Supplementary material for:

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

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Table S1: Name and location of 59 sites of wheat crop simulation.

State	Site	Latitude	Longitude
QLD	Goondiwindi	−28.55	150.31
	Meandarra	−27.33	149.88
	Dalby	−27.18	151.26
	Roma	−26.57	148.79
	Emerald	−23.53	148.16
NSW	Condobolin	−33.07	147.23
	Wellington	−32.8	148.8
	Dubbo	−32.24	148.61
	Gilgandra	−31.71	148.66
	Nyngan	−31.55	147.2
	Coonamble	−30.98	148.38
	Gunnedah	−30.98	150.25
	Narrabri	−30.34	149.76
	Walgett	−30.04	148.12
	Moree	−29.48	149.84
	Urana	−35.33	146.03
	Wagga Wagga	−35.16	147.46
	Yanco	−34.61	146.42
	Merriwagga	−33.92	145.52
	Parkes	−33.14	148.16
VIC	Longerenong	−36.67	142.3
	Dookie	−36.37	145.7
	Glenlee	−36.26	141.86
	Birchip	−35.98	142.92
	Hopetoun	−35.73	142.37
	Walpeup	−35.12	142.00
SA	Pinnaroo	−35.26	140.91
	Roseworthy	−34.53	138.69
	Loxton	−34.44	140.6
	Cummins	−34.27	135.73
	Waikerie	−34.18	139.98
	Balaklava	−34.14	138.42
	Rudall	−33.69	136.27
	Port Pirie	−33.17	138.01
	Minnipa	−32.84	135.15
	Ceduna	−31.9	133.42
WA	Katanning	−33.69	117.56
	Esperance	−33.61	121.78
	Ravensthorpe	−33.58	120.05
	Nyabing	−33.54	118.15
	Lake Grace	−33.1	118.46
	Salmon Gums	−32.99	121.62
	Wickepin	−32.78	117.5
	Hyden	−32.44	118.9
	Corrigin	−32.33	117.87
	Narembeen	−32.07	118.4
	Cunderdin	−31.66	117.25
	Northam	−31.64	116.67
	Kellerberrin	−31.62	117.72
	Merredin	−31.48	118.28
	Southern Gross	−31.23	119.33
	Wongan Hills	−30.84	116.73
	Bencubbin	−30.81	117.86
	Badgingarra	−30.34	115.54
	Dalwallinu	−30.28	116.66

	Carnamah	−29.69	115.89
	Morawa	−29.21	116.01
	Geraldton	−28.8	114.7
	Mullewa	−28.54	115.51

Table S2: Fixed and variable costs and associated assumptions for a PHEF-tolerant wheat seed development program.

Phase	Cost types	Items	Amount (AUD)	Method/Source	Assumption/comments
1	Fixed costs	Laboratory and a glass house construction for initially screening.	AUD 3.0 million	Expert subjective opinion and market price	The cost of the construction depends on the method and materials used for construction.
		Frost testing chamber	AUD 300,000	Market price	
	Variable costs	Staff salary	AUD 210,000 per year	Market price	Identification of a new frost tolerant gene and insertion of gene into current varieties and test of stability and efficacy required one senior scientists and support staff. Assuming salary rate of AUD 130,000 per year for senior scientists and AUD 80,000 for associate researcher, the estimated salary component will be about AUD 210,000 per year.
		Operating costs for the PHEF tolerance variety, including, media, conditioners and other laboratory scientific consumables	AUD 50,000 per year	Market price	Estimated subjectively by the plant breeders and other experts
2	Fixed costs	Small scale field and glass house trials: Testing the expression of frost tolerance in glass house, growth chambers and small scale field trails.	AUD 120,000	Market price based on estimate provided by Kalyx (-)	Based on discussions with industry experts (Kalyx; (https://www.kalyx.com.au/), the total costs of running trails would be around AUD 120,000. The total costs cover costs of running small (~20 m x 100 m plus buffers and standards) PHEF tolerant varieties field trials to test 40 or 50 PHEF tolerant varieties (5 m rows x 2 reps x 2 planting times x 2 treatments (with and without lights) x 2 sites for 2 years @ AUD 30,000 per year per site). The cost includes land, labour for running of the trial, necessary fencing and depreciation of the required equipment.
		Equipment purchase	AUD 20,000	Market price and expert subjective estimates	Equipment purchased not covered by the contract service: Seed storage facilities, balance, dockage tester, meteorological data logging, electronic data capture and computers, at a cost of around AUD 20,000
	Variable costs	Scientific input salary costs	AUD 210,000 per year	Market price	1 technical FTE is required to monitor frost responses, prepare seed, post-harvest weight etc. In addition, 1 senior researcher FTE is

					required to scientifically test the frost response stability and efficiency. Assuming AUD 80,000 for associate researcher and AUD 130,000 for senior scientist, the salary component will be AUD 210,000 per year
		Administration costs	AUD 95,000 per year	Market price	Administration costs: Dealing with administration matters and initiate deregulation requirements will require 0.5 FTE (or AUD 120,000 per year) of business manager and 0.5 FTE (or 70,000 per year) administration support. Total admin costs of about AUD 95,000 per year
		Biometry analysis	AUD 5,000 per year	Experts subjective estimates	
		Scientific expenses and consumables	AUD 50,000 per year	Market price	Estimated subjectively by the plant breeders and other experts
3	Fixed cost	Advancement development (large field testing for yield potential, plus test disease resistance and quality). The activities are aimed to test yield potential, disease resistance and quality of wheat in larger scale field trials, laboratory and glasshouse tests. Testing 5 PHEF frost resistant wheat lines in field in large (9 m x 2 m) plots	AUD 7.00 million	Market price based on estimate provided by Kalyx (https://www.kalyx.com.au/	This will be managed through a contractor for extended agronomic and phenotypic assessment. The field trials require running 3 trials in each of 5 states over 4 years. Sites to include both frost-prone and non-frost-prone sites, with three sites in each of the 5 mainland states. However, the first two years will be primarily for seed increase. Trials to include at least equal number of non-GM equivalent lines (5) for comparison. The field trial will include: • Year 1: Testing of 5 PHEF tolerant lines in the field with 2 reps x 1 site (20 plots). • Year 2: Testing of 5 PHEF tolerant lines in the field with 2 reps x 4 sites (80 plots). • Year 3: Testing of 5 PHEF tolerant lines in the field with 2 reps x 15 sites (300 plots). • Year 4: Testing of 5 PHEF tolerant lines in the field with 3 reps x 15 sites (450 plots).

		Cost of environmental, food safety (some countries) and product equivalence tests	AUD 9.00 million	Experts subjective estimates, supported by review	Cost of environmental, food safety (some countries) and product equivalence tests: Based on Phillips McDougall (2011) and Kalaitzandonakes et al (2006) the cost of environmental, food safety, feed safety ranges between AUD 9 million to AUD 18 million. However for this analysis, an estimated cost of about AUD 9 million is considered over 4 years. However, environmental cost could be much higher for GM crops.
	Variable costs	Cost of biometry	AUD 15,000 per year	Experts subjective estimates	
		Disease, agronomic and quality testing	AUD 60,000	Experts subjective estimates	These tests are those that would normally be conducted in preparation for release of non-GM varieties. The total estimated disease, agronomic and quality testing is about AUD 60,000. Some special provisions may need to be made for testing, such as using physical containment level 2 (PC2) rated laboratories and glasshouses.
		Scientific input salary costs	AUD 340,000 per year	Market price	1 technical FTE is required to monitor frost responses, prepare seed, post-harvest weight etc. In addition, 2 senior researchers FTE is required to scientifically test the frost response stability and efficiency. Assuming AUD 80,000 for associate researcher and AUD 130,000 for senior scientist, the salary component will be AUD 340,000 per year.
		Administration costs	AUD 95,000 per year	Market price	Dealing with administration matters and initiate deregulation requirements will require 0.5 FTE (or AUD 100,000 per year) of business manager and 0.5 FTE (or 70,000 per year) administration support
		Scientific expenses and consumables	AUD 75,000 per year	Market price	Estimated subjectively by the plant breeders and other experts
	Fixed costs	Large scale seed production to meet national PHEF wheat seed demand	AUD 1263.10 million	Market price based on estimate provided by Kalyx (https://www.kalyx.com.au/	Large scale seed production: Based on the domestic PHEF wheat seed demand assumptions of 303K tonnes of seed demand (see section 3), and PHEF frost resistant wheat yield of 5 tonnes/ha about 60,656 ha of land is required to meet the seed demand. This large scale will be managed through a contractor for extended agronomic and phenotypic assessment. The estimated cost for good quality land with suitable water allocation and management is about AUD 1,000

4					ha–1 year–1. Total cost then is up to AUD 1263.10 million over the life of the varieties, which may be up to 20 years
		Storage and related infrastructure	AUD 10.00 million	Experts subjective estimates	The estimated cost of storage and related infrastructure is about AUD 10 million. The cost could be lower if storage and related infrastructure was managed by local merchants.
	Variable costs	Marketing and distribution	AUD 2.00 million per year	Experts subjective estimates	
		Scientific input salary costs	AUD 630,000 per year	Market price	There may be some scientific input through some of this work from time to time to ensure seed purity. Three technical FTE is required to monitor frost responses, prepare seed, post-harvest weight etc. In addition, 3 senior researchers FTE is required to scientifically test the frost response stability and efficiency. Assuming AUD 80,000 for associate researcher and AUD 130,000 for senior scientist, the salary component will be AUD 630,000 per year.
		Administration costs	AUD 440,000 per year	Market price	Dealing with administration matters and requirements will require 3 FTE (or AUD 100,000 per year) of business manager (including financial accountants) and 2 FTE (or AUD 70,000 per year) administration support. Total admin costs of about AUD AUD 440,000 per year.
		Scientific expenses and consumables	AUD 150,000 per year	Market price	Estimated subjectively by the plant breeders and other experts

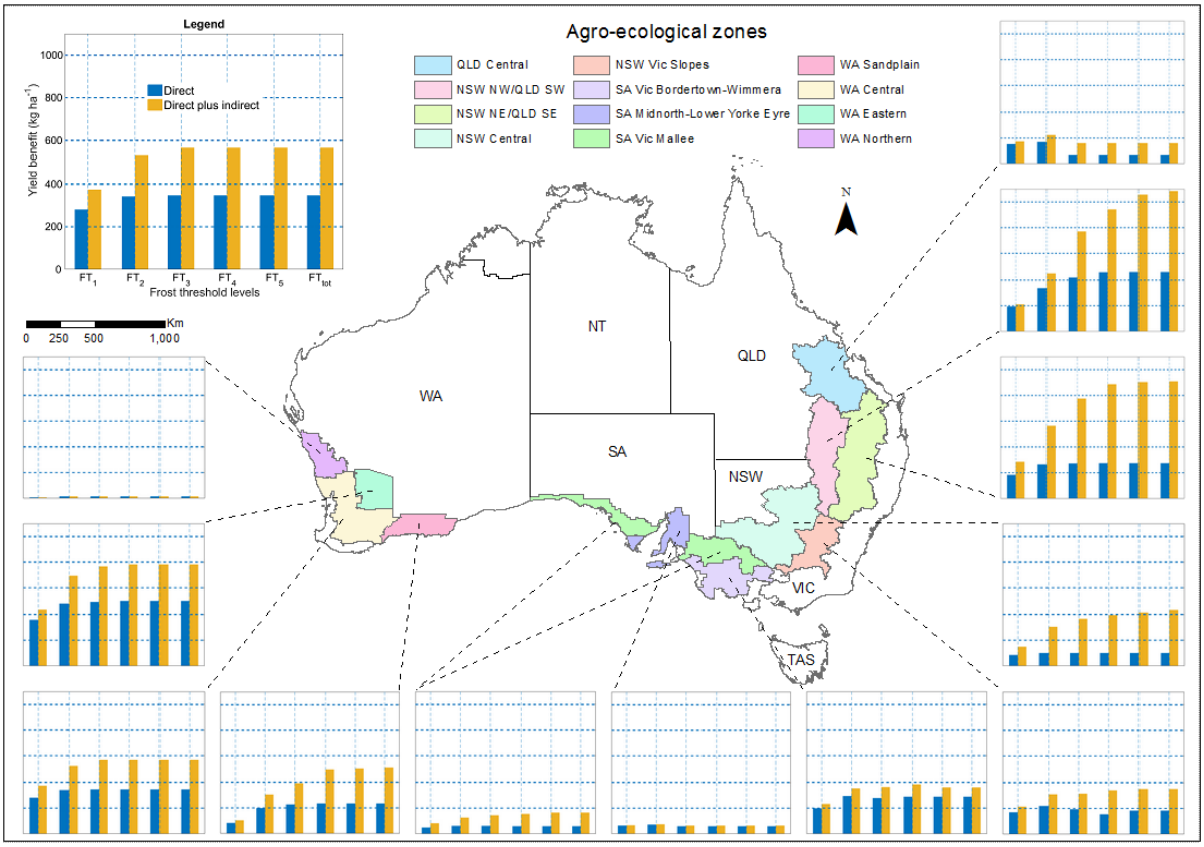

Figure S1: Direct (blue colour bars) and direct plus indirect (gold colour bars) yield benefits (kg ha^{-1}) of improved PHEF tolerance based on optimal profit and optimal nitrogen use for the agro-ecological zones. The average yield benefit (kg ha^{-1}) for improved PHEF tolerance to –1, –2, –3, –4, –5^{o}C and total tolerance (FT_1 – FT_5 and FT_{tot}) are given in each panel for each of the agro-ecological zones used in the analysis. The legend panel in the top left corner gives the axis scales for all graphs and colours for columns but does not represent any actual data.

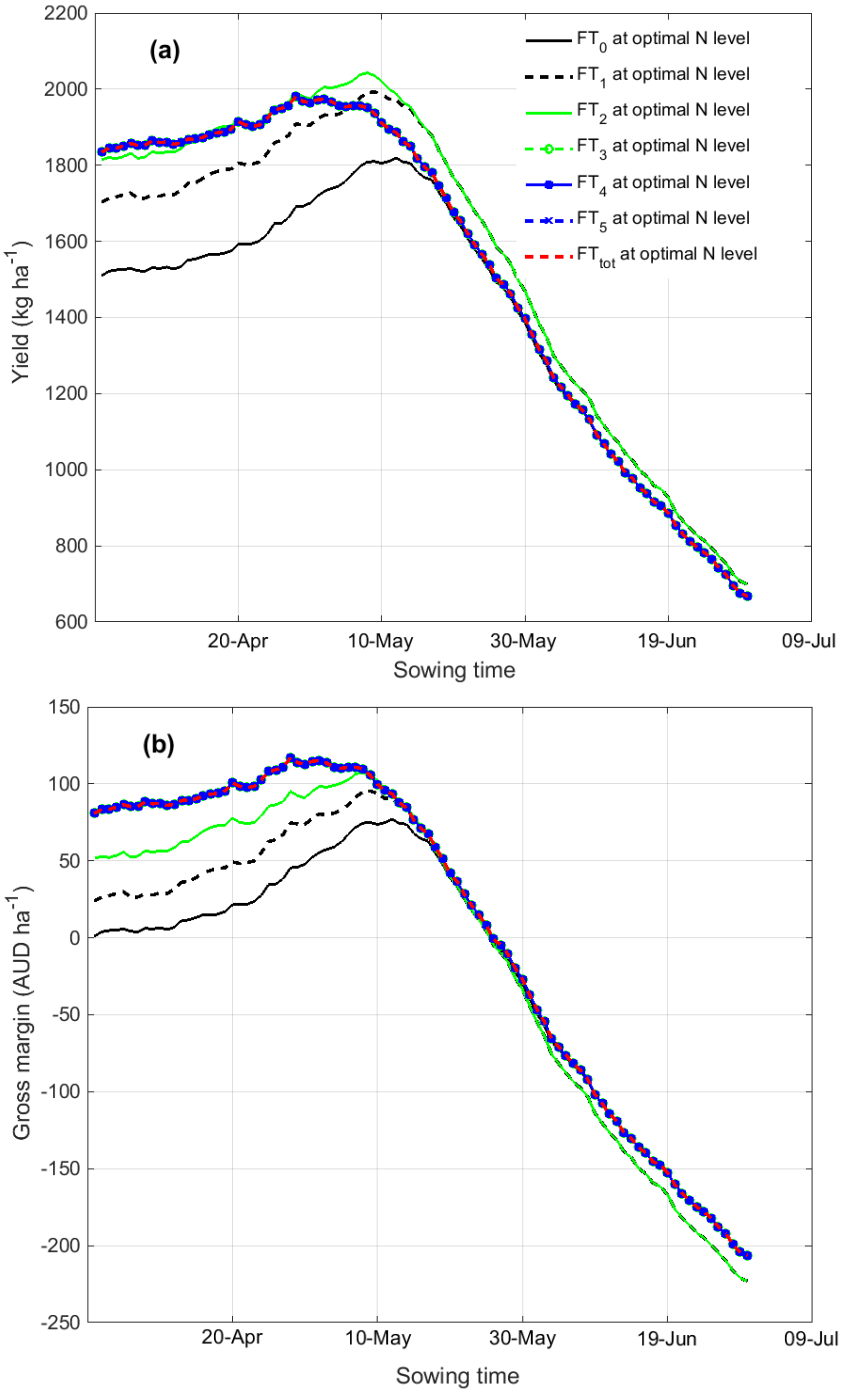

Figure S2: Long-term mean yield (a) and gross margin (b) distributions at Emerald (at optimal fertilisation) on the sowing window for the current cultivars (FT_0), improved frost tolerant genotypes (FT_1 – FT_5) and fully tolerant genotype (FT_{tot}). The yield distributions in (a) are improved with improved frost threshold temperatures till –2^{o}C but then reduced to a single distribution for all FT_3 – FT_5 and FT_{tot}. The yield distribution for FT_3 – FT_5 and FT_{tot}

was achieved at optimal N levels which are actually lower than those for FT_0, FT_1 and FT_2 and hence gained a better gross margin as shown in (b). The present optimal profit approach thus shows increases in direct plus indirect economic benefits at improved frost tolerant levels, while the direct and direct plus indirect yield benefits at certain improved frost tolerant levels might be reduced at some sites.

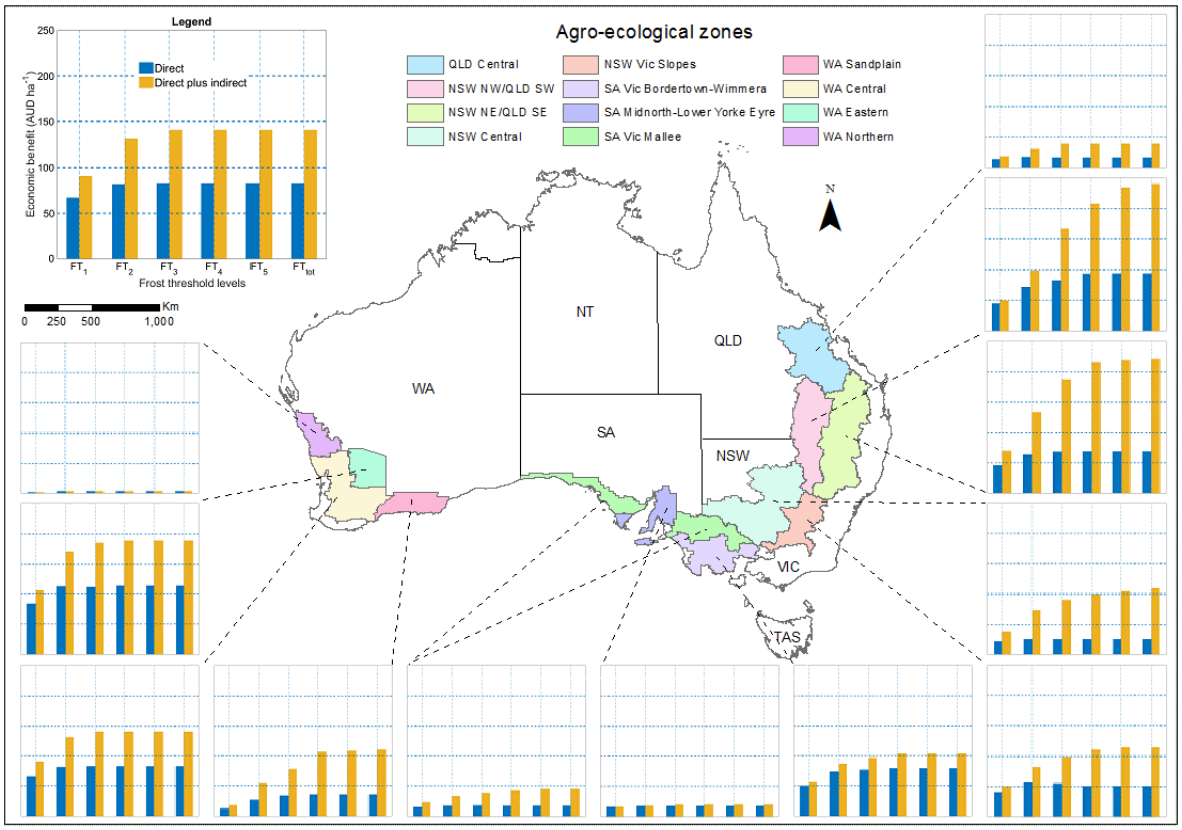

Figure S3: Economic benefits (AUD ha^{-1}) of various levels of PHEF tolerance both direct (blue colour bars) and direct plus indirect (gold colour bars) based on optimal profit and optimal nitrogen use for all current and tolerant varieties with regards to agro-ecological zones. The average economic benefit (AUD ha^{-1}) for improved PHEF tolerance to –1, –2, –3, –4, –5°C and total tolerance (FT_1 – FT_5 and FT_{tot}) are given in each panel for each of the agro-ecological zones used in the analysis. The legend in the top left corner gives the scale for all graphs and colours for columns but does not represent any actual data.

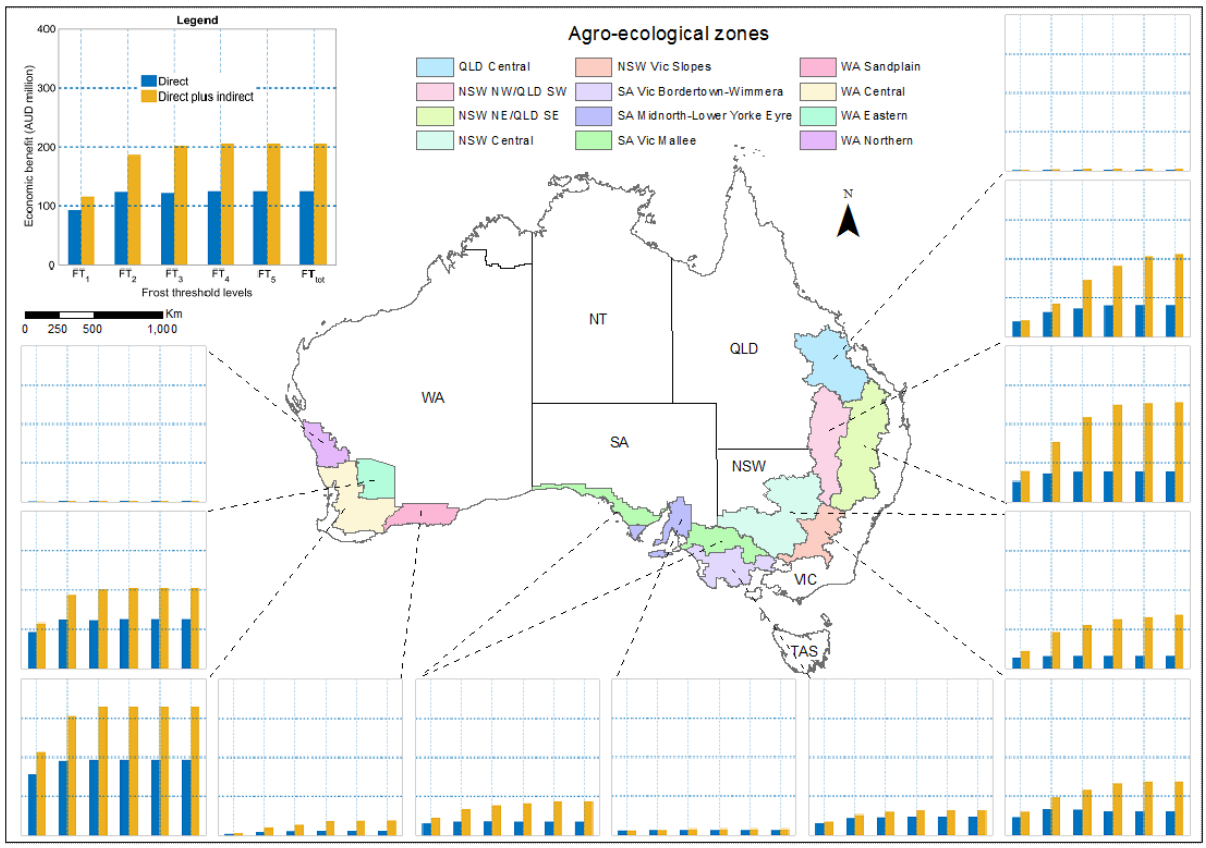

Figure S4: Estimation of direct (blue colour bars) and direct plus indirect economic benefits (gold colour bars) for each AEZ (AUD million AEZ^{-1}) based on optimal profit and optimal nitrogen use for all current and tolerant varieties with regards to agro-ecological zones (AEZs). The average economic benefit (AUD million AEZ^{-1}) for improved PHEF tolerance to –1, –2, –3, –4, –5°C and total tolerance (FT_1 – FT_5 and FT_{tot}) are given in each panel for each of the agro-ecological zones used in the analysis. 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. The legend panel in the top left corner gives the scale for all graphs and colour notation for bars but does not represent any actual data (adapted from An-Vo et al. 2016, submitted).

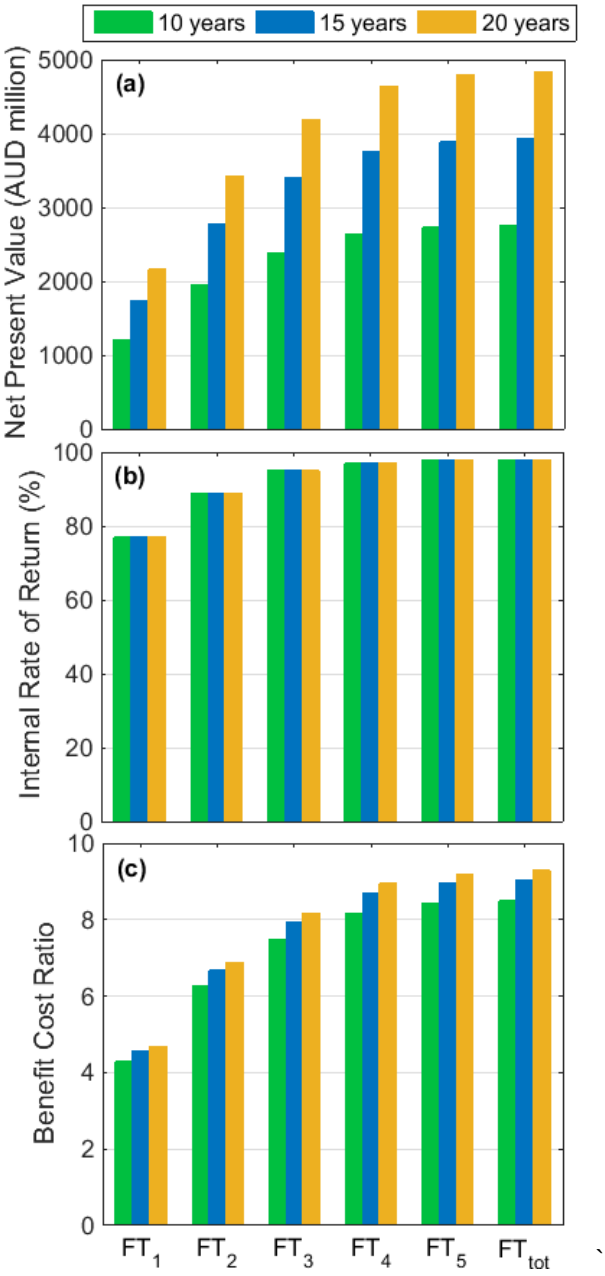

Figure S5: Economic evaluations of wheat breeding for various degrees of improved PHEF frost tolerance: (a) Net Present Value (NPV); (b) Internal Rate of Return (IRR); and (c) Benefit Cost Ratio (BCR); for variety market durations of 10, 15 and 20 years.

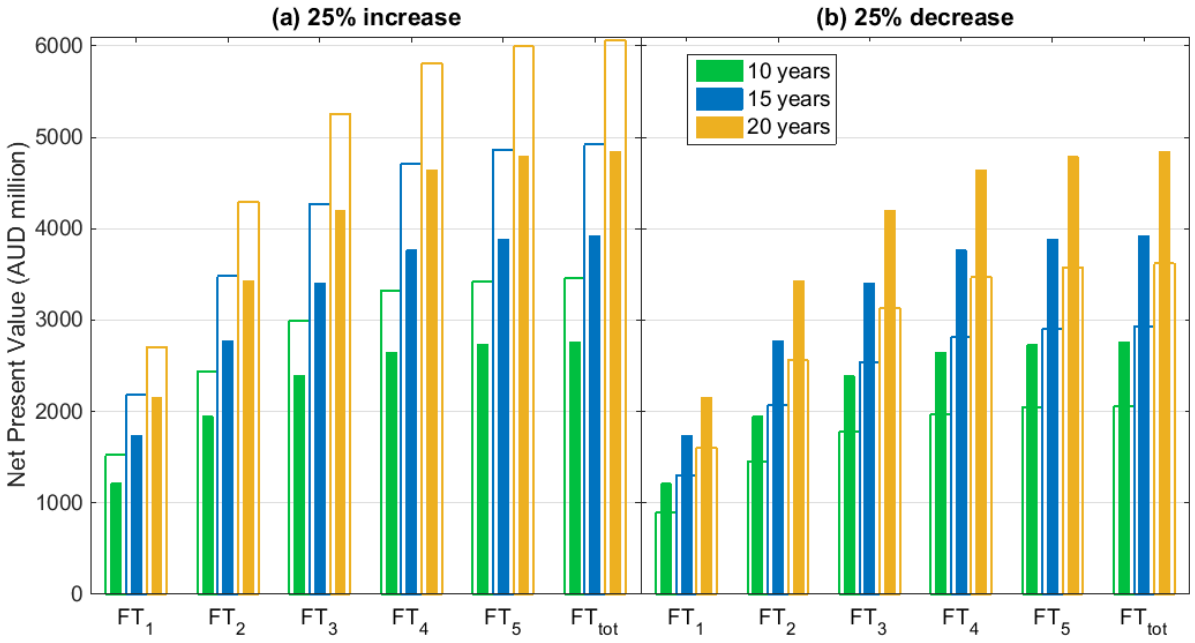

Figure S6: Net Present Value (NPV) of various degrees of improved wheat frost tolerance breeding options with changes in the seed demand; (a) 25% increase in the PHEF seed demand and (b) 25% decrease in the PHEF seed demand. The green, blue and gold colour bars show the baseline economic estimates for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

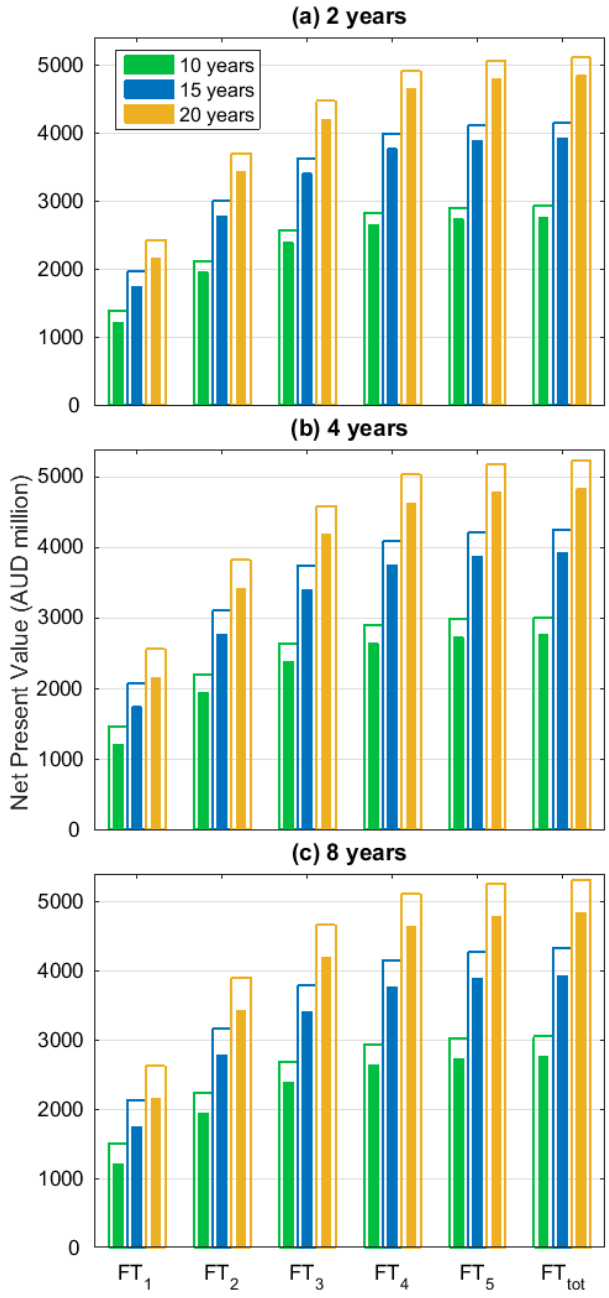

Figure S7: Net Present Value (NPV) of various degrees of improved wheat frost tolerance breeding options with replacement of PHEF seed rate: (a) replacement of PHEF wheat seed after 2 years; (b) after 4 years; and (c) after 8 years. The green, blue and gold colour bars show the baseline economic estimates 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.

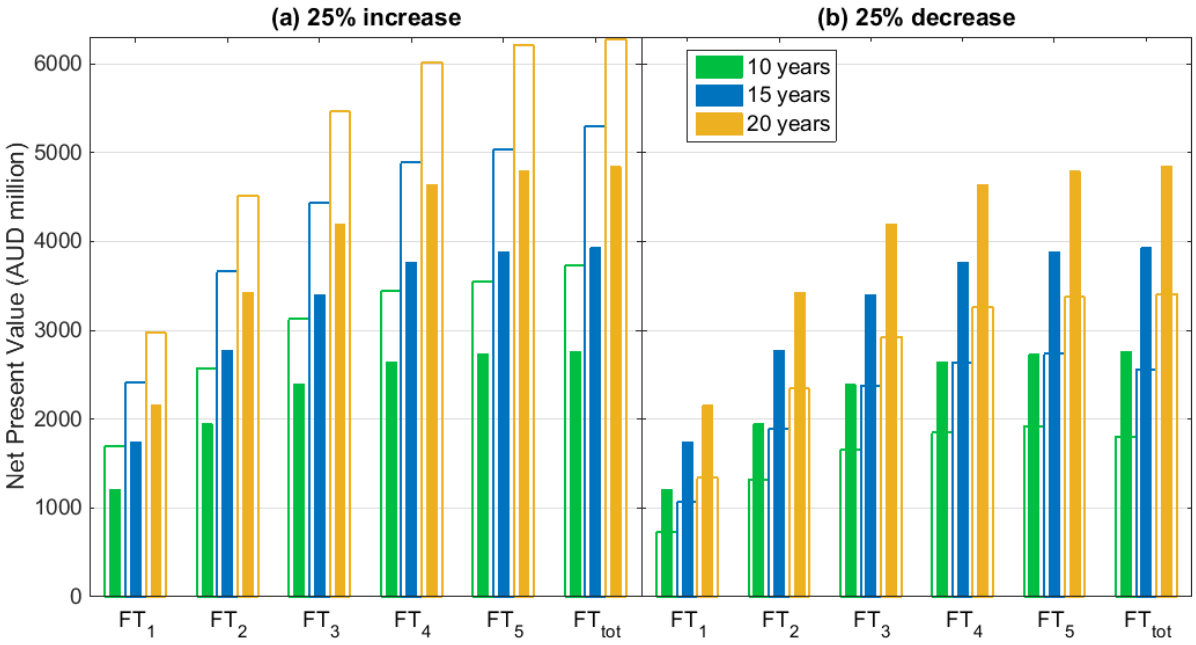

Figure S8: Net Present Value (NPV) of various degrees of improved wheat frost tolerance breeding options with changes in the farm gate price levels; (a) 25% increase in the farm gate prices and (b) 25% decrease. The green, blue and gold colour bars show the baseline economic estimates for variety market 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.

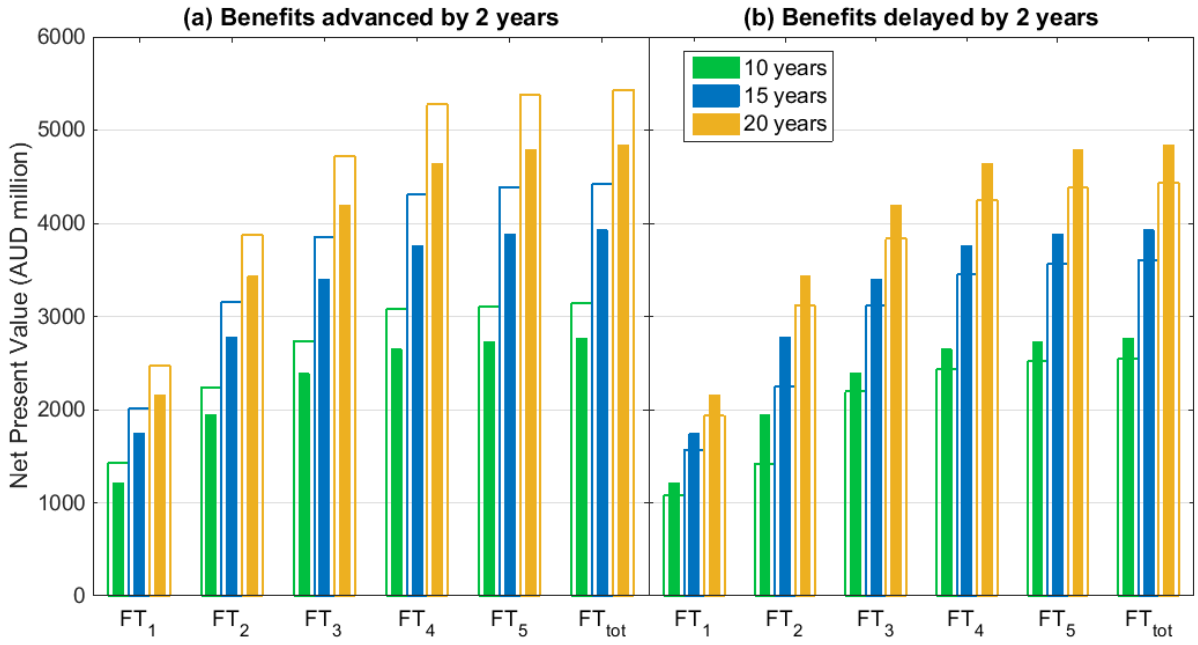

Figure S9: Net Present Value (NPV) of various degrees of improved wheat frost tolerance breeding options with changes in the net benefits streams; (a) benefits delayed by 2 years and (b) benefits advanced by 2 years. The green, blue and gold colour bars show the baseline economic estimates for variety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

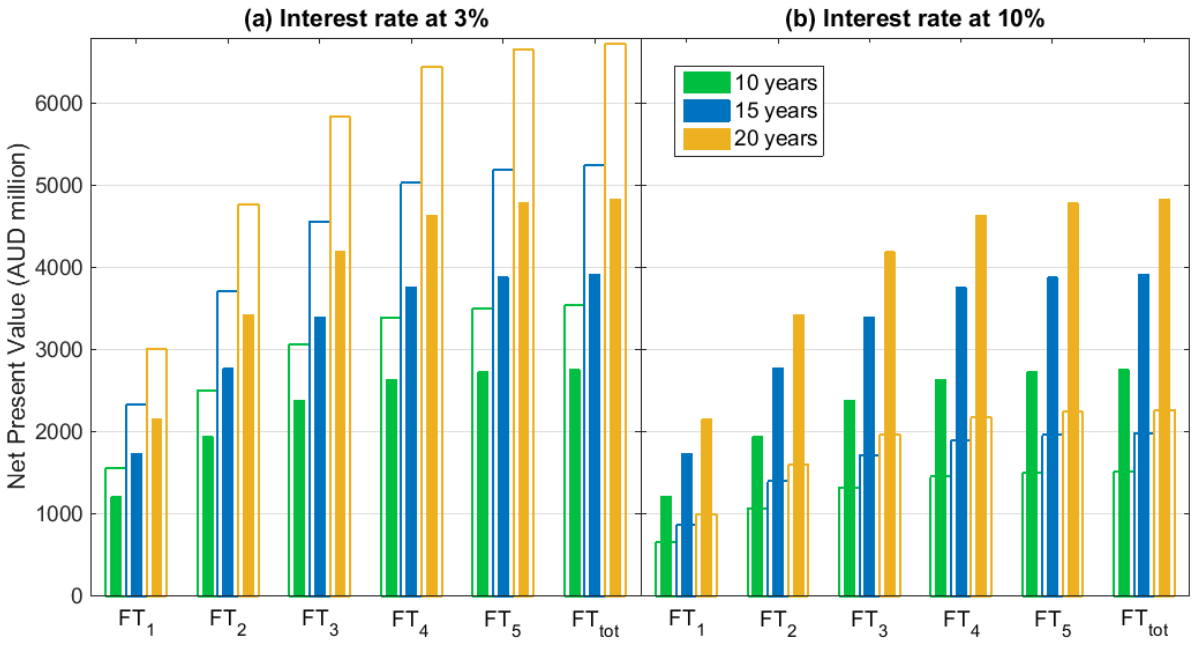

Figure S10: Net Present Value (NPV) of various degrees of improved wheat frost tolerance breeding options with changes in the interest rates; (a) decrease in interest rate at 3% and (b) increase in interest rate at 10%. The green, blue and gold colour bars show the baseline economic estimates for variety market durations of 10, 15 and 20 years, respectively (presented in Figure 6a) against which changing interest rate scenarios (corresponding transparent bars) can be compared.

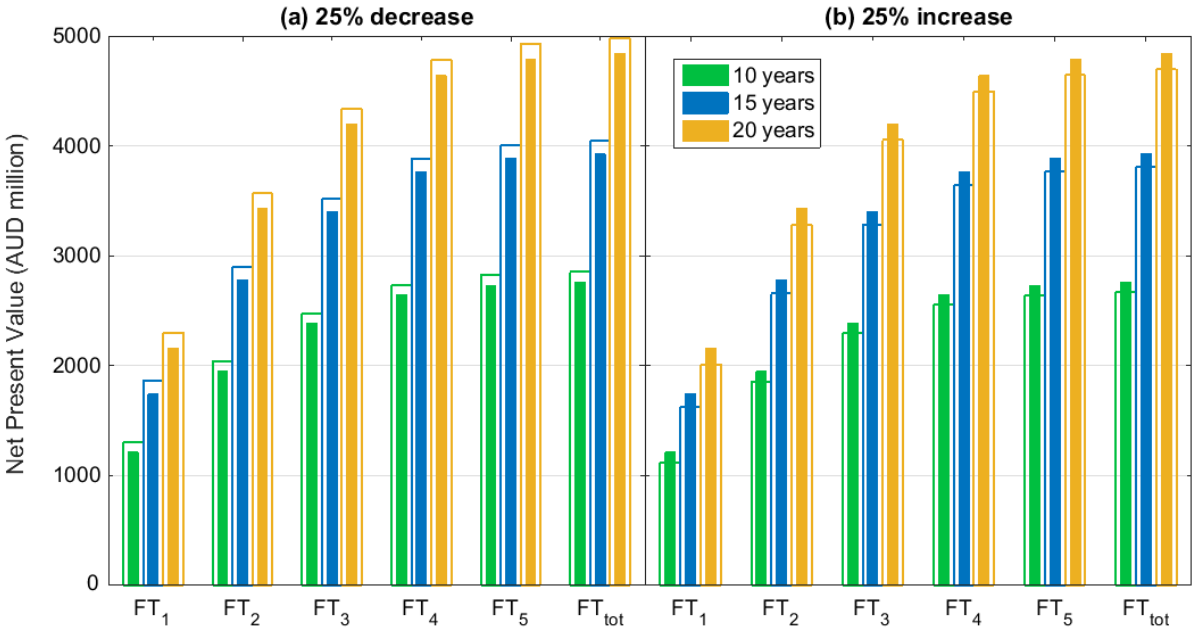

Figure S11: Net Present Value (NPV) of various degrees of improved wheat frost tolerance breeding options with changes in the fixed costs; (a) increase in the fixed cost by 25% or, (b) increase in the fixed cost by 25%. The green, blue and gold colour bars show the baseline economic estimates for variety 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.