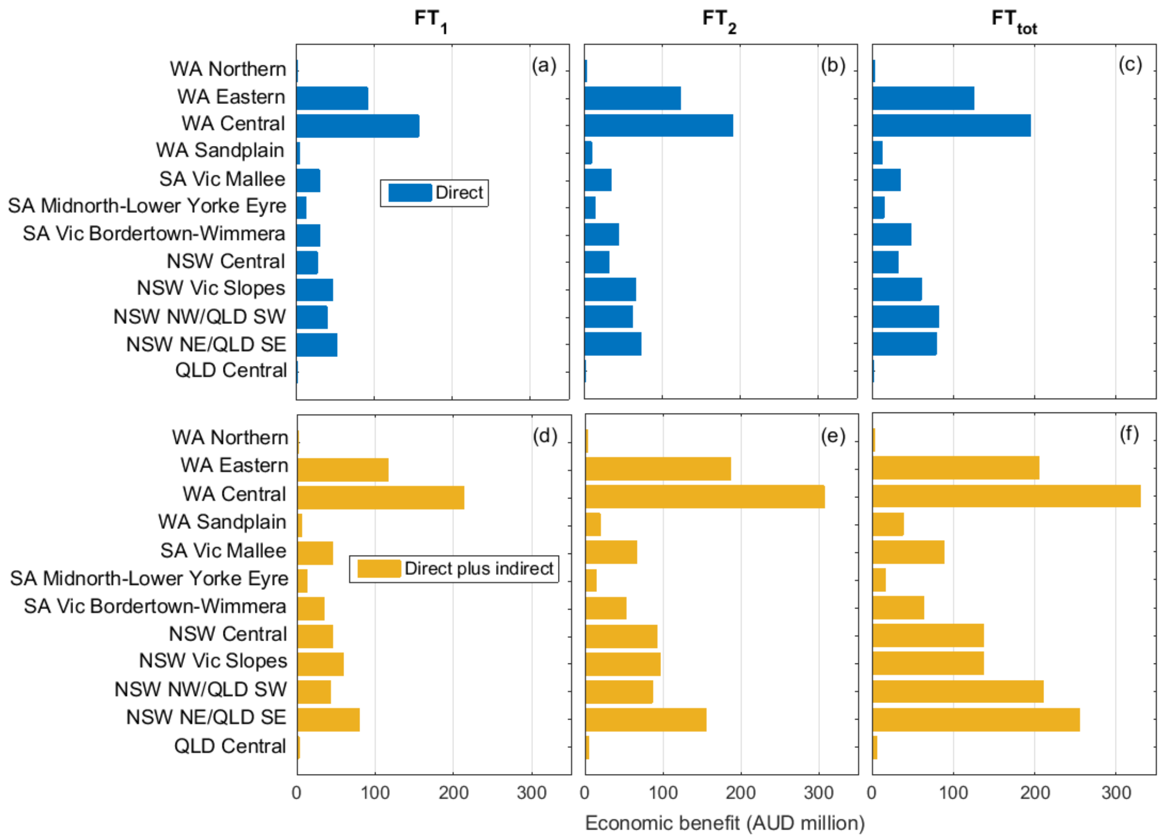

Figure 6. Estimation of direct (blue colour bars) and direct plus indirect economic benefits (gold colour bars) for each AEZ (AUD million AEZ^{-1}) based on optimal profit and optimal nitrogen use for improved PHEF tolerance to –1ºC (FT_1), –2ºC (FT_2) and total tolerance (FT_{tot}) with regards to agro-ecological zones (AEZs).

3.3 Estimation of potential improved wheat frost tolerant seed demand

Table 1 provides estimates of potential PHEF tolerant wheat seed demand. Assuming no change in technical, institutional, economical and sociological factors, the estimated national demand for PHEF tolerant wheat seed is estimated at 303,281 t year^{-1}. Based on the demand assessment criteria (as described in section 2.3) WA Central (78,318 t year^{-1}), NSW NE/QLD SE (43,271 t year^{-1}) and WA Eastern (36,924 t year^{-1}) are likely to have the highest PHEF tolerant wheat seed demand. Based on potential PHEF tolerant seed production of 5.0 t ha^{-1}, assuming good soil fertility and unrestricted water access, 60,656 ha may be required (over 20 years) for seed production to meet PHEF tolerant wheat seed demand.

Table 1: Estimation of potential frost tolerant wheat seed demand across all Australian AEZs.

Agro Ecological Zones (AEZs)	Average area (ha)	Potential for adoption (% of area planted)	Potential area under frost tolerant variety (ha)	Potential seed demand (tonnes)*
QLD Central	187,669	Low, 5%	9,383	563
NSW NE/QLD SE	1,201,981	High, 60%	721,189	43,271
NSW NW/QLD SW	716,955	High, 60%	430,173	25,810
NSW Vic Slopes	925,978	High, 60%	555,587	33,335
NSW Central	975,456	High, 60%	585,273	35,116
SA Vic Bordertown-Wimmera	551,011	Med, 30%	165,303	9,918
SA Midnorth-Lower Yorke Eyre	671,527	Low, 5%	33,576	2,015
SA Vic Mallee	1,592,250	Med, 30%	477,675	28,661
WA Sandplain	265,389	Low, 5%	13,269	796
WA Central	2,175,496	High, 60%	1,305,298	78,318
WA Eastern	1,025,677	High, 60%	615,406	36,924
WA Northern	786,777	Low, 5%	39,339	2,360
Total*	**11,076,166**		**5,054,690**	**303,281**

*The total demand for PHEF wheat seed was estimated by aggregating potential seed PHEF wheat demand of each AEZ. Potential demand of each AEZ was estimated by (seed rate =60 kg ha^{-1} x potential adoption rate x average wheat area/1000) – section 2.3.

3.4 Cost Estimates for wheat breeding options for PHEF tolerance

Cost data for breeding programs are hard to obtain, perhaps due to the commercial nature of the breeding businesses. Cost estimates used here are derived from published information on market rates, unpublished literature and discussions with experts in wheat breeding. Table 2 provides a summary of values used for total fixed and variable costs of breeding programs associated with different phases of PHEF tolerance breeding options. Seed production costs are based on estimated national PHEF tolerant wheat seed demand (see section 3.3). Detail of total fixed and variable costs, and associated assumptions, are provided in the supplementary material (Table S2).

The fixed costs of a PHEF tolerant breeding program are mainly associated with construction or lease of laboratory and glasshouse facilities, laboratory equipment and seed storage and fixed costs of land development and management (small and large scale field trials managed usually via contractors).

The total estimated fixed costs of discovery and testing, advanced development and large scale field experiments, and large scale seed production to meet PHEF tolerance seed demand were AUD 3.30 million, AUD 0.34 million, AUD 16.0 million, and AUD 1,273 million, respectively (Table S2). The estimated costs for large scale seed production largely depend on the estimated PHEF tolerant wheat seed demand.

The total estimated variable costs (mainly associated with salaries of scientists, support staff, admin staff and laboratory consumables) for stage one to four are AUD 0.52 million, AUD 0.72 million, AUD 2.16 million and AUD 24.40 million, respectively (Table S2). On average about AUD 1.2 million year^{-1} will be required to run a PHEF tolerant breeding program after advanced development and large scale field experiments (Stage 3).

Table 2: Estimated total fixed and variable costs associated with PHEF tolerance breeding program. Further details are provided in supplementary Tables S2.

Stage	Major phases of PHEF tolerance breeding	Total estimated costs* of PHEF

	program	tolerance breeding options (for the entire program) (AUD million)	
		Fixed costs	Variable costs
1	Discovery of PHEF	AUD 3.30	AUD 0.52
2	Test for PHEF tolerance early development	AUD 0.34	AUD 0.72
3	Advanced PHEF tolerance development	AUD 16.00	AUD 2.16
4	Large scale seed production to meet PHEF tolerant seed demand	AUD 1273.10	AUD 24.40

Source: Authors' estimate.

*Please see supplementary material for more details of costs estimate under each stage.

3.5 Cost Benefit Analysis value of various degrees of improved PHEF tolerance breeding options for varieties with varying periods of market life

The results of the baseline economic analysis, against which sensitivity analysis was conducted, are presented in Figure 7. The economic benefits to growers for PHEF-tolerance breeding options for virtual tolerant genotypes were compared with the current varieties (FT_0), when sown at the optimum sowing date and using the optimal nitrogen application rates for all the current and frost tolerant varieties, with market life periods of 10, 15 or 20 years. Taking the discount rate as 5% and estimated demand for PHEF-tolerant wheat seed as outlined in section 2.3, all economic indicators (NPV, IRR, BCR) suggest that investment in PHEF-tolerance breeding options, across all frost tolerant variety options (FT_1 to FT_{tot}), would be highly economically viable. The estimated returns on investment would be substantial, and certainly higher than many alternative uses of the investment.

The results indicate that NPV increases with improved levels of PHEF tolerance. For example NPV of fully PHEF tolerant wheat seed variety (FT_{tot}) when considering 20 years of PHEF-tolerant variety life would be AUD 4,841 million which is AUD 2,684 million higher than the NPV of FT_1 (AUD 2,157 million) (Figure 7a). However, the difference in NPVs between FT_4, FT_5 and FT_{tot} were small (Figure S5a).

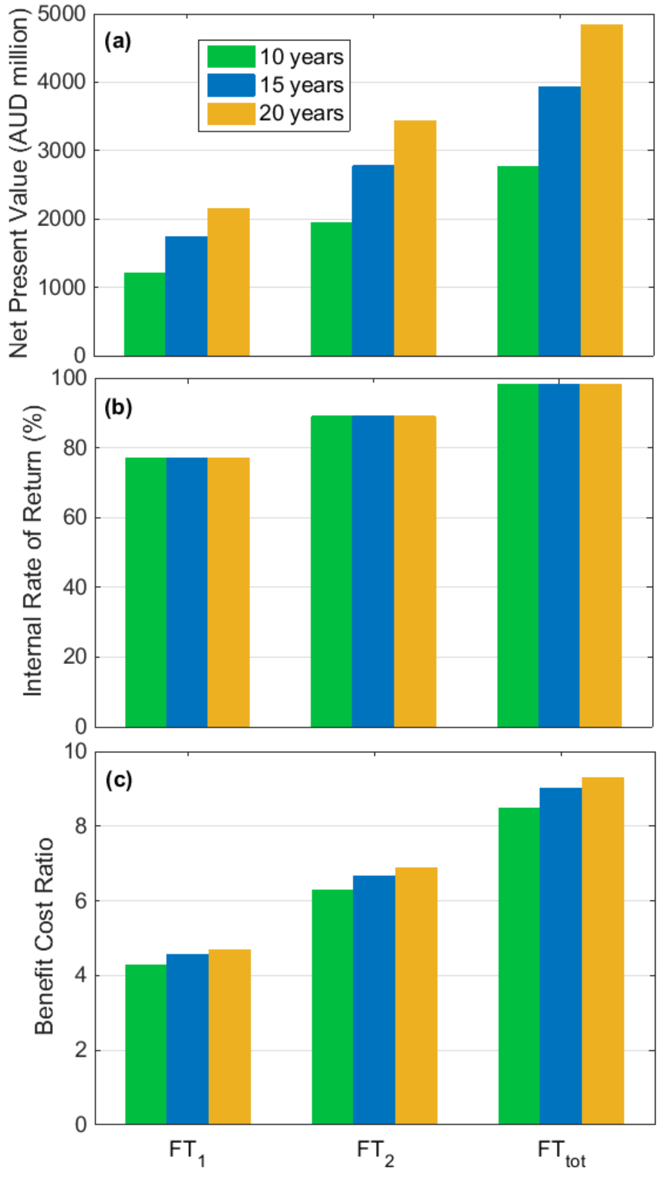

Figure 7: Economic evaluations of wheat breeding for FT_1, FT_2 and FT_{tot} (results for various degrees of improved PHEF frost tolerance can be found in Figure S5): (a) Net Present Value

(NPV); (b) Internal Rate of Return (IRR); and (c) Benefit Cost Ratio (BCR); for variety market durations of 10, 15 and 20 years.

The IRR also suggest strong economic returns on investment (Figure 7b). However, IRR was less sensitive with regards to PHEF frost tolerance variety life.

The BCR also suggests an attractive profit. For example, the BCR of complete PHEF-tolerant genotype (FT_{tot}) indicated that every dollar spent could lead to up to an AUD 9.29 return, over a 20 year PHEF-tolerant variety life (Figure 7c).

4. SENSITIVITY ANALYSIS

Sensitivity analysis was conducted to test the robustness of the economic analysis by systematically changing the values of key cost and benefit parameters. Sensitivity analyses were performed using a 5% discount rate, with all parameters other than the parameter for which sensitivity was being tested held at their base. An exception was made for the final sensitivity analysis where variations in discount rate were tested keeping all other variables constant. The results are mainly discussed using NPV as an evaluation criterion except for section 4.4 where variation in the discount rate is examined.

4.1 Change in the improved PHEF tolerant variety wheat seed demand (+/– 25%)

Changes in the NPV were modelled for scenarios where the national demand for PHEF resistant seed is either 25% more or 25% less than that calculated in Section 2.3, for example if the area sown varies by this amount (also see Table 1). For simplicity in this analysis, it was assumed that all PHEF seed planted over the estimated demand area (Table 1) would be purchased from breeding companies each year. However, farmers will often retain seed for sowing the following year as discussed below (Section 4.2). Figures 8 and S6 shows the results of sensitivity analysis when demand for seed varieties changes by +/–25%. With either 25% increase or 25 % decrease in the PHEF-tolerant variety seed demand the investment is still profitable. In case of increase in the PHEF tolerant variety seed demand the NPV increased considerably across all (FT_1 to FT_{tot}) frost tolerant breeding options (Figures 8a and S6a). With a decrease in the PHEF tolerant variety seed demand, the return from the investment reduced substantially, however, NPV remains positive for all scenarios indicating that investment would still be profitable (Figures 8b and S6b).

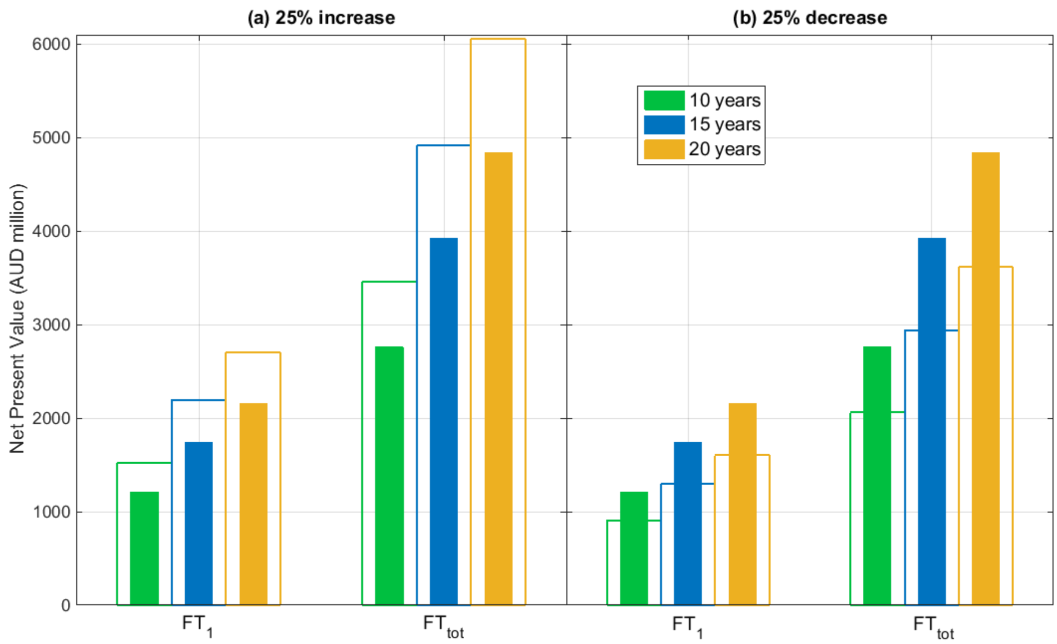

Figure 8: Net Present Value (NPV) of FT_1 and FT_{tot} with changes in the seed demand (results of various degrees of improved wheat frost tolerance breeding options can be found in Figure S6); (a) 25% increase in the PHEF seed demand and (b) 25% decrease in the PHEF seed demand. The green, blue and gold colour bars show the baseline economic estimates for

variety market durations of 10, 15 and 20 years, respectively (presented in Figure 7a) against which results for demand scenarios (corresponding transparent bars) can be compared.

4.2 Change in the improved PHEF tolerant variety wheat seed replacement

The baseline economic assessment above assumes that wheat PHEF tolerant variety seed will be replaced every year. However, wheat farmers may want to retain seed to plant in subsequent years. Seed replacement rates describes the frequency with which farmers purchase new seed versus how often they plant retained seed (Heffer, 2001). It has been reported (Heffer, 2001) that in Australia about 12.5% of the total harvested wheat area (about 13.05 million ha) purchases seed annually.

To cater for seed replacement, three PHEF tolerant variety seed replacement scenarios – seed replacement every 2, 4 and 8 years – were estimated based on the total seed demand calculated in Section 2.3 (also see Table 1) to assess changes in NPV. Figure 9 (and supplementary Figure S7) shows the results of sensitivity analysis at different PHEF wheat seed replacement rates. The sensitivity analysis indicates that retaining seed for longer periods up to 8 years leads to a greater NPV for the industry. This is mainly owing to reduction in PHEF seed production costs while realising corresponding yield increase benefits.

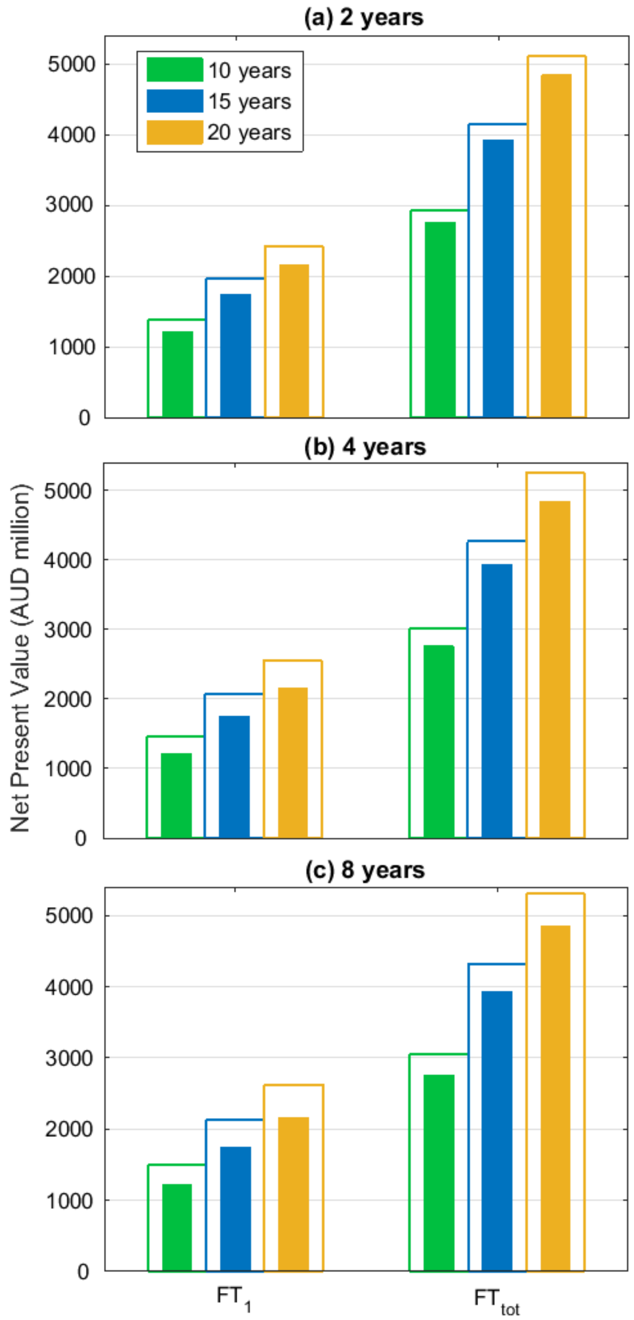

Figure 9: Net Present Value (NPV) of FT_1 and FT_{tot} with improved wheat frost tolerance breeding options, with replacement of PHEF seed rate (results for various degrees of improved wheat frost tolerance breeding options can be found in Figure S7): (a) replacement of PHEF wheat seed after 2 years; (b) after 4 years; and (c) after 8 years. The green, blue and gold colour bars show the baseline economic estimates for variety market durations of 10, 15

and 20 years, respectively (presented in Figure 7a) against which results for replacement scenarios (corresponding transparent bars) can be compared.

4.3 Change in the wheat farm gate price (+/–25%)

Changes in the net value of wheat when leaving the farm (farm-gate prices) will influence the expected NPVs for PHEF tolerant variety development options when compared with the baseline price level of AUD 230 t^{-1} (Section 2.5). Figures 10 and S8 show the results of sensitivity analysis when wheat farm gate price changes by +/–25%. In the situation when farm gate price increases by 25%, compared with baseline, the investment would yield considerably higher returns, as indicated by NPVs across all levels (FT_1 to FT_{tot}) of frost tolerant options (Figures 10a and S8a). On the other hand, 25% decrease in the farm gate prices would make investment in a PHEF tolerant program slightly less attractive but still feasible (Figures 10b and S8b).

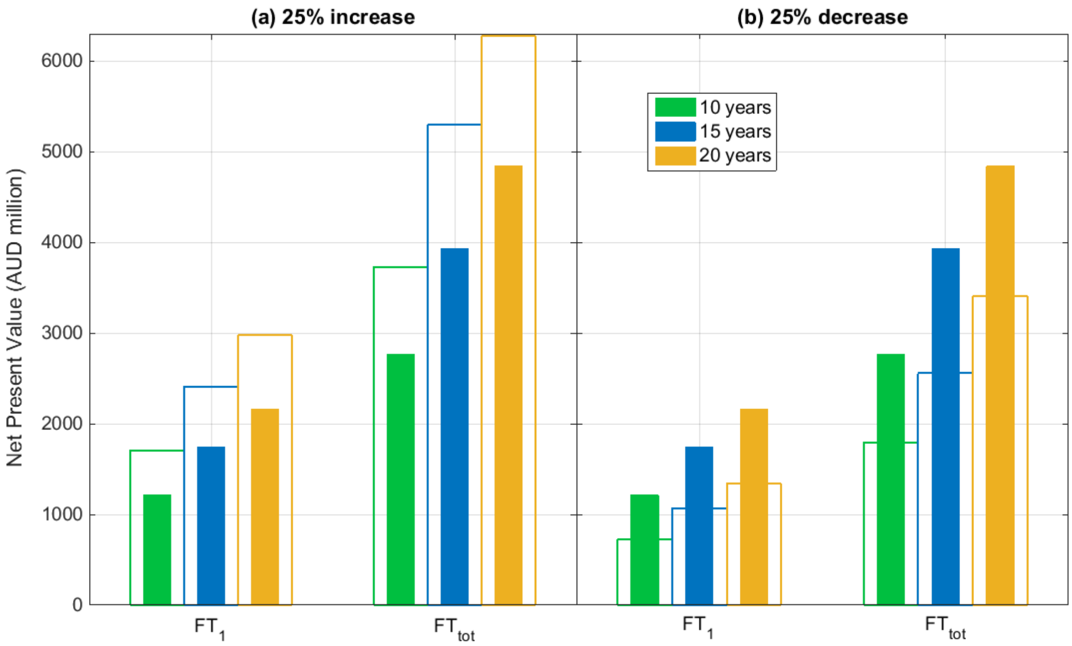

Figure 10: Net Present Value (NPV) of FT_1 and FT_{tot} with changes in the farm gate price levels (results for various degrees of improved wheat frost tolerance breeding options can be found in Figure S8); (a) 25% increase in the farm gate prices and (b) 25% decrease. The green, blue and gold colour bars show the baseline economic estimates for variety market durations of 10, 15 and 20 years, respectively (presented in Figure 7a) against which alternative farm gate price scenarios (corresponding transparent bars) can be compared.

4.4 Change in the timing of the net benefits stream starting earlier (+2 years) or later (–2 years)

Changes in the lag between the benefits streams and the discovery and testing of frost tolerance will affect returns. This delay can have considerable impacts on the viability of the investment. Figures 11 and S9 show the results of a sensitivity analysis when the rate of adoption is either increased or decreased such that the benefits stream commences either 2 years earlier or 2 years later than the base estimate (of 10 years). The results show, compared with baseline, earlier release of the PHEF tolerant wheat seed varieties will result in earlier realisation of the income stream, and would result in considerably higher benefits (Figures 11a and S9a). For a 2 year delay, while benefits reduced substantially, the investment is still feasible (Figures 11b and S9b).

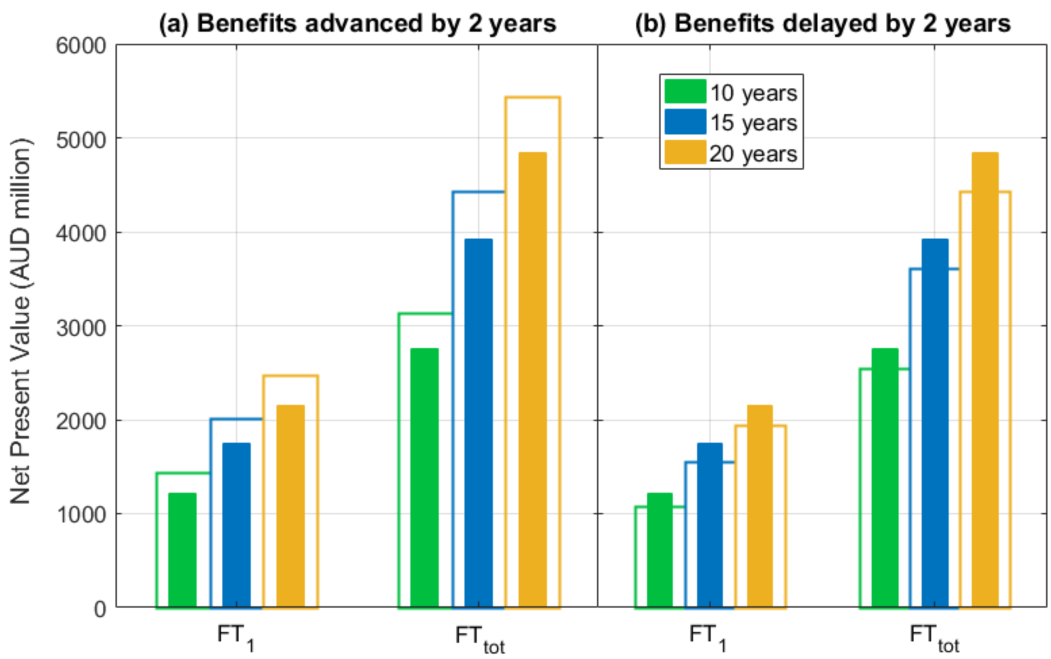

Figure 11: Net Present Value (NPV) of FT_1 and FT_{tot} with changes in the net benefits streams (results for various degrees of improved wheat frost tolerance breeding options can be found in Figure S9); (a) benefits delayed by 2 years and (b) benefits advanced by 2 years. The green, blue and gold colour bars show the baseline economic estimates for variety market durations of 10, 15 and 20 years, respectively (presented in Figure 7a) against which scenarios economic values (corresponding transparent bars) can be compared.

4.5 Change in the interest rate (3% and 10%)

The interest rates play a critical role in determining the returns from a PHEF tolerant breeding program. Higher interest rates will make investment in PHEF tolerant breeding programs less attractive while lower interest rates will result in more attractive financial returns. The NPVs of PHEF tolerant breeding program options in response to changes in the interest rates are presented in Figures 12 and S10. Although a higher interest rate of 10%

makes investment somewhat less attractive, the returns remain feasible (Figures 12b and S10b). On the other hand reduction of interest rate from the base line 5% to 3% will make PHEF tolerant breeding wheat programs more viable (Figures 12a and S10a).

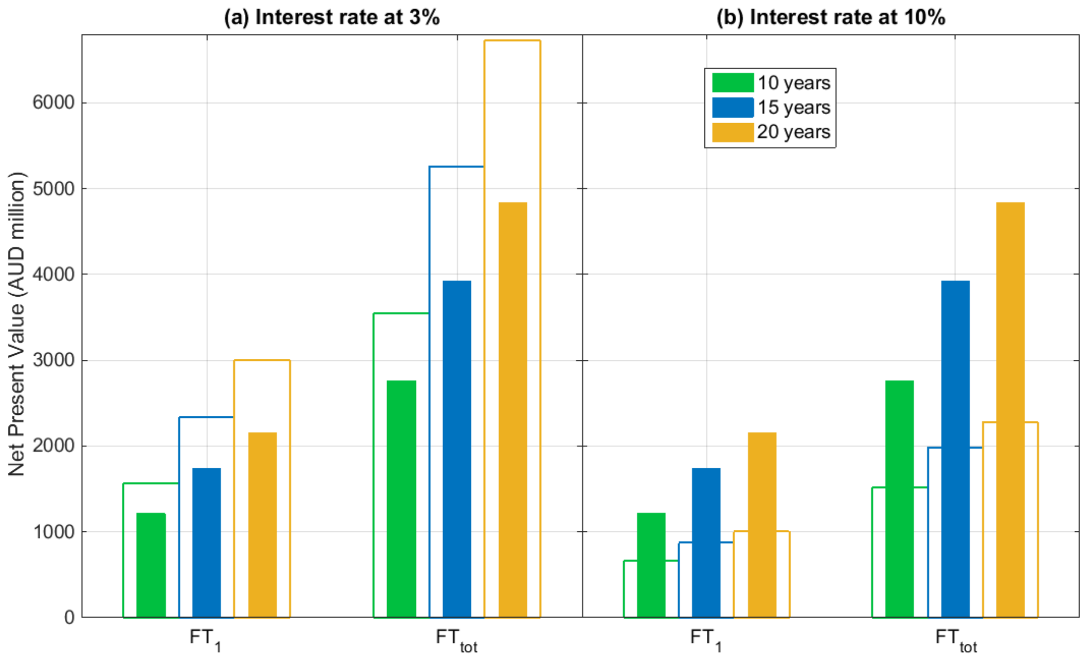

Figure 12: Net Present Value (NPV) of FT_1 and FT_{tot} with changes in the interest rates (results for various degrees of improved wheat frost tolerance breeding options can be found in Figure S10); (a) decrease in interest rate at 3% and (b) increase in interest rate at 10%. The green, blue and gold colour bars show the baseline economic estimates for variety market durations of 10, 15 and 20 years, respectively (presented in Figure 7a) against which changing interest rate scenarios (corresponding transparent bars) can be compared.

4.6 Change in the fixed costs (+/–25%)

Cost structures can change noticeably overtime which can impact the financial outcomes of a PHEF tolerant wheat breeding program. Sensitivity of the baseline economic values have been analysed by changing fixed costs (see in Table 2) by +/– 25% (Figures 13 and S11). Change in fixed costs does not impact the financial returns significantly. With either a decrease or an increase of fixed cost by 25% frost tolerant breeding programs returns exhibit relatively modest change when compared to the overall values. For FT_1 to FT_{tot}, estimated returns increased by approximately AUD 150 million with decrease in fixed cost (Figures 13a and S11a) or decreased by a similar amount with increased fixed costs (Figures 13b and S11b).

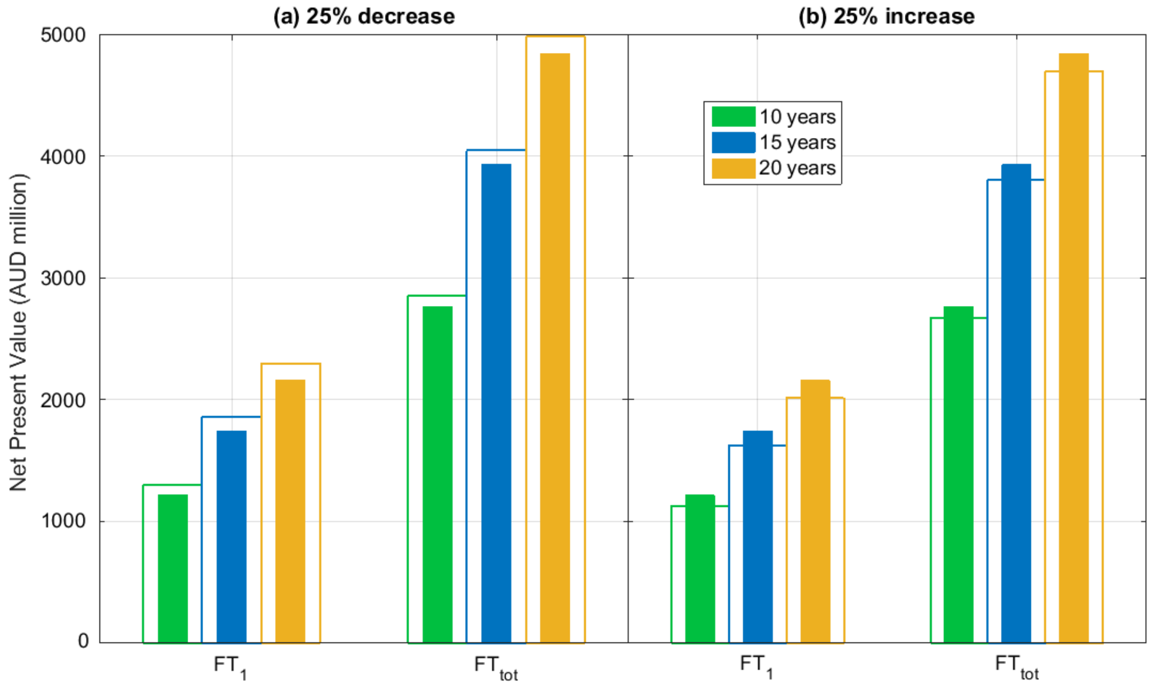

Figure 13: Net Present Value (NPV) of FT_1 and FT_{tot} with changes in the fixed costs (results for various degrees of improved wheat frost tolerance breeding options can be found in Figure S11); (a) increase in the fixed cost by 25% or, (b) increase in the fixed cost by 25%. The green, blue and gold colour bars show the baseline economic estimates for variety market durations of 10, 15 and 20 years, respectively (presented in Figure 7a) against which changed fixed costs scenarios (corresponding transparent bars) can be compared.

5. CONCLUSION

Our analysis suggests that, if it were possible to breed wheat varieties with improved PHEF tolerance, the aggregated improvement in farmer returns would greatly exceed the cost under most scenarios tested. Farmer returns would be increased owing to direct benefits from reduced direct frost damage and owing to an indirect effect of changes in sowing date and fertilizer application. Results suggest that at the national level, up to a 20.3% yield improvement, including both direct (10.8%) and indirect (9.5%) effects, could be achieved from the breeding of frost tolerant lines if genetic variation can be found. Consequently, economic modelling results indicate that a benefit of up to AUD 135 ha^{-1} is possible with fully frost tolerant (FT_{tot}) varieties and up to AUD 130 ha^{-1} with varieties of 4°C more frost tolerant (FT_4) depending on the AEZs. Australia could potentially reap a total economic benefit of AUD 1,431 million $year^{-1}$ if frost tolerant wheat to –4°C (FT_4) was available to growers.

At the national scale, the yield and economic benefits increased with the potential improved frost tolerant levels. The direct yield benefits varied from 7.7% for a –1°C frost tolerance (FT_1) up to 10.8% for total frost tolerance (FT_{tot}). The direct plus indirect yield benefits ranged from 10.3% for –1°C frost tolerance and 20.3% for total tolerance. As a result, the direct plus indirect economic benefits increased from FT_1 (AUD 45 ha^{-1}) to FT_{tot} (AUD 112 ha^{-1}). The results also indicate that improved frost tolerance beyond –4°C resulted in little if any further yield gains in terms of direct frost impact. There was also not much difference in economic benefits between FT_4 (AUD 107 ha^{-1}), FT_5 (AUD 110 ha^{-1}) and FT_{tot} (AUD 112 ha^{-1}).

Regionally, the effect of improved frost tolerance and associated changes in management varied. In the Western zones, especially WA Central and WA Eastern AEZs, the improved frost tolerance directly enhanced profits. On the other hand, at certain AEZs in the Northern and Southern regions, profits were also remarkably increased, arising from the opportunity to exploit earlier sowing times and longer growing seasons.

Benefit Cost Analysis results, expressed as NPV, IRR, and BCR all suggest that investment in PHEF tolerant breeding options (from FT_1 to FT_{tot}) would be an economically viable opportunity. The returns are attractive, especially when compared with the prevailing interest rate. The results indicate that NPV increases with the enhancement in PHEF resilience. The NPV to growers of fully frost tolerant conventional variety (FT_{tot}) was estimated at AUD 4,841 million, when considering 20 years of variety life. A sensitivity analysis was conducted to test the robustness of the economic analysis by systematically changing the values of key benefit parameters. While the results of the sensitivity analysis show that NPV are sensitive to changes in farm gate price, interest rates, seed replacement and seed demand, the investment are still economically viable for all PHEF tolerant breeding options examined.

Based on comparative economic benefits, if the breeders were able to develop PHEF tolerant varieties that could withstand cold temperatures as low as –4 °C below the current threshold, the investment on the PHEF tolerant breeding program would be highly attractive. While this paper does not address the feasibility of finding and incorporating PHEF tolerance genes into varieties adaptable to all Australian production environments, the analysis indicates that the search for such tolerances has high potential returns.

REFERENCES

An-Vo, D.-A., Mushtaq, S., Zheng, B., Christopher, J.T., Chapman, S.C., Chenu, K. (2016). Direct and indirect costs of frost in the Australian wheat belt. Submitted to *Ecological Economics*.

An-Vo, D.-A., Mushtaq, S., Nguyen-Ky, T., Bundschuh, J., Tran-Cong, T., Maraseni, T., Reardon-Smith, K. (2015a). Nonlinear optimisation using production functions to estimate economic benefit of conjunctive water use for multicrop production. *Water Resources Management* **29**, 2153-2170.

An-Vo, D.-A., Mushtaq, S., Reardon-Smith, K. (2015b). Estimating the value of conjunctive water use at a system-level using nonlinear programing model. *Journal of Economic and Social Policy* **17**, 9.

Boer, R., Campbell, L.C., Fletcher, D.J. (1993). Characteristics of frost in a major wheat-growing region of Australia. *Australian Journal of Agricultural Research* **44**, 1731–1743.

Bond, G. and Wonder, B. (1980). Risk attitudes amongst Australian farmers. *Australian Journal of Agricultural Economics* **24**, 16–34.

Barlow, K.M., Christy, B.P., O'Leary, G.J., Riffkin, P.Q. and Nuttall, J.G. (2013). Simulating the impact of extreme heat and frost events on wheat production: the first steps. 20th International Congress on Modelling and Simulation, Adelaide, Australia, 1–6 December 2013. www.mssanz.org.au/modim2013.

Brennan, J.P. and Bialowas, A. (2001). *Changes in Characteristics of NSW Wheat Varieties, 1965-1997*, Economic Research Report No. 8, NSW Agriculture, Wagga Wagga.

Brennan, J.P., Martin, P.J. and Mullen, J.D. (2004). *An Assessment of the Economic, Environmental and Social Impacts of NSW Agriculture's Wheat Breeding Program*, Economic Research Report No. 17, NSW Agriculture, Wagga Wagga.

Chenu, K., Deihimfard, R., Chapman, S.C. (2013). Large-scale characterization of drought pattern: a continent-wide modelling approach applied to the Australian wheatbelt–spatial and temporal trends. *New Phytologist* **198**, 801 – 820.

DEPI Victoria (2012). Growing Wheat. Note Number: AG0548. http://www.depi.vic.gov.au/agriculture-and-food/grains-and-other-crops/crop-production/growing-wheat accessed July 2015.

DPI NSW (2015). Winter crop variety sowing guide 2015. http://www.dpi.nsw.gov.au/agriculture/broadacre/guides/winter-crop-variety-sowing-guide accessed July 2015.

FAO (2002). Bread wheat: Improvement and Production. Curtis B.C., S. Rajaram, H. Gómez Macpherson, eds. FAO Plant Production and Protection Series No. 30, Rome, 2002.

Frederiks, T.M., Christopher, J.T., Borrell, A.K. (2004). Investigation of post head-emergence frost resistance in several CIMMYT synthetic and Queensland wheats. In: Fisher

T, Turner N, Angus J, McIntyre L, Robetson M, Borrell A, Lloyd D, eds. 4th International Crop Science Congress. Brisbane, Australia.

Frederiks, T.M., Christopher, J.T., Harvey, G.L., Sutherland, M.W., Borrell, A.K. (2012). Current and emerging screening methods to identify post-head-emergence frost adaptation in wheat and barley. *Journal of Experimental Botany* **63**, 5405–5416.

Frederiks, T.M., Christopher, J.T., Fletcher, S.E.H., Borrell, A.K. (2011). Post head-emergence frost resistance of barley genotypes in the northern grain region of Australia. *Crop and Pasture Science* **62**, 736–745.

Ghadim K.A.A., Pannell, D.J. (2003). Risk Attitudes and Risk Perceptions of Crop Producers in Western Australia. Risk Management and the Environment: Agriculture in Perspective. Editors: Babcock, B.A., Fraser, R.W., Lekakis, J.N. eds pp 113-133. Kluwer Academic Publishers.

GRDC (2007). An Economic Analysis of GRDC Investment in the Australian Cereal Rust Control Program. GRDC Impact Assessment Report Series.

GRDC (2011). An Economic Analysis of Investment in the National Variety Trials (NVT). Impact Assessment Report Series.

GRDC (2015). Wheat: Western region grow notes. http://content-au.secure-zone.net/grdc/western_region_wheat/ access on July 2015.

Heffer, P. (2001). Wheat seed and seed supply. In: Wheat in a Global Environment. Proceedings of the 6th International Wheat Conference, 5–9 June 2000, Budapest, Hungary. Z. Bedö and L. Láng eds. Developments in Plant Breeding. Springer Netherlands. 9, 141-148.

Holzworth, D.P., Huth, N.I., Zurcher, E.J. et al. (2014). APSIM–evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software* **62**, 327-350.

Kalaitzandonakes, N., Alston, J.M. and Bradford, K.J. (2006). Compliance Costs for Regulatory Approval of New Biotech Crops. In: Regulating Agricultural Biotechnology: *Economics and Policy. Natural Resource Management and Policy Volume* **30**, 37-57.

Langridge, P., and Gilbert, M.J. (2008). From gene discovery to paddock reality. In: 'Global Issues Paddock Action.' Proceedings of the 14th Australian Agronomy Conference, September 2008. Adelaide, South Australia." MJ Unkovich ed. Australian Society of Agronomy.

Monsanto (2009). Pipeline for genetically modified crop development. http://www.monsanto.com/products/Documents/pipeline-flash/pdfs/pipeline_2009_phase.pdf accessed August 2014.

Mushtaq, S., Dawe, D., and Hafeez, M. (2007). Economic Evaluation of Small Multi-Purpose Ponds in the Zhanghe Irrigation System, China. *Journal of Agricultural Water Management*. **91**, 61-70.

Paulsen, G.M., Heyne, E.G. (1983). Grain production of winter wheat after spring freeze injury. *Agronomy Journal* **75**, 705–707.

Richards, R.A., Hunt, J.R., Kirkegaard, J.A. and Passioura, J.B. (2014). Yield improvement and adaptation of wheat to water-limited environments in Australia – a case study. *Crop and Pasture Science* **65**(7), 676 – 689.

Zadoks, J.C., Chang, T.T., Konzak, C.F. (1974). A decimal code for the growth stages of cereals. *Weed Research* **14**, 415–421.

Zheng, B.Y., Chenu, K., Dreccer, M.F. and Chapman, S.C. (2012). Breeding for the future: what are the potential impacts of future frost and heat events on sowing and flowering time requirements for Australian bread wheat (*Triticum aestivium*) varieties? *Global Change Biology* **18**(9): 2899-2914.

Zheng, B.Y, Biddulph, B., Li, D., Kuchel, H., Chapman, S.C. (2013). Quantification of the effects of VRN1 and Ppd-D1 to predict spring wheat (*Triticum aestivum*) heading time across diverse environments. *Journal of Experimental Botany* **64**, 3747–3761.

Zheng, B.Y., Chapman, S.C., Christopher, J.T., Frederiks M.T., Chenu K. (2015). Frost trends and their estimated impact on yield in the Australian wheat belt. *Journal of Experimental Botany. doi:10.1093/jxb/erv163*