Should we invest in cereal pre-breeding now for biosecurity threats?

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Abstract

Investing in pre-breeding for exotic pests and diseases in cereals is characterised as investing in an option of preparedness regardless of whether an incursion occurs. The return to pre-breeding depends on the likelihood of pest arrival, its spread across cereal producing regions and how damaging it will be through time. Any delay in the release of resistant varieties after an incursion translates into yield losses, chemical costs and, for some pests and diseases, price discounts. However, returns to pre-breeding investment are limited by delay time without pre-breeding, management alternatives and the adoption rates for resistant varieties by producers. Our analysis has estimated returns to investment for pre-breeding for six high priority exotic wheat and barley pests and diseases. The methods developed here allows for regional disaggregation and regional pest suitability across Australia's cereal production landscape. Results indicate that pre-breeding investment is viable for only half of the pest and diseases studied. The relatively high return to these can be explained by significant yield effects, rapid spread and widespread pest suitability across regions. Furthermore, a higher average yield loss can offset lower incursion probability. In contrast, those not viable are due to slow spread, small or erratic yield effect and biosecurity trade issues not addressed by resistance. Investing in pre-breeding is highly risky as the modal investment return for all pests and diseases is zero and returns to breeders are short lived.

Keywords: Agricultural investment; Biosecurity; Bioeconomic modelling; Cereal breeding; Risk assessment; CLIMEX, Real options, Karnal bunt, exotic wheat stem rust, barley stripe rust, Russian wheat aphid, Hessian fly, sunn pest

JEL classifications: Q1, O31, O32

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Extended summary

Pre-breeding for exotic pests and diseases involves a set of procedures which include the testing of existing Australian varieties and breeding material for resistance, and the integration of the resistance genes from overseas varieties into Australian adapted cultivars. This type of R&D activity is complex, time consuming and expensive. With pre-breeding investment before the incursion, resistant varieties can be released earlier. In the absence of pre-breeding the expected immediate response to an incursion is the use of chemicals, and an investment in fast-track pre-breeding and breeding to develop and release resistant varieties. The aim of this paper is to measure returns to pre-breeding investment and provide a prioritisation of investment.

Investing in pre-breeding for exotic pests and diseases is characterised as investing in an option of preparedness regardless of whether an incursion occurs. Any delay in the release of resistant varieties translates into yield losses, chemical costs and, for some pests and diseases, price discounts. Our analysis has assessed the returns to investment for pre-breeding for six of Australia's high priority exotic wheat and barley pests and diseases: (i) Karnal bunt; (ii) exotic wheat stem rust; (iii) Russian wheat aphid; (iv) Hessian fly; (v) sunn pest; and (vi) barley stripe rust. We make three critical assumptions: (i) there is a straightforward choice between investing in pre-breeding and always being ready, or waiting until an incursion occurs before investing in a fast-track pre-breeding and breeding program; (ii) resistant varieties and chemicals are the only control options; and (iii) there is no resistance to the new pest or disease in current or ready to release varieties in Australia. The return to pre-breeding depends on the likelihood of pest or disease arrival to Australia, its spread across cereal producing regions and how damaging it will be through time. The benefits come from reducing the delay between pest and disease arrival and the availability of resistant varieties.

Results indicate that pre-breeding investment is viable for exotic wheat stem rust, Russian wheat aphid and barley stripe rust with benefit cost ratios (BCR) of 29, 14 and 13 over 50 years at a 5% discount rate. The BCR and reasoning for the rate of return for each pest and disease is summarised below:

(i) Karnal bunt (BCR, approximately 0) a slow spreading disease, negligible yield effect, spraying is not economically feasible, and once infected grain quality cannot be improved by spraying, high costs are due to biosecurity issues and trade restrictions that are not addressed by resistant varieties.

(ii) Exotic wheat stem rust (BCR, 29) relatively high probability of arrival, rapid spread with significant yield effect and spray costs, and the majority of cereal region is susceptible.

(iii) Russian wheat aphid (BCR, 14) low probability of arrival, rapid spread with significant yield effect and spray costs, and majority of cereal region is susceptible.

(iv) Hessian fly (BCR, 0.1) low probability of arrival, slow spread with small yield effect, spraying not an effective control and the majority of cereal region is susceptible.

(v) Sunn pest (BCR, 0.7) low probability of arrival, slow spread, erratic yield effect which impacts on quality, significant spray costs and the majority of cereal region is susceptible.

(vi) Barley stripe rust (BCR, 13) relatively high probability of arrival, rapid spread with significant yield effect and spray costs, and the majority of cereal region susceptible.

Our analysis showed that there was considerable risk associated with pre-breeding investment. Pre-breeding does protect against low probability events that can result in substantial losses, but the expected returns from this investment are low.

Chemical demand to control the rusts and Russian wheat aphid may be substantial after an incursion but before resistant varieties become available. Although demand is not expected to be excessive initially, it will increase as the pest or disease spreads over time. But this gives time to increase chemical supply stocks. Average annual volumes of chemical at standard concentration and application rate are: propiconazole for exotic wheat stem rust, 185,700 L with pre-breeding and 448,900 L without pre-breeding; chlorpyrifos for Russian wheat aphid, 179,500 L with pre-breeding and 427,100 L without pre-breeding; and propiconazole for barley stripe rust, 86,000 L with pre-breeding and 200,700 L without pre-breeding.

The industry benefits from investment in pre-breeding will depend upon industry funding. It is unlikely that commercial breeding companies would have an incentive to bear the costs of investment when the returns are extremely risky. In addition, the competitive advantage in terms of increased end point royalties is short lived as breeding firms use other firms' varieties in their new breeding programs.

The results presented here come with the caveat that estimating costs of exotic pests and diseases across the Australian cereal industry is subject to a high level of uncertainty. This study was also based upon a set of restrictive assumptions relating to producer strategies for adapting to new pests and diseases. Given these limitations there is a case for a moderate level of investment in exotic wheat stem rust, Russian wheat aphid and barley stripe rust. This investment should ensure that Australia has the research capacity to respond to high priority cereal pests and diseases, and maintain close links with international groups involved in developing new varieties and adaptation responses in regions where it is endemic. It is expected that the approach and methodology developed in this paper will be easily applicable to a wide range of biosecurity-related investment decisions where there is considerable uncertainty as to the nature of a future threat.

1. Introduction

> *"Invention is here interpreted broadly as the production of knowledge. From the viewpoint of welfare economics, the determination of optimal resource allocation for invention will depend on the technological characteristics of the invention process and the nature of the market for knowledge."* (Arrow, 1962, p. 609)

One of the main determinants of increased productivity in agriculture is the development of new cereal varieties. New varieties are estimated to have increased yields by one percent per annum over the last century (Duvick, 2005; Fischer and Edmeades, 2010). Cereal breeding can select for traits such as yield and quality, as well as pest and disease resistance. In Australia, cereal breeding is largely a commercial enterprise with three main breeding companies, Australian Grain Technologies, Intergrain and LongReach Plant Breeders. Their income depends upon seed sales and endpoint royalties (EPRs) earned from producers. For producers to adopt new varieties and pay the EPRs the new variety must increase their expected profits.

The Australian grains industry is at risk from high priority exotic cereal pests and diseases (pest), some of which have been listed as Emergency Plant Pests[1] (EPPs) (PHA, n.d.; Phillips Fox, 2013). The value of pre-breeding cereal varieties that show resistance to these pests is contingent upon the pest establishing in Australia. For our purposes, pre-breeding is defined as:

> "*various activities of plant breeding research that have to precede the stages involved in cultivar development, testing and release"* (GIPB and FAO, 2011)

Investing in pre-breeding is intrinsically risky as there is uncertainty about the use of the resulting genetic material, adoption of the new varieties and the time of release. Due to uncertainty about the incursion of an exotic pest the return on investment for pre-breeding for resistance would tend to be more variable than for existing pests. High risk investments of this type may warrant public investment if they represent an efficient social return on capital, but for undiversified cereal breeders the variance of returns is too high to invest in. Further, the 'genetic' spillover effects that characterise cereal pre-breeding and breeding would mean that varieties providing resistance to pests would only provide a short-term competitive advantage to the breeding firm that releases the first resistant variety (Alston *et al.*, 2011). Thus there is potential for a market failure that results in an underinvestment in pre-breeding for exotic pests.

The aim of this study was to assess the returns to investment in pre-breeding for six of Australia's high priority cereal pests and diseases. The pests are (i) Karnal bunt (KB), *Tilletia indica* (Mitra); (ii) exotic wheat stem rust (EWSR), *Puccinia graminis* f. sp. *tritici* (Eriks. & E. Henn.), *Pgt* such as Ug99 or its derivatives; (iii) Russian wheat aphid (RWA), *Diuraphis noxia* (Mordovilko); (iv) Hessian fly (HF), *Mayetiola destructor* (Say); (v) sunn pest (SP), *Eurygaster integriceps* (Puton); and (vi) barley stripe rust (BSR), *Puccinia striiformis* Westend f. sp. *hordei* (Eriks. & E Henn.), *Psh*. In addition, the economic feasibility and

[1] An emergency plant pest (EPP) is defined in the Emergency Plant Pest Response Deed PHA (Phillips Fox, 2013).

expected chemical use to control the pest and reduce losses has been assessed to forecast future demands in the event of an incursion with and without pre-breeding.

The paper is organised as follows. The next section gives a general model of the costs of an incursion, adaptation and benefits of resistant varieties. Section 3 gives data sources and parameter values. Section 4 presents expected returns on investment and a sensitivity analysis. Section 5 provides concluding comments and discussion. The Appendices gives reference tables of the assumptions, breeding summaries and parameters.

2. Investment return model

In describing investment decisions in general, Dixit and Pindyck (1994, p. 3) identify three characteristics that apply to cereal pre-breeding. First, investment expenditure is largely irreversible. Second, future rewards from investment are uncertain. Third, the timing of investment is not fixed, for instance investment could be immediate or delayed until the pest incursion occurs or the risk of an incursion reaches a critical level. In this setting there may be a so-called real option value of investing.

The investment return model estimates the benefits of investing in pre-breeding as a real option. The benefits were determined by the time delay between pest incursion and resistant variety release. These benefits vary across cereal producing regions due to variations in yield and pest suitability, and over time due to discounting. Further, pest characteristics are critical in determining the costs of delaying resistant variety availability. The pest characteristics, such as biosecurity status, spread rate, damage and treatment costs were included in the model.

The model makes the following simplifying assumptions.

> *Assumption 1. The return on investment in pre-breeding before the incursion occurs were measured as returns to the Australian grains industry over a 50 year planning horizon, and compared to an alternative of fast-track investment in response to an incursion. The planning horizon encompasses approximately five cereal breeding cycles and, for most pests, at least one expected incursion.*
>
> *Assumption 2. The analysis assumes a base year of 2011 and that production data from the ABS Agricultural Census 2011 is typical. This enables regional disaggregation and regional pest suitability across the cereal production landscape of 195 ABS level 2 statistical areas (SA2) selected.*[2]
>
> *Assumption 3. If an incursion occurs, then with pre-breeding there is a relatively short delay, assumed to be 5 years, before resistant varieties are released. Without pre-breeding there is a longer delay, assumed to be 10 years, and additional costs.*

[2] The Australian Bureau of Statistics (ABS) 2010-11 production data was the first to be reported at the Bureau's statistical area level 2 aggregations. As future Agricultural Census data becomes available in this format the measures of yield and area could be given as averages.

Assumption 4. The pest does not affect other production costs (such as fertiliser, endemic pest chemical control and herbicides) and the area of the cereal crops remains constant.

Assumption 5. No incursion control, containment or eradication takes place. At most there were only two options to reduce losses from the pest, chemicals (where feasible) and resistant varieties. Other options such as cultural control, integrated pest management, altering trade agreements and area wide freedom were not assessed.

Assumption 6. At present there is no resistance to the pest in current or ready for release varieties in Australia.

The pre-breeding investment decision is summarised in Figure 1. If an incursion occurs at time t^*, the following occurs. The net margin is reduced from $\pi^{\text{no pest}}$ to π^{pest} if no suitable chemicals are available in Australia, or to $\pi^{\text{pest, spray}}$ if chemicals are used to control the pest (Figure 1a). When resistant varieties become available profitability recovers to $\pi^{\text{pest, resist}}$. This occurs either after a short delay with pre-breeding Δt^{pb} or a longer delay without pre-breeding Δt^{nopb} and a fast-track breeding response following the incursion.

Investment into pre-breeding I^* can occur before the pest incursion is observed (Figure 1b) and indicates a level of readiness that reduces the time of Δt^{pb}. Alternatively, the breeding investment response with no pre-breeding is initally a period of high invesment at I^{max} (Figure 1b) towards fast-track pre-breeding for the pest. Once varieties are established after Δt^{nopb}, investment is reduced to I^* per annum to cover the costs of maintaining resistant varieties. This is a level of pre-breeding investment assumed to be equivalent to that for pre-breeding before the pest incursion.

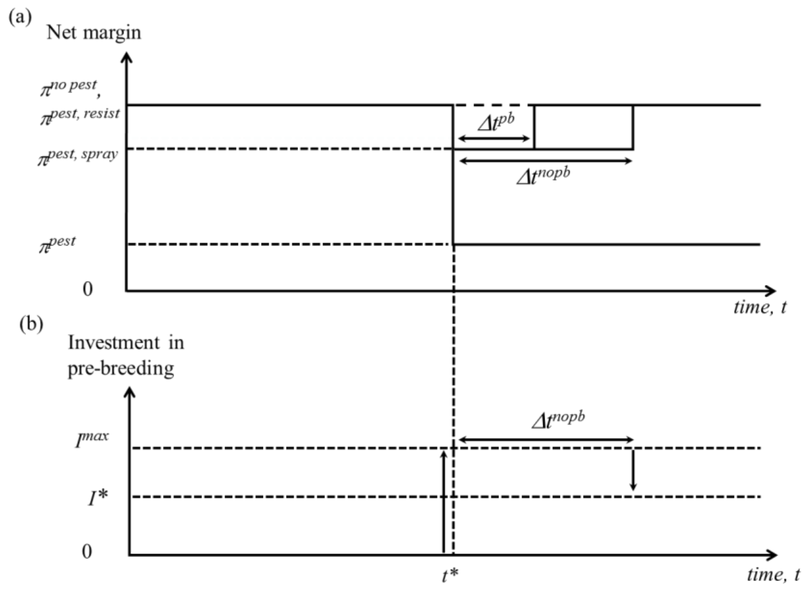

Figure 1. Investment and incursion impact on the net margin. In the event of an incursion the level of investment in pre-breeding impacts on the net margin for options with and without pre-breeding and the use of chemical treatment. (a) Net margin, revenue less variable costs of adapting to the pest, $\pi^{no\ pest}$ = prior to incursion, π^{pest} = with no control or resistance, $\pi^{pest,\ spray}$ = with chemical use, and $\pi^{pest,\ resist}$ = variety with resistance. (b) Investment options into pre-breeding, 0 = no investment, I^* = invest in pre-breeding, I^{max} = fast-track breeding response.

2.1. Production revenue and costs

The term π^j defined below in (1) is the expected present value of profit from Australian wheat or barley production across all regions before and after a pest incursion and with pre-breeding (j = pb) or without pre-breeding (j = *nopb)*. Calculated by the following piecewise function:

$$\pi^j = \begin{cases} \sum_s^S \sum_t^T \{(a_{st}(p_{st}y_{st} - c_{st})\}\,\delta^t, \quad t < t_I \\ \sum_s^S \sum_t^T \left\{(a_{st} - a_{st}^I)(p_{st}y_{st} - c_{st}) + \sum_{k \in R_{st}^{j,t_I}} \omega_{st}^k\, a_{st}^I((p_{st}\theta_{st}^k)\,(y_{st}\varphi_{st}^k) - c_{st}^k - c_{st}\right\}\delta^t, t \geq t_I < t_I + \Delta t^j \\ \sum_s^S \sum_t^T \left\{(a_{st} - a_{st}^I)(p_{st}y_{st} - c_{st}) + \sum_{k \in R_{st}^{j,t_I}} \omega_{st}^k\, a_{st}^I((p_{st}\theta_{st}^k)\,(y_{st}\varphi_{st}^k) - c_{st}^k - c_{st}\right\}\delta^t, t \geq t_I + \Delta t^j \end{cases} \quad (1)$$

where subscript s (s = 1, …, S) gives the wheat or barley producing regions, t (t = 1, …, T) is the year, and T the end of the planning horizon. The variables are defined as follows: a_{st} is the total production area, a_{st}^I is the infested/infected production area, p_{st} the wheat or barley price per tonne, y_{st} the yield per tonne, and c_{st} other production costs per hectare. The term δ^t is a discount factor, where $\delta^t = (1 + r)^{-t}$ and r is the discount rate.

A pest incursion has two potential effects that depend on the management adaptation (no action, chemicals and resistant varieties) indicated by superscript k, these are: (i) a proportional yield penalty ($0 \leq \varphi_{st}^k \leq 1$); and (ii) a price reduction ($0 \leq \theta_{st}^k \leq 1$). The variable cost of the management option is given by c_{st}^k. The proportion of the area subject to management option k is ω_{st}^k. Here $R_{st}^{jt_I}$ is the set of all management options available at time t across the infested/infected area. The sum of ω_{st}^k over available management options must equal one.

2.2. Probability of incursion and spread

The analysis used a simple model of incursion and spread based on Stansbury *et al.* (2002). This model identifies three stages: (i) pest establishment; (ii) local spread diffusion; and (iii) jumps between regions.

(i) Pest establishment.[3] The number of pest establishments in Australia (I_t) is assumed to be derived from a Poisson distribution:

$$I_t \sim Poisson(n_t) \quad (2)$$

[3] Stansbury *et al.* 2002 distinguished between pest entry and establishment. In this model we adopt a reduced form of their analysis that only includes the probability of successful establishment.

where n_t gives the average number of established incursions per year in Australia. Typically these are very low. When an incursion event occurs, it is randomly allocated to a cereal producing region. This is converted into a binary vector indicating the presence or absence of an incursion at time t, z_t. The incursion establishes an arbitrarily small outbreak area of 100 ha.

(ii) Local spread diffusion. Once a pest has established in a region, then uniform spread of the infested/infected area occurs according to a logistic growth function:

$$\frac{da_{st}^{I}}{dt} = \rho_s a_{st}^{I}\left(1 - \frac{a_{st}^{I}}{a_{st}}\right) \qquad (3)$$

where ρ_s is the intrinsic spread rate of the pest.

(iii) Jumps between regions. The probability of an uninfested/uninfected region (s) becoming infested/infected from all other regions (ψ_{st}), is given by a binomial distribution:

$$\psi_{st} = [1 - (1 - \psi_c)^{h_{st}}] \qquad (4)$$

where ψ_c is the probability of spread between a hectare of infested/infected land and a region (s) and h_{st} is the weighted area infested/infected and calculated as follows:

$$h_{st} = \left(\sum_{s' \neq s} w_{s,s'} a_{s't}^{I}\right)/A \qquad (5)$$

where *A* is the total area of wheat or barley in mainland Australia. The distance weight $w_{s,s'}$ is species specific and determined by pest dispersal distances per year:

$$w_{s,s'} = e^{\vartheta d_{s,s'}};\ \vartheta = ln(w^{min})d^{max} \qquad (6)$$

The parameter ϑ reduces the distance weight to w^{min} at the maximum expected annual dispersal distance for a pest. Where *ln* indicates natural logarithms and d^{max} is the maximum annual dispersal of the pest.

2.3. Real option value

To simplify the analysis the investment decision was assessed as if an amount is invested in a fund that provides ongoing investment into pre-breeding for new varieties that are resistant to an exotic pest over the planning horizon. Thus, this initial investment could be considered as if the investor pays a premium for the option in the future to have resistant varieties available quickly in the event of an incursion. Another analogy that could be drawn here, is investing in pre-breeding is similar to purchasing an insurance contract that reduces costs in the event of an incursion. The maximum real option value of pre-breeding (J) is the expected difference between the present value of net margins and the expected cost of a fast-track breeding response C^{nopb}. For any pest the option value of pre-breeding is:

$$J = E[\pi^{pb} - \pi^{nopb} - C^{nopb}] \quad (7)$$

The expected value was estimated by Monte Carlo simulation where a thousand time paths for the incursion were simulated.

3. Model parameters

Estimating the real option value of investing in pre-breeding at the start of the planning horizon requires the following sets of parameters: (i) pre-breeding costs and time delays; (ii) effects of the pest relating to chemical control costs, yield and price; (iii) pest incursion risk and spread rate; and (iv) region specific pest suitability and yield losses. This section draws from the review for each pest by Christopher *et al.* (2014) and other references as listed. The parameter values, relevant details and sources are presented in Appendix D Table 9.

3.1. Pre-breeding costs, time delays and adoption

International collaboration with countries that have already experienced a pest and identified resistance genes are a source for germplasm and phenotypic data which helps to reduce costs of pre-breeding and time delays. For pests such as Karnal bunt, exotic wheat stem rust, Russian wheat aphid, Hessian fly and barley stripe rust, resistance genes have been identified and the cost of pre-breeding is relatively low. However, when genes are not yet identified, for example sunn pest, the cost is much higher and development time may be longer. The status of cereal breeding for these pests are summarised in Appendix B Table 7. The steps and the costs involved in pre-breeding are presented in Appendix C Table 8. When the resistance source is unknown pre-breeding is expected to cost $1,282,848 over ten years and $532,848 when the source is known (Diane Mather Uni. of Adelaide, 2014 pers. comm.). The additional $750,000 for sunn pest is attributed to the discovery of the gene for resistance. Ongoing expenditure to maintain the pre-breeding program as the pest evolves and varieties change can be expected at a similar value to the initial cost ($532,848) over the remaining time horizon. These costs are consistent with funding allocated to pre-breeding projects by The Grains and Research and Development Corporation (GRDC) (White and Christopher, 2014).

Our assumptions about the cost of pre-breeding:

> *Assumption 7. The cost of the pre-breeding investment in year 1 to fund a pre-breeding program is $1,282,848 for sunn pest and $532,848 for Karnal bunt, exotic wheat stem rust, Russian wheat aphid, Hessian fly and barley stripe rust. After the initial investment, a further $532,848 discounted at 5% is required every ten years thereafter, to maintain the pre-breeding program at the same level. Net present value of investment for sunn pest is $2,009,773 and $1,259,773 for all other pests over the planning horizon.*

Adoption of any single variety regardless of its resistance is rarely above 50 – 60% of the total cropping area in Australia, particularly within the first five years (Shackley *et al.*, 2014; Trainor *et al.*, 2015). The proportion of infested/infected cropping land adopting the resistant variety was set at 60%.

3.2. Chemical costs, yield and price effects

The chemical controls selected are those applied in countries where the pest has established, and are also available in Australia. The costs of chemicals (c_{st}^{k}), application rates and application costs used to control the pest in the absence of resistant varieties are given in Table 5. Chemical use reduces the yield losses that would have occurred without control however, the effectiveness is never 100%, therefore has been set at 80%. Chemicals were only applied in a statistical area if economically the benefit exceeded the cost in the statistical area.

Yield losses due to pest damage are key to determining the return to pre-breeding. The approach used to estimate losses was a review of the literature to calibrate a PERT distribution that describes a minimum, maximum and modal proportional yield loss without control, similar to that used by Hodda and Cook (2009). The yield loss ranges and their frequency were used to calibrate a distribution for each pest. The mode and shape parameter (λ) were adjusted to align with the expected minimum, maximum and modal yield loss years given the frequency and range described in the literature. This method helps to overcome the uncertainty of yield losses in different environments, particularly for Australia where the outcome of the pest is unknown. This also avoided using a single rate of yield loss over the 50 years in the simulations, and includes an upper bound for occasional epidemic years that may occur.

The yield reduction distributions for the six pests are given in Figure 2. The modal yield loss given here has been interpreted as the mode in a perfectly suitable area for the pest. To accommodate spatial yield variability the pest suitability index described in subsection 3.4 adjusted the mode and redefined the distribution across the cropping landscape conditional on the level of pest suitability in each statistical area. For example, any statistical area with a pest suitability of less than 100% the potential yield loss is scaled down, since the mode shifts to the left. The minimum and maximum losses do not change, but the distribution that the proportional yield loss draws from has. The yield loss was drawn randomly from the adjusted distribution for each statistical area in each of the 50 years and applied to the yields given for the base year of that area.

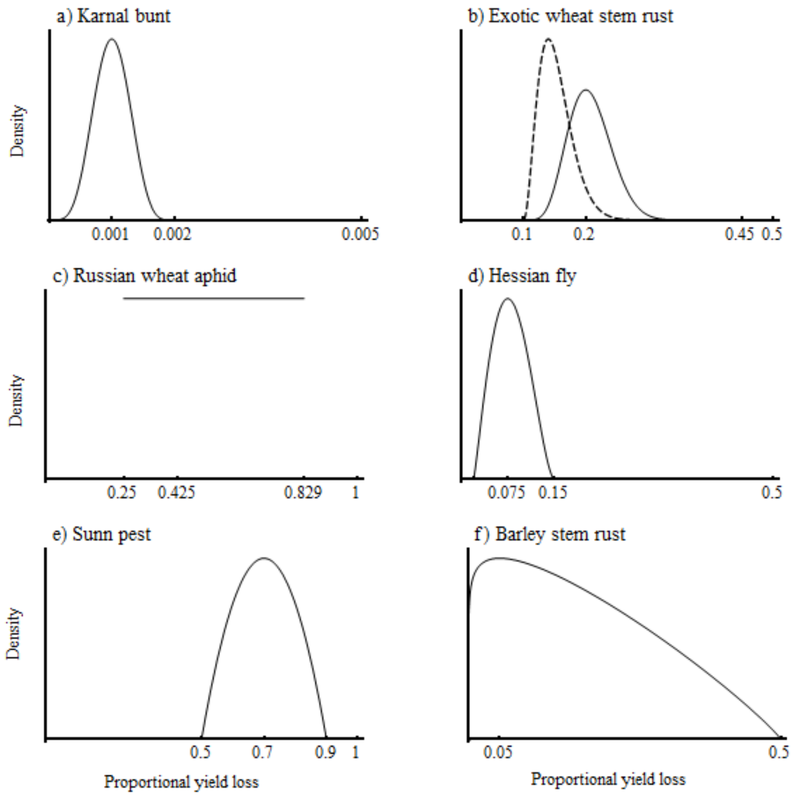

Figure 2. Probability density functions for proportional yield loss with minimum, maximum, modal and PERT shape given for a) Karnal bunt (0.00001, 0.002, 0.001, 10), b) exotic wheat stem rust (0.10, 0.45, 0.20, 20) , c) Russian wheat aphid (0.250, 0.829, 0.425, 0), d) Hessian fly (0.020, 0.150, 0.075, 3), e) Sunn pest (0.50, 0.90, 0.70, 1) and f) barley stripe rust (0.0001, 0.50, 0.05, 1). —— Pest suitability high ----- Pest suitability adjusted. Example of the shift in mode for a region that is less suitable to exotic wheat stem rust (b). *Note: Different X-axis scales.*

Incursions can result in a price reduction (θ_{st}^{k}) due to biosecurity related issues such as quality downgrades from milling to feed wheat, as is the case of Karnal bunt, or grain damage caused by the pest itself such as sunn pest (Critchley, 1998; Murray and Brennan, 1998). The regional price is reduced by 20% for these two pests, which is the average difference between the milling and feed wheat price (Murray and Brennan, 1998).

3.3. Incursion risk and spread rate

Other parameters difficult to estimate were the probability of establishment after an incursion for each pest, their spread rate and long distance jump probabilities. Economic analysis requires probabilities to be assigned to simulate incursions. To estimate a consistent set of subjective probabilities and rates, biological and spread evidence from countries where the pest is established, or similar pests in Australia and elsewhere were gathered. The evidence is summarised in Christopher *et al.* (2014).

Pest incursion establishment probability (n_t) has considered the likelihood and related factors that lead to the pest arriving in Australia. For example, the rusts are expected to arrive and establish much sooner than Karnal bunt, Russian wheat aphid, Hessian fly and sunn pest. An implication of the probability of incursion is a pest free “survival probability” across the planning horizon. The probability of remaining incursion free for 1 in 25 year and 1 in 100 year incursions from a Poisson distribution is illustrated in Figure 3.

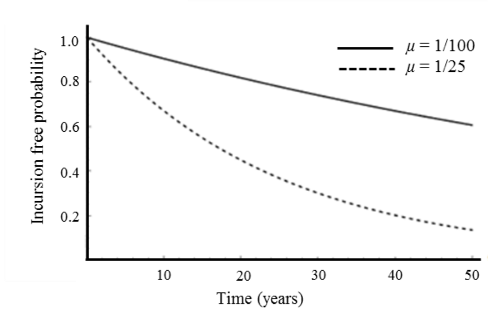

Figure 3. Survival probability from a Poisson distribution of remaining pest free for two arrival periods, 1 in 25 years and 1 in 100 years.

The initial incursion is randomly assigned to a statistical area suitable for the pest. In addition to the pest spreading (ρ_s) within the statistical area, it can jump to another statistical area. The probability of jump (ψ_{st}) is driven by the area infested/infected in statistical areas, the pace at which the pest spreads at and the maximum distance (d^{max}) the pest is likely to disperse in a year. In effect, the rusts and Russian wheat aphid were equal in our estimates of their spread at 600% per year, probability to jump to another area and disperse up to 2,000 kms per year. The remaining pests, Karnal bunt, Hessian fly and sunn pest have a slower spread rate at 100 – 170% per year, a lower probability of jump and dispersal distances limited to 300, 45 and 250 kms per year respectively. Figure 4 illustrates how distance between statistical areas is weighted.

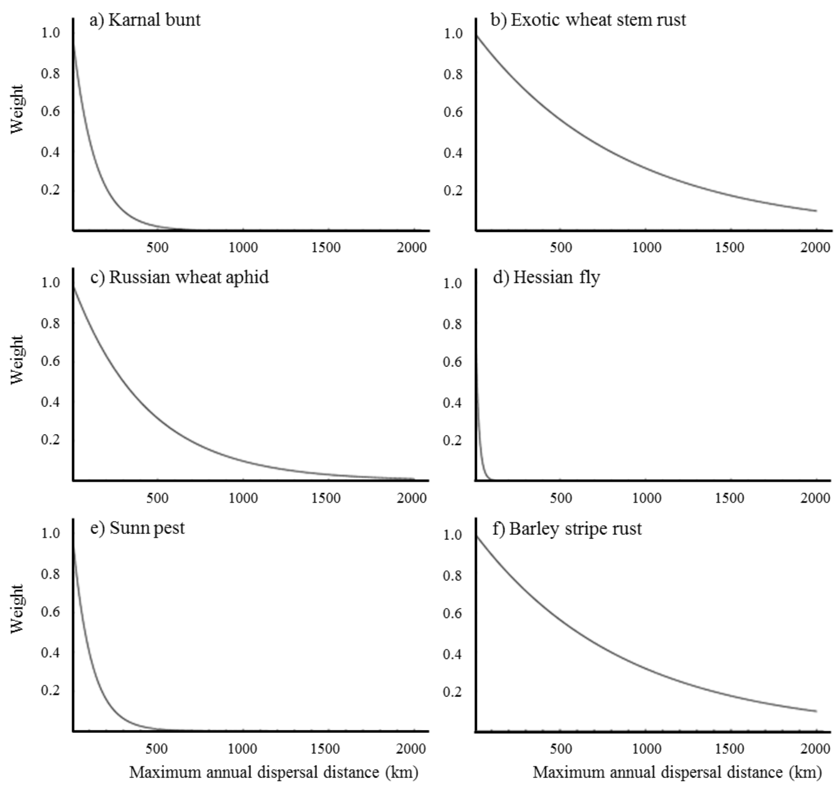

Figure 4. Weighted annual dispersal distances for each pest.

3.4. Region specific pest suitability and yield losses

The economic effect of a pest incursion is largely determined by the pest distribution and level of yield losses that occur. Here, Australia’s susceptibility to each pest was predicted by climate suitability across the 195 SA2 areas growing cereals.

Assumptions adopted to construct the climate suitability indices include:

Assumption 8. Climate is the only factor determining the presence of the pest.

Assumption 9. Climatic suitability determines the damage and yield loss expected.

This analysis used the CLIMEX v3 model software (Sutherst *et al.*, 2007; Sutherst and Maywald, 1985) and ArcGIS to investigate climatic suitability and yield risk. Different CLIMEX applications were used depending on the information available about each pest, with the exception of Karnal bunt as described later. A spatial model and database was developed in ArcGIS to integrate the ABS 2010-11 production data for wheat and barley (ABS, 2012a, 2012b); the land use data from the Department of Agriculture 2005-06 for cereals (excluding rice), legumes and oilseeds (ABARES and DA, 2006); and the CLIMEX results. From the spatial intersection of the CLIMEX suitability indices and the specified cropping areas an estimate of the damage to wheat and barley yield was derived for each SA2.

This section describes the methods used to determine the pest distribution and suitability for each pest in Australia’s cereal growing regions. Firstly, is Karnal bunt. This is followed with a brief description of the dynamic climate suitability CLIMEX model and the ArcGIS modelling used for exotic wheat stem rust, barley stripe rust and Russian wheat aphid, and then evidence of synchronisation of the cropping season and pest at two specific locations. Next is Hessian fly and sunn pest, which used the climate matching model.

(i) Karnal bunt

For Karnal bunt, 15 regions were identified by Murray and Brennan (1998) as suitable for development using the Heat Thermal Index (Jhorar *et al.*, 1992) . These have been linked with the current SA2 regions and expected to have the same level of impact throughout these regions.

CLIMEX dynamic climate suitability model and ArcGIS

The dynamic CLIMEX model was used for exotic wheat stem rust, barley stripe rust and Russian wheat aphid. In this model the climate data used was the CliMond global climate data at 10’ resolution (Kriticos *et al.*, 2011). This climate data is based on historical datasets from 1951-2000, and is centred on 1975. CLIMEX calculates the potential for population growth and persistence for each 10 arc minute or geo-referenced grid cell in a uniform format across the landscape. As well as a distribution map, CLIMEX offers an array of indices that describe the constraints or favourableness of the location for the species in terms of growth and stress, based on the climate.

CLIMEX estimates an Ecoclimatic Index (EI), this is an aggregate measure of climatic suitability scaled between 0 and 100. In general, an EI greater than 30 represents a favourable climate (Sutherst *et al.*, 2007). The annual Growth Index (GI_a), generated from the weekly Growth Index (GI_w) measures the potential for population growth during favourable climate conditions (Wharton and Kriticos, 2004). The Growth Index indicates suitability of conditions for growth, but not necessarily ongoing persistence. The union of the GI_w and stress indices (Dry, Wet, Cold, Heat and Hot-wet) form the overall annual EI.

The CLIMEX data was imported into ArcGIS, as was the statistical regions and corresponding grain production data, and land use data (ABARES and DA, 2006; ABS, 2012a, 2012b, 2012c). The geostatistical procedure kriging, was used to spatially interpolate a raster surface from the CLIMEX data points. This was then intersected with the statistical regions, the grain production data, and the land use data. The interpolated EI results were divided into bands from 1 through to 7, where (1) is when the EI was equal to 0; (2) EI 1 – 10; (3) EI 11 – 20; (4) EI 21 – 30; (5) EI 31 – 40; (6) EI 41 – 50; (7) EI 51 - 100. Wheat stem rust is expected to persist where the EI band is 2 or more (Beddow *et al.*, 2013). After reviewing known locations of Russian wheat aphid from the global distribution and testing the EI at a sample of locations, we concluded that Russian wheat aphid damage can be expected where the EI band is 4 or more.

(ii) Exotic wheat stem rust and barley stripe rust

The exotic wheat stem rust parameters are from Beddow *et al.* (2013) and adjusted to fit known local distribution in Queensland and New South Wales. Only rainfed wheat was analysed. To ensure our results coincided with Beddow *et al.* (2013) the Dry, Cold, Heat and Hot-wet Stress Indices maps were replicated and visually compared. Validation with known locations where wheat stem rust occurs in Australia identified the need for an adjustment in a few parameter values. Areas known to suffer from wheat stem rust such as Emerald, Theodore and Biloela in Central Queensland, Dalby, Brookstead, Pittsworth and Goondiwindi in Southern Queensland, and Narrabri, Tamworth, Gatton, Casino, Kyogle in New South Wales (G. Platz DAF Qld, personal communication, 2014) had been excluded in the potential distribution. To include these locations without significant changes in the general distribution of the disease the minimum soil moisture parameters were adjusted downward. The minimum soil moisture was changed from 0.30 to 0.15, and the optimum soil moisture changed from 0.60 to 0.20. The CLIMEX model parameters are presented in Appendix E Table 10.

Further distribution validation occurred by adding the known locations of wheat stem rust, Ug99 or derivatives from sources such as CABI (2015a), the CIMMYT RustMapper (2012) and Department of Agriculture Western Australia (Beard *et al.*, 2004). A significant discrepancy was the presence of stem rust in the northern states of the U.S., whilst CLIMEX indicated it was not climatically suitable. In the northern states the winter conditions are not favourable for continued persistence of wheat stem rust, however wheat stem rust epidemics do occur. These northern areas are reinfected by airborne urediniospores blown from the southern states and northern Mexico annually causing epidemics, particularly when the weather is conducive to infection and spread (Leonard, 2013; Milus *et al.*, 2010). Beddow *et al.* (2013) suggest that an area with an EI equal to zero and a GI_a equal to or greater than 10 is an area where persistence of wheat stem rust is not likely, but epidemics could occur during favourable seasons. The global maps for the Ecoclimatic suitability and known distribution of wheat stem rust and Ug99 or its derivatives are displayed in Figure 5a and b. These same results were used for barley stripe rust.

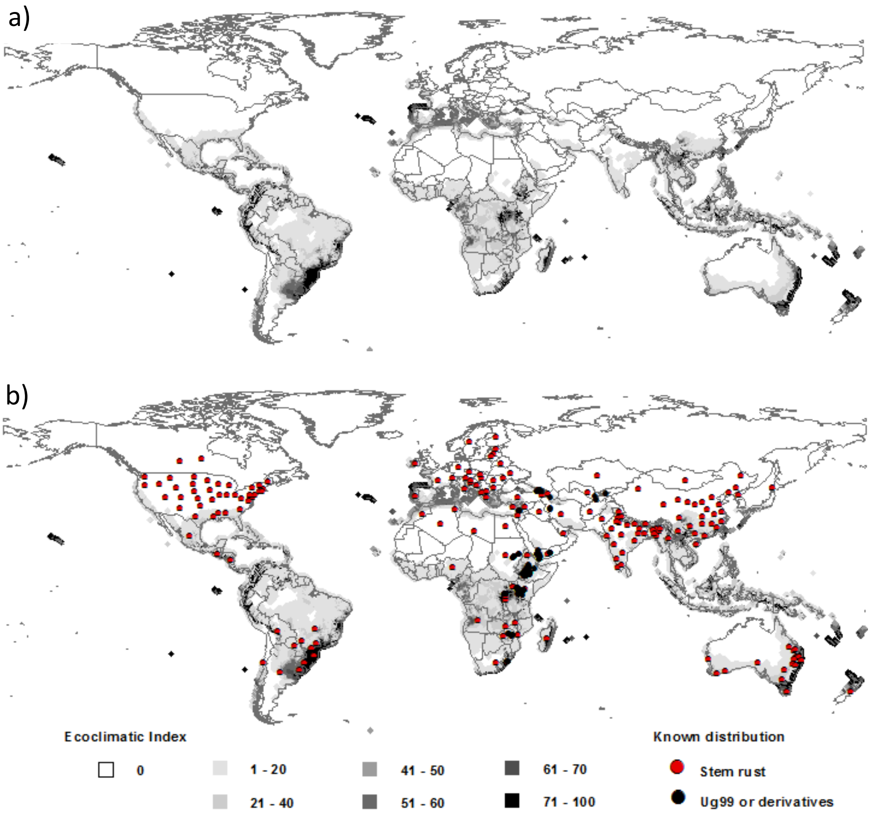

Figure 5. Potential and known distribution of wheat stem rust. a) Global vulnerability for persistent wheat stem rust based on the CLIMEX climate suitability model results and b) the known locations or regions that wheat stem rust has been recorded. The Ecoclimatic indices favourability increases from 0 to 100. Indices above 0 were considered suitable in our analysis. Distribution source: CABI (2015a), CIMMYT (2012) and Beard *et al.* (2004) Map author: Day, C 2015

(iii) Russian wheat aphid

The Climex software comes with parameters for Russian wheat aphid based on the original work of Hughes & Maywald (1990) with adjustments made by Sutherst *et al.*(2007). For distribution validation GPS locations described in the literature that identified where Russian wheat aphid had been reported were used to reaffirm the original parameter distribution and improve the parameters. To better fit the current global distribution of Russian wheat aphid parameters were adjusted as follows. The upper optimal moisture was shifted from 0.275 to 0.3, limiting high moisture from 0.5 to 0.8, limiting low temperature from 3°C to 2°C, and the lower optimal temperature and cold stress degree-day threshold moved from 15°C to 10°C. Parameters for the CLIMEX model are presented in Appendix E Table 10, and the global suitability maps and distribution are shown in Figure 6a, b.

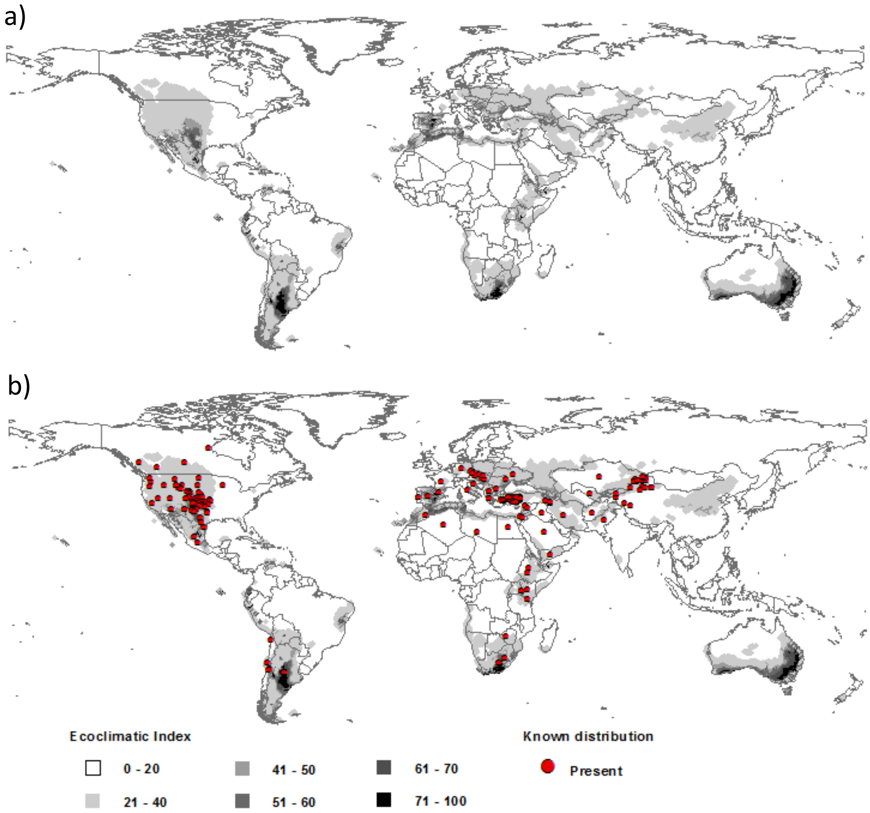

Figure 6. Potential and known distribution of Russian wheat aphid. a) Global suitability based on the CLIMEX climate model results and b) the locations or regions pest has been reported. The Ecoclimatic indices favourability increases from 0 to 100. Indices above 20 were considered suitable for our analysis. Distribution source: Aalbersberg *et al.* (1989), Amulaka *et al.* (2013), Backoulou *et al.* (2013), CABI (2015b), Liu *et al.* (2010), Puterka *et al.* (2007), Turanli *et al.*(2012), Zhang *et al.* (2012) Map author: Day, C 2015

Synchronisation of climate, growing season and pest

CLIMEX also estimates the Weeks of Positive Growth. The growth chart was assessed for Australian cropping locations to check that the growth period of the wheat stem rust and Russian wheat aphid coincide with the cropping season. This could also be used to indicate the "risk window" during the year. Two locations are shown to illustrate how temperature and rainfall affect the weekly growth index and the period at risk due to suitable conditions. The first location is in the Western Australian Central and South Wheat Belt in the Esperance growing region (33°42'S, 122°58'E). This is an area with a Mediterranean climate of warm dry summers and wet cool winters, and known to be at high risk of wheat stem rust (Beard *et al.*, 2004). The rainfall and temperature affects the moisture and temperature indices and consequently the weekly growth index. The window of risk for infection and damage from wheat stem rust extends throughout the whole growing season from late March until mid-late November, as shown in Figure 7a, b. This location has an EI of 40, a GI_a of 41 and 31 weeks of positive growth for wheat stem rust. For Russian wheat aphid, conditions remain suitable throughout the year. Russian wheat aphid has a higher EI and GI_a of 68 than wheat stem rust. The wetter and cooler climate during winter impacts on Russian wheat aphid growth more than wheat stem rust, but for a shorter period, Figure 7c.

The second location is in the New South Wales (NSW) North-west Slopes and Plains region of Moree (29°59’S, 149°90’E) in the north-east of NSW. This region has a different climate with long warm to hot summers, moderate and variable rainfall and clear cool winter days as shown in Figure 7d (BOM, n.d.). The moisture and temperature conditions at this location extend the wheat stem rust growth period to 41 weeks from mid-late March through to early December (Figure 7e). However, with an EI of 35 and GI_a of 36 the conditions are not as favourable as the Esperance location, although conditions are suitable for an additional 10 weeks. For Russian wheat aphid, the warmer temperatures affect growth in the summer months, but growth is more consistent from April to November than in Esperance (6f). Conditions for Russian wheat aphid extend throughout the whole year, and the EI and GI_a is 69.

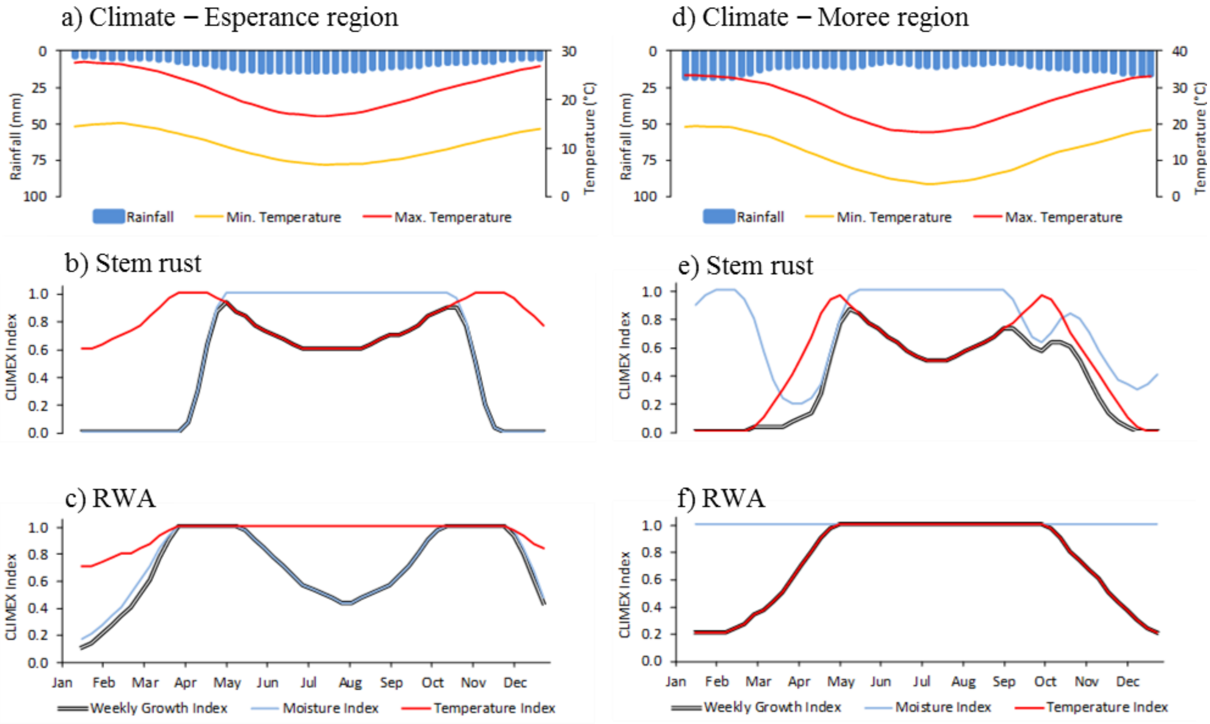

Figure 7. Climatic conditions at two locations in Australia and the CLIMEX growth, moisture and temperature indices indicative of the climate suitability for wheat stem rust and Russian wheat aphid. First location is at a site in the Esperance region of Western Australia and the second is near Moree, New South Wales. a) Climate Esperance region site (33°42’S, 122°58’E): average weekly rainfall and minimum and maximum temperatures. b) Wheat stem rust at Esperance site: weekly growth, moisture and temperature indices. The suitable growth period begins late March through to mid-late November, which coincides with the wheat growing period. Low temperatures decrease the suitability, however growth can continue. c) RWA at Esperance site: weekly growth, moisture and temperature indices. The growth period is all year in varying degrees of suitability. Drier periods are more favourable, and increased moisture during winter decreases growth during mid-May to mid-September. d) Moree region site (29°59’S, 149°90’E): average weekly rainfall and minimum and maximum temperatures. e) Wheat stem rust at Moree site: weekly growth, moisture and temperature indices. Rainfall and temperatures create unstable and less favourable growth conditions, although the growth period is longer than in Esperance. f) RWA at Moree site: weekly growth, moisture and temperature indices. Warm temperatures reduce suitability over summer. Growth period spans the whole year, and is most favourable between May and mid-October.

(iv) Hessian fly and sunn pest

For Hessian fly and sunn pest, climate matching was used in CLIMEX. The *Match Climates* model is a simplified function that does not require species specific parameters, but can still predict species distributions at a location based on climate (Sutherst *et al.*, 2007). Climate similarity was based on minimum, maximum and average temperature, total rainfall and rainfall pattern. The level of match is measured by the Composite Match Index (CMI) and a result from 0.6 to 0.9 indicates a match corresponding to the similarity. Sample locations in areas where the pests are known to exist and cause yield loss were selected from the literature. The closest meteorological point to each location was then used for climate matching to the Australian CLIMEX meteorological station data within the cereal growing SA2 regions of Australia. See Table 1 for the pest locations, GPS coordinates and references. The variance of the CMI results for the different locations for Hessian fly were minimal, therefore the average CMI was used as an indication of the climate similarity and suitability for the pest. The variance between the sunn pest locations was much greater therefore the maximum CMI was used, since this better represented the suitability for the pest in specific climates.

Table 1. **Sample locations where Hessian fly and sunn pest are known to exist. These locations were used for climate matching to the Australian cereal growing regions to estimate the distribution and suitability for these pests. Sources given.**

Pest	Location	Country	Longitude	Latitude	Reference
Hessian fly	Sidi Aissa - Algiers	Algeria	3.75011	35.75239	PBCRC, 2015
	M'Saken	Tunisia	10.58002	35.58023	PBCRC, 2015
	Texas	USA	-99.83514	31.38530	Garcés-Carrera *et al.*, 2014
	Louisiana	USA	-92.52854	31.08164	Garcés-Carrera *et al.*, 2014
Sunn Pest	Galbinasi - Calarasi	Romania	26.25369	44.19192	Rosca *et al.*, 1996
	Saveh - Teheran	Iran	51.14363	35.36346	Rosca *et al.*, 1996
	Tel Hadya	Syria	36.56506	36.01079	Parker *et al.*, 2002
	Afak	Iraq	45.14014	32.01067	Critchley, 1998
	Islahiye Zincirli	Turkey	36.40286	37.06256	Canhilal *et al.*, 2005

Australia's pest suitability in cereal regions

The cereal producing statistical regions and land use data used for GIS analysis are displayed in Figure 8a. Areas expected to be suitable for Karnal bunt are shown in Figure 8b. Australia's modelled climatic suitability to exotic wheat stem rust is illustrated in Figure 8c. This was also considered applicable for barley stripe rust. Russian wheat aphid is illustrated in Figure 8d, followed by the estimated distribution of Hessian fly and sunn pest in Figure 8e and f. The pest suitability index used to adjust the yield loss distribution for each statistical area, as described earlier in sub-section 3.2, was based on the weighted average of the wheat or barley cropping area within each band. Bands included were: suitable for Karnal bunt; > 2 (EI > 1) for exotic wheat stem rust and barley stripe rust; > 4 (EI > 20) for Russian wheat aphid; CMI > 0.50 for Hessian fly and Sunn pest.

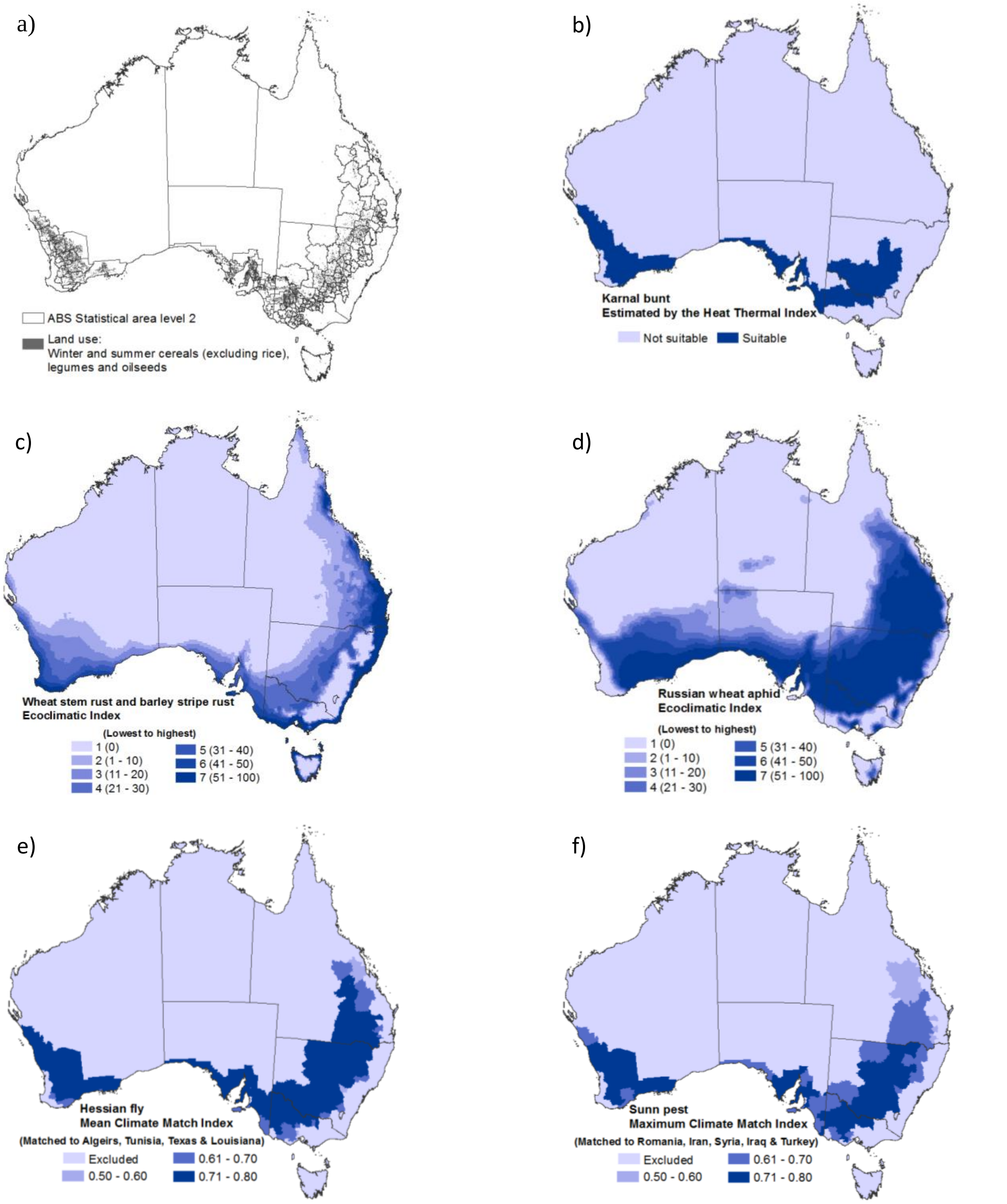

Figure 8. Maps indicate the Australian cereal growing regions and the suitability for Karnal bunt, exotic wheat stem rust and barley stripe rust, Russian wheat aphid, Hessian fly and sunn pest. a) Combination of the ABS Statistical area level 2 (SA2) for the large grain production states of Queensland, New South Wales, South Australia and Western Australia and the winter and summer cereals (excluding rice), legumes and oilseeds land use map. Sources: ABS (2012c), ABARES (2006). The potential distribution of b) Karnal bunt based on Heat Thermal Index indicating suitability for development (Murray and Brennan, 1998); c) exotic wheat stem rust and barley stripe rust and d) Russian wheat aphid based on climatic suitability as modelled by CLIMEX and ArcGIS. The Ecoclimatic Index 1 – 7 (0 – 100) indicates increasing suitability with 1 (0) meaning unfavourable conditions and 7 (51 – 100) being very suitable with highly favourable conditions. The potential distribution of e) Hessian fly and f) sunn pest based on the *Match Climates* model in CLIMEX. The Climate Match Index indicates the level of similarity between sample locations and the destination. An index of 0.6 to 0.9 indicates a good fit at an increasing level. *Note: Four SA2 regions had no selected land use data and were manually amended to total the grains area from the ABS data in the appropriate suitability band.* Map Author: Day, C 2015

4. Results

4.1. Expected return on investment

Ranked first to last in order of mean return on pre-breeding investment was exotic wheat stem rust, Russian wheat aphid, barley stripe rust, sunn pest, Hessian fly and Karnal bunt. The simulated return to pre-breeding over 50 years has resulted in the first three pests generating significant mean returns to investment of $36.2 million, $18.0 million and $16.7 million respectively (Table 2). The relatively high return is explained by significant yield effects and rapid spread. High coefficient of variation indicates that returns are highly variable. Sunn pest requires a higher investment value, but still surpasses Hessian fly and Karnal bunt in terms of return to investment.

Table 2. **Return on pre-breeding investment.**

Pest	Mean return ($ million)	SD	Coefficient of variation	Rank on mean return	NPV of pre-breeding costs ($ millions)	BCR
EWSR	36.2	48.2	1.3	1	1.3	28.73
RWA	18.0	54.5	3.0	2	1.3	14.29
BSR	16.7	22.3	1.3	3	1.3	13.27
SP	1.3	3.4	2.6	4	2.0	0.65
HF	0.2	0.2	1.1	5	1.3	0.12
KB	0.0003	0.001	2.6	6	1.3	0.00

Note: The results are based on 1000 Monte Carlo simulations.

Second-order stochastic dominance (Davidson and Duclos, 2000) was applied as an alternative method of selecting between investments and accounts for the full distribution of returns. Investments selected are those that would be selected by a risk averse investor. In all cases the selections are predicted by the mean return, and exotic wheat stem rust stochastically dominates all other pests as indicated by a 1 in Table 3. Karnal bunt on the other hand, does not show second-order stochastic dominance over any other pest in terms of investment in pre-breeding, indicated by a 0. Russian wheat aphid only dominates Hessian fly and sunn pest, no dominance was shown over barley stripe rust due to there being more zero returns to pre-breeding.

Table 3. **Second-order stochastic dominance.**

Pest	EWSR	RWA	HF	SP	BSR
KB	0	0	0	0	0
EWSR		**1**	**1**	**1**	**1**
RWA			**1**	**1**	0
HF				0	0
SP					0

Note: A one (zero) in the body of the table indicates that the pest in the left column shows (does not show) second order stochastic dominance over the pest given in the first row.

Although exotic wheat stem rust, Russian wheat aphid and barley stripe rust on average give a viable return on pre-breeding investment the modal returns in all cases is equal to zero indicating investing is risky. The high coefficient of variation shown previously and the histograms for investment returns shown in Figure 9 indicate an extremely high level of uncertainty relating to returns.

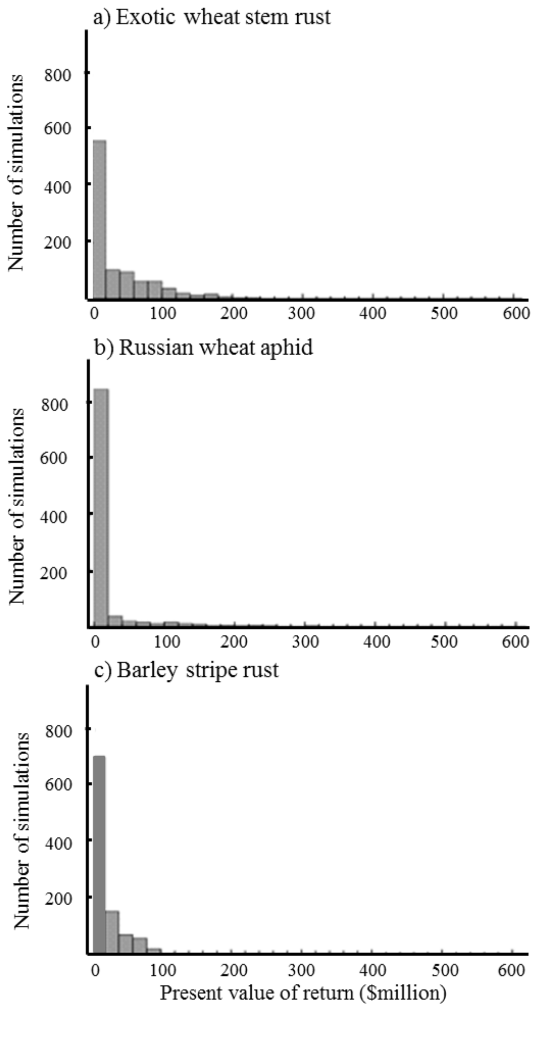

Figure 9. The distribution of the present value of returns to pre-breeding over 50 years at 5% discount rate for 1000 simulations. The pests with the highest mean return a) exotic wheat stem rust, b) Russian wheat aphid and c) barley stripe rust are given.

4.2. Sensitivity analysis

A sensitivity analysis was applied to test the sensitivity of returns to changes in parameter values. These results are summarised in Table 4 as percent change relative to the baseline when the parameters are set at their assumed minimum and maximum values. The results are also given as arc elasticities which are interpreted as the percent change in return with respect to a 1% change in a parameter. Using the elasticities as the basis for comparison, investment returns are most sensitive to changes in the percent of the area adopting new varieties, followed by the discount rate and the probability of incursion.

Table 4. **Sensitivity analysis results for return to pre-breeding.**

	KB	EWSR	RWA	HF	SP	BSR
Baseline mean return to pre-breeding ($ million)	0.0003	36.2	18.0	0.2	1.3	16.7
Percent change relative to the baseline:						
Delay pre-breeding +1 years (6 years)	-6.5	-2.7	-3.1	-3.0	-6.2	-5.5
Delay pre-breeding -1 years (4 years)	3.5	1.2	1.6	1.4	3.1	1.7
Discount rate +0.03 (8%)	-42.4	-37.7	-44.5	-58.8	-44.1	-39.0
Discount rate -0.03 (2%)	91.6	71.8	97.6	189.4[1]	99.4	78.6
Probability of incursion +30% (various)	7.1	14.2	31.0	-49.5	15.4	7.6
Probability of incursion -30% (various)	-28.2	-19.0	-27.7	-75.7	-22.5	-25.9
Adoption of resistant variety +40% (100%)	66.7	65.1	65.5	29.5	66.7	63.4
Adoption of resistant variety -40% (20%)	-66.7	-65.1	-65.5	-29.5	-66.7	-63.4
Elasticities[2]						
Delay pre-breeding +1 years (6 years)	-0.09	-0.04	-0.04	-0.04	-0.09	-0.08
Delay pre-breeding -1 years (4 years)	-0.04	-0.01	-0.02	-0.02	-0.03	-0.02
Discount rate +0.03 (8%)	-0.29	-0.25	-0.31	-0.45	-0.31	-0.26
Discount rate 0.03 (2%)	-0.24	-0.20	-0.25	-0.36	-0.25	-0.21
Probability of incursion +30% (various)	0.06	0.11	0.22	-0.55	0.12	0.06
Probability of incursion -30% (various)	0.27	0.18	0.27	1.02	0.21	0.25
Adoption of resistant variety +40% (100%)	0.31	0.31	0.31	0.16	0.31	0.30
Adoption of resistant variety -40% (20%)	0.62	0.60	0.61	0.22	0.63	0.58

Note:[1] The difference between two very small returns can be large. [2] Parameter changes described for elasticities were the range used to determine discrete changes. These results given are for a 1% change in the parameter.

4.3. Chemical demand

To predict future chemical demand during the delay period between incursion and release of resistant varieties with and without pre-breeding we calculated the volume of chemicals used in the simulations over the 50 years. This volume is contingent upon an incursion occurring, the production area infested/infected each year and whether it was economically feasible to use a chemical to reduce losses. We assumed the chemical was applied at the standard concentration at recommended rates (Table 5). The yield effect for Karnal bunt was too small to ever cover the costs of spraying and therefore not feasible. For Hessian fly, insecticides are seldom justified and the most effective control is delayed planting. Assuming producers adopt the resistant variety when available and do not double up control with chemicals as well, Russian wheat aphid has the most significant call on insecticide. Approximately 144,000 litres of chlorpyrifos was applied in the first five years after an incursion, followed by 1.65 million litres with pre-breeding and 4.13 million litres without pre-breeding in year's six to ten. Both rusts make use of a fungicide propiconazole with exotic wheat stem rust required 102,000 litres in years 1 – 5, and 1.75 million litres thereafter with pre-breeding, and 4.39 million litres in years 6 – 10 without pre-breeding. A further 96,000 litres were used for barley stripe rust in the five years post incursion, and 764,000 litres the following years with pre-breeding and 1.91 million litres without pre-breeding up to year 10. Fenitrothion for Sunn pest is required in much smaller volumes.

Table 5. **Chemical treatment, costs and application rates for the pests and the annual average volume used for the 10 years post incursion with and without pre-breeding.**

Pest	Active ingredient (a.i.)	Chemical ($/L)	Application rate (L/ha)	Applications (per yr)	Cost* ($/ha)	Annual average volume of chemical used at standard a.i. concentration for 10 years post incursion ('000 L)	
						Pre-breeding	No pre-breeding
KB	Propiconazole	13.50	0.5	1	19.75	0	0
EWSR	Propiconazole	13.50	0.5	1	19.75	185.7	448.9
RWA	Chlorpyrifos	10.00	0.9	1	22.00	179.5	427.1
HF	Not recommended	-	-	-	-	-	-
SP	Fenitrothion	33.92	0.65	2	70.09	12.8	28.7
BSR	Propiconazole	13.50	0.5	1	19.75	86.0	200.7

*Notes: * Includes average spray application cost of $13.00/ha (Murray et al., 2013).*
KB: Option to spray with propiconazole $13.50/L applied at 0.5 L/ha multiple applications may be required (Rural Solutions SA, 2015); however, price penalty still applies since wheat infected at any level is downgraded (Murray and Brennan, 1998). EWSR and BSR: Propiconazole $13.50/L applied at 0.5 L/ha multiple applications may be required (Rural Solutions SA, 2015). RWA: Chlorpyrifos $10.00/L applied at 0.6 - 1.2 L/ha (Dow AgroSciences, 2000; Rural Solutions SA, 2015). HF: Delayed planting after Hessian fly free dates is most effective control (Johnson, 2007; Penn State University, 2015); Carbofuran has restricted use, banned or under review in Canada, EU, United States and South Africa (FMC Corporation, 2015; U.S. EPA, 2009); Imidacloprid and thiamethoxam are seed treatments and Lambda-cyhalothrin foliar is an insecticide available, but rarely warranted (Johnson, 2007; Penn State University, 2015). SP: Deltamethrin is an option at $41.60/ha (Norco-Bowdlers, 2015 pers. comm.; (Karimzadeh et al., 2011) or Fenitrothion the preferred option $32.33/L - $35.50/L applied at 0.65 L/ha two applications may be required (HerbiGuide, 2015; Hertel et al., 2013; Karimzadeh et al., 2011).

Chemical demand estimates are based upon the initial incursion area of 100 hectares and the parameters used in the model. Demand following an incursion is not expected to be excessive initially, giving time to increase supply of stocks as the pest spreads over time. Once a resistant variety becomes available and 60% of infested/infected cropping area adopts the variety, chemical use declines as shown in Figure 10. This reduction in chemical use represents a non-market benefit of pre-breeding investment to society.

Figure 10. Average volume of chemicals used from 1000 simulations for the 10 years following a pest incursion with and without pre-breeding and 50% confidence intervals.

5. Discussion and conclusions

This paper used a detailed spatial and temporal simulation model to predict how exotic pests interact with the cereal crops. The return to pre-breeding investment depends upon this interaction and hinges on the gains from having breeding material available sooner rather than later when an incursion occurs. The analysis assumed a straightforward choice between always being ready (investing in pre-breeding) and waiting until an incursion occurs before investing in fast- track breeding.

The immediate response by producers to an incursion is to use chemicals or other management adaptations and these responses can be highly effective. In addition, following an incursion investment into fast-track breeding can be initiated. Thus the return to pre-breeding investment is limited by the delay time without pre-breeding, management alternatives and the adoption rates for resistant varieties by producers. These limitations have been observed in other regions, especially in the US with Russian wheat aphid (Christopher *et al.*, 2014).

Of the six high priority cereal pests exotic wheat stem rust, Russian wheat aphid and barley stripe rust with benefit cost ratios of 29, 14 and 13 over 50 years give a relatively high return on investment. This is explained by significant yield effects, rapid spread and widespread suitability across regions. Furthermore, the rusts have a relatively high probability of incursion. Russian wheat aphid has a low probability of incursion (one in 90 years) but this is offset by a higher average yield loss. The ranking of these pests by return to investment is insensitive to changes in parameters.

The Australian grain industry invests in a portfolio of research projects across all aspects of the industry. These projects can be characterised by their risk and returns. Investing in pre-breeding for exotic pests represents a project with very high returns in the event of an incursion, combined with high risk because incursion events are rare and the modal returns for all pests is zero. The choice faced by industry is whether these high risk high return investments represent an efficient use of research funds relative to other projects with more reliable returns.

Despite returns to the industry from investment for these three pests, it is unlikely that a commercial cereal breeder would invest in pre-breeding for them. There are five reasons for this. First, end point royalties to the cereal breeder only capture a fraction of the industry benefits of having a resistance variety. Second, ‘genetic’ spillover effects would mean that benefits of releasing the first resistant variety would be short lived as other commercial breeders developed their own resistant varieties. Thirdly, new resistant varieties are not necessarily widely adopted, especially if they carry yield penalties or producers can adapt to the pest in other ways. Fourthly, investing in pre-breeding is intrinsically highly risky as the modal investment return in all cases is zero. Lastly, a strategy of waiting for the pest incursion to occur may represent a more profitable strategy for cereal breeders. Therefore, the industry benefits from investment in pre-breeding would depend largely upon industry funding. There is the potential for market failure where cereal breeders focus exclusively on yield and quality traits in pursuit of market share at the expense of pest resistance.

The limitations of this study relate to the uncertainty of the pest incursion and spread process as well as the restrictive assumptions made in constructing the economic analysis. These limitations are described in the text. This economic model has the potential to include a wider range of adaptation strategies for producers, including changing cropping rotations, a larger set of cultural methods and integrated pest management options.

6. References

Aalbersberg, Y.K., van der Westhuizen, M.C., Hewitt, P.H., 1989. Characteristics of the population build-up of the Russian wheat aphid *Diuraphis noxia* and the effect on wheat yield in the eastern Orange Free State. Ann 114, 231–242.

ABARES, DA, 2006. ACLUMP National scale land use data version 4 2005-06.

ABS, 2012a. 7121.0 - Agricultural Commodities, Australia, 2010-11.

ABS, 2012b. 7503.0 - Value of Agricultural Commodities Produced, Australia, 2010-11.

ABS, 2012c. 1270.0.55.001 - Australian Statistical Geography Standard (ASGS): Statistical Area Level 2 (SA2). Australian Bureau of Statistics. URL http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1270.0.55.001July%202011?OpenDocument (accessed 1.27.15).

Alston, J.M., Andersen, M.A., James, J.S., Pardey, P.G., 2011. The economic returns to U.S. public agricultural research. American Journal of Agricultural Economics 93, 1257 – 1277.

Amulaka, F.O., Maling'a, J.N., Pathak, R.S., Cakir, M., Mulwa, R.M.S., 2013. Yield evaluation of a wheat line with combined resistance to Russian wheat aphid and stem rust race "Ug99" in Kenya. American Journal of Plant Sciences 4, 1494 – 1499.

Arrow, K.J., 1962. Economic welfare and the allocation of resources for invention, in: The Rate and Direction of Inventive Activity: Economic and Social Factors. Princeton University Press, Princeton, pp. 609 – 626.

Backoulou, G.F., Elliott, N.C., Giles, K.L., Rao, M.N., 2013. Differentiating stress to wheat fields induced by *Diuraphis noxia* from other stress causing factors. Computer and Electronics in Agriculture 90, 47 – 53.

Beard, C., Jayasena, K., Thomas, G., Loughman, R., 2004. Managing Stem Rust of Wheat.

Beddow, J.M., Hurley, T.M., Kriticos, D.J., Pardey, P.G., 2013. Measuring the global occurrence and probabilistic consequences of wheat stem rust.

BOM, n.d. Climate of Moree Climate. URL http://www.bom.gov.au/nsw/moree/climate.shtml (accessed 1.12.15).

Botha, J., Szito, A., Hardie, D.C., 2005. Industry Biosecurity Plan for the Grains Industry Threat-Specific Contingency Plan - Hessian fly *Mayetiola destructor* (Say) 1817.

Bouhssini, M.E., Ogbonnaya, F., Chen, M., Lhaloui, S., Rihawi, F., Dabbous, A., 2013. Sources of resistance in primary synthetic hexaploid wheat (L.) to insect pests: Hessian fly, Russian wheat aphid and Sunn pest in the fertile crescent. Genetic Resources Crop Evolution 60, 621 – 627.

Bouhssini, M.E., Street, K., Joubi, A., Ibrahim, Z., Rihawi, F., 2009. Sources of wheat resistance to Sunn pest, *Eurygaster integriceps* Puton, in Syria. Genetic Resources Crop Evolution 56, 1065 – 1069.

Butts, R.A., Thomas, J.B., Lukow, O., Hill, B.D., 1997. Effect of fall infestations of Russian wheat aphid (Homoptera: Aphididae) on winter wheat yield and quality on the Canadian Prairies. Journal of Economic Entomology 90, 1005 – 1009.

CABI, 2015a. Datasheet *Puccinia graminis* - Distribution: In Invasive Species Compendium.

CABI, 2015b. Datasheet *Diuraphis noxia* In: Invasive Species Compendium. URL http://www.cabi.org/isc/datasheet/9887 (accessed 1.30.15).

Canhilal, R., Kutuk, H., Kanat, A.D., Islamoglu, M., Haramein, F.E., Bouhssini, M E, 2005. Economic threshold for the sunn pest, *Eurygaster integriceps* Put. (Hemiptera: Scutelleridae), on wheat in southeastern Turkey. Journal of Agricultural Urban Entomology 22, 191 – 201.

Christopher, M., White, B., van Klinken, R.D., Day, C.L., 2014. A review of relative risks, likely area of impact, potential economic impact of an incursion of six target pests and diseases in Australia (A report to the Grains Research and Development Corporation and the Plant Biosecurity CRC).

CIMMYT, 2012. RustMapper.

Critchley, B.R., 1998. Literature review of sunn pest *Eurygaster integriceps* Put. (Hemiptera, Scutelleridae). Crop Protection 17, 271 – 287.

Davidson, R., Duclos, J., 2000. Statistical inference for stochastic dominance and for the measurement of poverty and inequality. Econometrica 69, 1435 – 1464.

Dixit, A.K., Pindyck, R.S., 1994. Investment under uncertainty. Princeton University Press, Princeton.

Dow AgroSciences, 2000. Specimen Label - Lorsban 4E-SG.

Du Toit, F., 1986. Economic thresholds for *Diuraphis noxia* (Hemiptera: Aphididae) on winter wheat in the eastern Orange Free State. Phytophylactica 18, 107–109.

Du Toit, F., Walters, T.C., 1984. Damage assessment and economic threshold values for the chemical control of the Russian wheat aphid, *Diuraphis noxia* (Mordvilko) on winter wheat, in: Progress in Russian Wheat Aphid (*Diuraphis Noxia* Mordw.) Research in the Republic of South Africa. Presented at the Proceedings of a meeting of the Russian Aphid Task Team 5 - 6 May 1982, Republic of South Africa Department of Agriculture, Bloemfontein, Orange Free State, pp. 58 – 62.

Duvick, D.N., 2005. The contribution of breeding to yield advances in maize (*Zea mays* L.). Advances in Agronomy 86, 83 – 145.

Fischer, R.A., Edmeades, G.O., 2010. Breeding and cereal yield progress. Crop Science 50, S85 – S98.

FMC Corporation, 2015. Furadan Facts. Furadan Facts - Frequently asked questions. URL http://www.furadanfacts.com/FAQs.aspx (accessed 4.13.15).

Garcés-Carrera, S., Knutson, A., Wang, H., Giles, K.L., Huang, F., Whitworth, R.J., Smith, C.M., Chen, M., 2014. Virulence and biotype analyses of Hessian fly (Diptera: Cecidomyiidae) populations from Texas, Louisiana, and Oklahoma. Plant Resistance 107, 417 – 423.

GIPB, FAO, 2011. Pre-breeding for effective use of plant genetic resources. URL http://www.fao.org/fileadmin/templates/agphome/documents/PGR/Announcements/PB-elearningcourse_GIPB_en.pdf (accessed 5.18.15).

GRDC, Cakir, M., 2011. Global approach to a small green monster. URL https://www.grdc.com.au/Media-Centre/Ground-Cover-Supplements/Ground-Cover-Issue-93-JulyAugust-2011-International-Collaboration-Supplement/Global-approach-to-a-small-green-monster (accessed 6.9.15).

HerbiGuide, 2015. Fenitrothion. HerbiGuide - Fenitrothion. URL http://www.herbiguide.com.au/Descriptions/hg_FENITROTHION.htm (accessed 5.13.15).

Hertel, K., Roberts, K., Bowden, P., 2013. Insect and mite control in field crops 2013 - NSW DPI Management Guide.

Hodda, M., Cook, D.C., 2009. Economic impact from unrestricted spread of potato cyst nematodes in Australia. Phytopathology 99, 1387–1393. doi:10.1094/PHYTO-99-12-1387

Hughes, R.D., Maywald, G.F., 1990. Forecasting the favourableness of the Australian environment for the Russian wheat aphid, *Diuraphis noxia* (Homoptera: Aphididae), and its potential impact on Australian wheat yields. Bulletin of Entomological Research 80, 165–175.

Jhorar, O.P., Mavi, H.S., Sharma, I., Mahi, G.S., Mathauda, S.S., Singh, G., 1992. A biometeorological model for forecasting karnal bunt disease of wheat. Plant Disease Research 7, 204 – 209.

Johnson, D., 2007. Managing insects in wheat: An overview, in: Serving Agriculture and the Environment. Presented at the Crop Protection Technology Conference, University of Illinois, pp. 57 – 60.

Karimzadeh, R., Hejazi, M.J., Helali, H., Iranipour, S., Mohammadi, S.A., 2011. Assessing the impact of site-specific spraying on control of *Eurygaster integriceps* (Hemiptera: Scutelleridae) damage and natural enemies. Presicion Agriculture 12, 579 – 593.

Kolmer, J.A., 2005. Tracking wheat rust on a continental scale. Current Opinion in Plant Biology 8, 441–449.

Kriticos, D.J., Webber, B.L., Leriche, A., Ota, N., Macadam, I., Bathols, J., Scott, J.K., 2011. CliMond: global high-resolution historical and future scenario climate surfaces for bioclimatic modelling. Methods in Ecology and Evolution 3, 53–64.

Leonard, K.J., 2013. Black stem rust biology and threat to wheat growers.

Liu, X., Marshall, J.L., Stary, P., Edwards, O., Puterka, G., Dolatti, L., Bouhssini, M.E., Malinga, J., Lage, J., Smith, C.M., 2010. Global phylogenetics of *Diuraphis noxia* (Hemiptera: Aphididae), an invasive aphid species: Evidence for multiple invasions into North America. Journal 103.

Loughman, R., Jayasena, K., Majewski, J., 2005. Yield loss and fungicide control of stem rust of wheat. Australian Journal of Agricultural Research 56, 91–96.

Malipatil, M., PHA, 2008a. Industry Biosecurity Plan for the Grains Industry Threat Specific Contingency Plan - Sunn pest *Eurygaster integriceps*.

Malipatil, M., PHA, 2008b. Industry Biosecurity Plan for the Grains Industry Threat Specific Contingency Plan - Barley stem gall midge *Mayetiola hordei*.

Milus, G., DeWolf, E., Dill-Macky, R., Steffenson, B., Wegulo, S., Bergstrom, G., Sorrells, M., McMullen, M., Paul, P., Hunger, R., Mundt, C., Isard, S., Stein, J., Murray, T., Baker, H., Bulluck, R., Divan, C., Engle, J., Hebbar, P., Bowden, B., Carson, M., Chen, X., Jin, Y., Marshall, D., Smith, K., Szabo, L., Draper, M., 2010. Recovery plan for stem rust of wheat caused by *Puccinia graminis* f. sp. *tritici* Ug99 (race TTKSK) and its derivatives. USDA - Agricultural Research Service.

Mirik, M., Ansley, J., Michels Jr, J., Elliott, N., 2009. Grain and vegetative biomass reduction by the Russian wheat aphid in winter wheat. Southwestern Entomologist 34, 131 – 139.

Morgan, G., Sansone, C., Knutson, A., 2005. Hessian fly in Texas wheat. AgriLife Extension Texas A&M University. URL https://insects.tamu.edu/extension/publications/epubs/e-350.cfm (accessed 4.14.15).

Murray, D.A.H., Clarke, M.B., Ronning, D.A., 2013. The current and potential costs of invertebrate pests in grain crops.

Murray, G.M., Brennan, J.P., 2009. The Current and Potential Costs from Diseases of Wheat in Australia.

Murray, G.M., Brennan, J.P., 1998. The risk to Australia from *Tilletia indica*, the cause of Karnal bunt of wheat. Australasian Plant Pathology 27, 212 – 225.

Pardey, P.G., Beddow, J.M., Kriticos, D.J., Hurley, T.M., Park, R.F., Duveiller, E., Sutherst, R.W., Burdon, J.J., Hodson, D., 2013. Right-sizing stem-rust research. Science 340.

Parker, B.L., Costa, S.D., Skinner, M., Bouhssini, M.E., 2002. Sampling sunn pest (*Eurygaster integriceps* Puton) in overwintering sites in Northern Syria. Turkish Journal of Agriculture and Forestry 26, 109 – 117.

Park, R.F., 2008. Breeding cereals for rust resistance in Australia. Plant Pathology 57, 591–602.

Park, R.F., 2007. Stem rust of wheat in Australia. Australian Journal of Agricultural Research 58, 558–566.

Parry, H.R., 2013. Cereal aphid movement: general principles and simulation modelling. Movement Ecology 1.

PBCRC, 2015. Hessian Fly (Mayetiola destructor) Current Distribution - PaDIL Plant Biosecurity Toolbox. Pests and Diseases Image Library. URL http://pbt.padil.gov.au/index.php?q=node/6&pbtID=167 (accessed 4.10.15).

Penn State University, 2015. Suggested insecticides, rates, and restrictions for small-grain insect control. Penn State Extension. URL http://extension.psu.edu/agronomy-guide/pm/tables/table-2-5-8 (accessed 4.13.15).

PHA, n.d. High priority exotic pests of the Australian grains industry. Grain pests. URL http://www.planthealthaustralia.com.au/national-programs/grains-farm-biosecurity-program/grains-pests/ (accessed 5.14.15).

Phillips Fox, 2013. Government and Plant Industry Cost Sharing Deed in respect of Emergency Plant Pest Responses.

Puterka, G.J., Burd, J.D., Shufran, K., Baker, C., Bowling, B., Patrick, C., 2007. Distribution and diversity of Russian wheat aphid (Hemiptera: Aphididae) Biotypes in North America. Journal of Economic Entomology 100.

Rosca, I., Popov, C., Barbulescu, A., Vonica, I., Fabritius, K., 1996. The role of natural parasitoids in limiting the level of sunn pest populations, in: Sunn Pests and Their Control in the Near East. (FAO Plant Production and Protection Paper - 138). Food and Agriculture Organization of the United Nations, Rome.

Rural Solutions SA, 2015. 2015 Farm Gross Margin Guide. Primary Industries and Regions South Australia Government.

Schotzko, D.J., Knudsen, G.R., 1992. Use of geostatistics to evaluate a spatial simulation of Russian wheat aphid (Homoptera: Aphididae) movement behavior on preferred and nonpreferred hosts. Envionmental Entomology 21, 1271 – 1282.

Shackley, B., Zaicou-Kunesch, C., Dhammu, H., Shankar, M., Amjad, M., Young, K., 2014. 2014 Wheat variety guide for WA.

Sharma, I., Bains, N.S., Sharma R C, 2012. Resistance in wheat to Karnal bunt, in: Disease Resistance in Wheat. CABI International, Oxfordshire UK, pp. 190 – 219.

Stansbury, C.D., McKirdy, S.J., Diggle, A.J., Riley, I.T., 2002. Modeling the risk of entry, establishment, spread, containment, and economic impact of *Tilletia indica*, the cause of Karnal bunt of wheat, using an Australian context. Phytopathology 92, 321 – 331.

Sutherst, R.W., Maywald, G.F., Kriticos, D.J., 2007. CLIMEX V3 User's Guide.

Texas Invasives Org., 2011. *Diuraphis noxia* Russian wheat aphid. URL http://www.texasinvasives.org/pest_database/detail.php?symbol=25 (accessed 4.17.15).

Trainor, G., Zaicou-Kunesch, C., Dhammu, H., Shackley, B., Shankar, M., 2015. Wheat variety guide for Western Australia 2015.

Turanli, F., Jankielsohn, A., Morgounov, A., Cakir, M., 2012. The distribution of Russian wheat aphid, *Diuraphis noxia* (Kurdjumov) (Hemiptera: Aphididae) in Turkey. African Journal of Agricultural Research 7, 5396–5404.

U.S. EPA, 2009. Carbofuran Registration Review Status December 2009 Case 0101.

Wharton, T.N., Kriticos, D.J., 2004. The fundamental and realized niche of the Monterey Pine aphid, *Essigella californica* (Essig) (Hemiptera: Aphididae): implications for managing softwood plantations in Australia. Diversity and Distributions 10, 253–262.

White, B., Christopher, M., 2014. Costs of cereal pre-breeding and breeding for high priority exotic pests (Report to the Grains Research and Development Corporation and the Plant Biosecurity CRC).

Zhang, B., Edwards, O.R., Kang, L., Fuller, S.J., 2012. Russian wheat aphids (*Diuraphis noxia*) in China: native range expansion or recent introduction? Molecular Ecology 21, 2130–2144.

Appendix A Table 6. Analysis assumptions.

Number	Section	Assumption
1	2. Investment return model	The return on investment in pre-breeding before the incursion occurs were measured as returns to the Australian grains industry over a 50 year planning horizon, and compared to an alternative of fast-track investment in response to an incursion. The planning horizon encompasses approximately five cereal breeding cycles and, for most pests, at least one expected incursion.
2	2. Investment return model	The analysis assumes a base year of 2011 and that production data from the ABS Agricultural Census, 2011 is typical. This enables regional disaggregation and regional pest suitability across the cereal production landscape of 195 ABS level 2 statistical areas (SA2) selected.
3	2. Investment return model	If an incursion occurs, then with pre-breeding there is a relatively short delay, assumed to be 5 years, before resistant varieties are released. Without pre-breeding there is a longer delay, assumed to be 10 years, and additional costs.
4	2. Investment return model	The pest does not affect other production costs (such as fertiliser, endemic pest chemical control and herbicides) and the area of the cereal crops remains constant.
5	2. Investment return model	No incursion control, containment or eradication takes place. At most there were only two options to reduce losses from the pest, chemicals (where feasible) and resistant varieties. Other options such as cultural control, integrated pest management, altering trade agreements and area wide freedom were not assessed.
6	2. Investment return model	At present there is no resistance to the pest in current or ready for release varieties in Australia.
7	3.1 Pre-breeding costs, time delays and adoption	The cost of the pre-breeding investment in year 1 to fund a pre-breeding program is $1,282,848 for sunn pest and $532,848 for Karnal bunt, exotic wheat stem rust, Russian wheat aphid, Hessian fly and barley stripe rust. After the initial investment, a further $532,848 discounted at 5% is required every ten years thereafter, to maintain the pre-breeding program at the same level. Net present value of investment for sunn pest is $2,009,773 and $1,259,773 for all other pests over the planning horizon.
8	3.4 Region specific pest suitability and yield losses	Climate is the only factor determining the presence of the pest.
9	3.4 Region specific pest suitability and yield losses	Climatic suitability determines the damage and yield loss expected.

Appendix B Table 7. Cereal breeding summary.

Pest	Type of resistance	Markers available	Yield penalty	Resistance breakdown	Comment	References
Karnal bunt	Quantitative genes	Yes	No	Limited evidence	Resistant varieties unlikely to be the only response. Area freedom used in the US. Phenotyping may be relatively high cost due to difficulty of assessing resistance. Breeding due to multiple genes may be relatively expensive. Karnal bunt resistance is used in India. Developed in the USA but not deployed.	Sharma *et al.*, 2012, R. Bowden pers. comm.
Exotic wheat stem rust	Single gene resistance replaced by multiple genes and gene pyramiding, increases costs	Yes for major genes	Yes	Common	Breeding for resistance to new strains of rust is not considered by breeders to be specific to exotic pathogens, since new pathotypes often arise within the local population. The Australian Cereal Rust Control Program is specifically dedicated to research and pre-breeding for rust resistance.	Murray and Brennan, 2009
Russian wheat aphid	Single gene resistances, some biotype specific, and less specific.	Yes	No	Ten years between *Dn4* resistance to Biotype 1 and appearance of Biotype 2.	Development of locally adapted pre-breeding material, through the GRDC funded project UMU00029.	GRDC and Cakir, 2011
Hessian fly	Genes are available (for example H24 and H26) which confer broad resistance. Breeding with these may take more time, with 'pyramiding' recommended.	Yes	5%	Biotypes	A GRDC project DAN00174 has been funded to address pre-emptive pre-breeding for Hessian fly, Karnal bunt and sunn pest. There is no evidence of resistance to Hessian fly in any Australian wheat.	Botha *et al.*, 2005, M. Francki, pers. comm.
Sunn pest	The genetic nature of resistance is unknown	No	Unknown		A few sources of genetic resistance to feeding at the vegetative stage have been identified in wheat, 'synthetic' hexaploid wheat, durum (including the cultivar 'Langdon') and the wild relative *Aestivum umbellulate* Zhuk.. These factors will make pre-breeding and breeding for resistance to sunn pest difficult, costly and time consuming.	Bouhssini *et al.*, 2013, 2009
Barley stripe rust	Single gene resistance	Yes	No	Unknown	Some resistance in Australian varieties.	

Appendix C Table 8. Illustrative steps in pre-breeding for an exotic pest or disease.

Step	Description	Comment	Total cost ($)
1.	If source of resistance is not known screen sources of resistance. Estimate from RWA is to screen 30,000 lines it took 3 years of a senior scientist and a technician in Colorado. They identified 14 sources of resistance. Could use FIGS (Focussed Identification of Germplasm Strategy) to reduce costs.	Costs $250,000 per annum over three years. (Probably only required for Sunn pest as source of resistance not identified).	750,000
2.	Confirm that Australian varieties are susceptible to the pest/pathogen – presumably requires phenotyping overseas and/or in containment in Australia.	The cost depends on where the phenotyping is carried out. For instance from project UMU00029 there is an estimate of $65,000 for phenotyping 100 lines in the US. The total cost is for a program with 300 lines.	195,000
3.	Cross it with a susceptible Australian variety and develop progeny populations. The costs depend on whether or not crossing is done overseas.	$30 per line, 3 resistance sources, 2 adapted lines per GRDC region, 18 populations in total.	540
4.	Extract DNA. Using AGRF services.	$5 per sample, 18 lines including 100 plants.	9,000
5.	Genotype the population. One approach is genotyping-by-sequencing (GBS). In-house cost (University) based on 4 96-well plates. In the empty wells, susceptible Australian varieties can be used for 'pre-validation' to identify promising sequences for marker design. Requires bioinformatics capability.	Service cost for this at DArT is $50 per sample so $15,000. In-house $100 per sample. Total cost is based on 18 lines of 100 plants.	90,000
6.	Construct a linkage map. The quality of the map does not have to be great at this point. Generates a large database that requires specialist analytical skills and a fast computer.	Two weeks' time from a postdoc. Assume $110,000 per annum including on-costs.	4,231
7.	Increase the seed.	Glasshouse space and services.	1,000
8.	Phenotype the population overseas.	Assumes 100 lines in one country.	65,000
9.	Quarantine clearance through AQIS.	$80 per line for 18 populations Greg Grimes (Australian Winter Cereal Collection) (2014, pers. com.).	144,000
10.	Process the phenotypic data – this will probably consume a lot of time on the part of an experienced technician decode what the overseas researchers have sent and check for problems.	Two weeks of a postdoc.	4,231
11.	Analyse for marker-trait association. This involves statistician. Find a QTL (Quantitative trait loci) for resistance. (Keep in mind that you may need to multiply all of the above steps by the number of sources you wish to pursue in parallel in order to get a valuable QTL.)	Two weeks of a statistician. As for postdoc.	4,231
12.	Do some bioinformatics with the GBS tags that are linked to the QTL. Perhaps a Postdoc for a week. Pick the SNPs that seem best for marker design. Design KASP markers and run them on the population and on a panel of wheat lines.	$10,000 plus 3 weeks for a technician. $80,000 per annum including on costs.	14,615
13.	Reanalyse the data and pick the best ones. Start using them in marker-assisted germplasm development.		1,000
		Resistance source unknown - Total	**1,282,848**
		Resistance source known - Total	**532,848**

Source: Professor Diane Mather (University of Adelaide) (2014, per com)

Appendix D Table 9. Model parameters

Notation	**Details**	**Units**	KB	EWSR	RWA	HF	SP	BSR
Δt^{nopb}	Delay resistant variety release - no pre-breeding	years	10	10	10	10	10	10
Δt^{pb}	Delay resistant variety release - pre-breeding	years	5	5	5	5	5	5
	Net present value of the cost of pre-breeding over the planning horizon[1]	$	1,259,773	1,259,773	1,259,773	1,259,773	2,009,773	1,259,773
r	Discount rate	%	5	5	5	5	5	5
c_{st}^{k}	Additional pest control costs following incursion[2]	$/ha per year	19.75	19.75	22.00	0	70.09	19.75
	Pest control effectiveness against yield losses	%	n/a	80	80	n/a	80	80
φ_{st}^{k}	Maximum yield loss without control[3]	%	0.2	45	82.9	15	90	50
	Minimum yield loss without control[3]	%	0.001	10	25	2	50	0.01
	Modal yield loss without control[3]	%	0.1	20	42.5	7.5	70	5
λ	PERT shape parameter		10	20	0	3	1	1
θ_{st}^{k}	Proportion of commodity price with disease/pest	%	80 [4]	100	100	100	80[5]	100
n_t	Probability of established incursion (Poisson)[6]	$year^{-1}$	0.011	0.057	0.011	0.011	0.011	0.044
	Minimum area of initial infestation/infection	ha	100	100	100	100	100	100
ρ_s	Intrinsic spread rate of pest area (logistic)[7, 8]	ha per year	0.69	2	2	1	1	2
ψ_{st}	Jump probability (binomial)[9]		0.2	0.3	0.3	0.2	0.2	0.3
d^{max}	Maximum distance of spread[10]	km per year	300	2000	1000	45	250	2000
ω_{st}^{k}	Proportion of infested area adopting resistant variety[11]	%	60	60	60	60	60	60

Notes:

1. *Estimate of the required cost to firstly begin a pre-breeding program and maintain the program over the planning horizon. For KB, EWSR, RWA, HF, BSR resistance*

source is assumed to be known therefore cost lower than for SP where the resistance source is unknown (Diane Mather, Uni. of Adelaide, 2014 pers. comm.). Costs incurred every ten years, at the beginning of years 1, 11, 21, 31 and 41.

2. *Control costs: Average spray application cost $13.00/ha* (Murray *et al.*, 2013)*. KB: Option to spray with propiconazole $13.50/L applied at 0.5 L/ha multiple applications may be required* (Rural Solutions SA, 2015)*; however, price penalty still applies since wheat infected at any level is downgraded* (Murray and Brennan, 1998)*. EWSR & BSR: Propiconazole $13.50/L applied at 0.5 L/ha multiple applications may be required* (Rural Solutions SA, 2015)*. RWA: Chlorpyrifos $10.00/L applied at 0.6 - 1.2 L/ha* (Dow AgroSciences, 2000; Rural Solutions SA, 2015)*. HF: Delayed planting after Hessian fly free dates is most effective control* (Johnson, 2007; Penn State University, 2015)*; Carbofuran has restricted use, banned or under review in Canada, EU, United States and South Africa* (FMC Corporation, 2015; U.S. EPA, 2009)*; Imidacloprid and thiamethoxam are seed treatments and Lambda-cyhalothrin foliar is an insecticide available, but rarely warranted* (Johnson, 2007; Penn State University, 2015)*. SP: Deltamethrin is an option at $41.60/ha (Norco-Bowdlers, 2015 pers. comm.; (Karimzadeh et al., 2011) or Fenitrothion the preferred option $32.33/L - $35.50/L applied at 0.65 L/ha two applications may be required (HerbiGuide, 2015; Hertel et al., 2013; Karimzadeh et al., 2011).*
3. *KB: <1 - 20% yield loss, generally 0.1%* (Murray and Brennan, 1998)*; $0.10/ha yield loss* (Stansbury *et al.*, 2002)*; Benefit from control treatment negligible because price penalty applies to wheat at any infection level* (Murray and Brennan, 1998)*. EWSR & BSR: 10 - 45% yield losses* (Loughman *et al.*, 2005)*; 25 - 35% during severe stem rust epidemic in south-eastern Australia in 1973* (Park, 2007)*; 46.3% maximum potential yield loss for Australia, 78.4% for northern region, 50.8% southern region and 25.0% for western region (Murray and Brennan, 2009a, 2009b); 2.5% average losses in wheat the United States during 1918 - 1960 prior to resistant varieties, and 0.3% with resistant varieties* (Pardey *et al.*, 2013)*. RWA: Yield losses in the Canadian Prairies 25 - 37%* (Butts *et al.*, 1997)*; between 35 - 60% in South African wheat fields* (Du Toit, 1986; Du Toit and Walters, 1984)*; and up to 82.9% in the United States* (Mirik *et al.*, 2009)*. HF: 5 - 15% yield loss estimated for Australia, hot dry summer conditions may reduce yield losses to < 5%* (PBCRC, 2015)*. SP: approximately 2.5 - 3 months/year as an active insect in cereal fields causing damage* (Critchley, 1998)*; optimal conditions causing outbreaks occur usually every 5 - 8 years* (Malipatil and PHA, 2008a)*; yield losses estimated at 50 - 90% in wheat and 20 - 30% in barley* (Canhilal *et al.*, 2005)*; Control effectiveness 80%, used 70% every 1 in 5 years yield penalty with control.*
4. *Karnal bunt infection results in a crop downgrade from milling wheat to feed* (Murray and Brennan, 1998).
5. *Sunn pest estimate based on effect on baking quality* (Critchley, 1998).
6. *Mean value, μ for a Poisson distribution. Probability of incursions are discussed in Christopher et al.* (2014)*. Probability ranges – KB: 1/75 – 1/100, EWSR: 1/10 – 1/25, RWA: 1/80 – 1/100, HF: 1/80 – 1/100, SP: 1/80 – 1/100, BSR: 1/15 – 1/30.*
7. *The intrinsic growth rate gives the change in area per year at a uniform pest/disease population density from a logistic area spread model with an initial incursion of 100 ha. It gives the proportional growth as $a_{st}^{I} \rightarrow 0$, that is the (rate of maximum area spread).*
8. *Specific values for the intrinsic growth rate are not reported in the literature except for Karnal bunt at 0.69 implying a 100% increase in pest area in a year* (Stansbury *et al.*, 2002) *.Others are set at 2 for a rapidly spreading pest (600% increase) or 1 for a slow spreading pest (170% increase).*
9. *Gives the probability parameter for the binomial distribution. The probability of spread to a statistical area depends upon the distance weighted sum of infested areas. Assumes jump between statistical areas from SA2 centroid to centroid. This can be interpreted as the probability in a binomial distribution that a pest will spread from 1 ha of infested/infected land in a surrounding statistical area to another. Given as high and low values based on rates of spread.*
10. *Calibrates a function that reduces the weight on surrounding infested/infected statistical areas on the basis of the cut-off distance d^{max}. KB: Estimate based on sporidia and teliospores dispersal by seed, machinery or wind* (Murray and Brennan, 1998)*. EWSR & BSR: Rusts have spread across Australia in 1 to 2 years* (Park, 2008, 2007)*; Rust causing fungi urediniospores can be blown for thousands of kilometres, for example wheat leaf rust (Puccinia triticina) is moved from the south of the United States*

to northern United States and Canada by southerly winds each spring and summer (Kolmer, 2005). *RWA: Aphid movement is complex and includes behavioural and migratory movement by walking, flight and aerial transport* (Parry, 2013). *Behavioural movement due to host quality and population density usually initiates random aphid movement. Directional movement is known to occur where the aphid moves from leaf to leaf of adjacent plants* (Schotzko and Knudsen, 1992). *In general alate aphids usually move short distances of 20 - 100 m in their lifetime, 20 - 50 km in flight for migration* (Parry, 2013). *However, long range dispersal activity via air currents and jet-streams also occurs* (Parry, 2013). *It was first detected in North America near Mexico City in 1980, and was discovered near Lubbock, Texas in March 1986. By the fall of that year, infestations were reported in New Mexico, Oklahoma, Colorado, Nebraska, Wyoming and Kansas and the remainder of the western United States and Canada by 1988* (Halbert & Stoetzel 1998 cited in Liu *et al.*, 2010; Texas Invasives Org., 2011). *HF: Up to 45 kms based on 3 - 5 generations each year and majority of life is in egg, pupae or larvae form and adults lives generally no more than 3 days. It is a weak flier of distances and disperses from emergence sites by winds and thermal currents over distances up to 9 kms. If all 5 generations travel 9 kms, maximum distance likely is 45 kms per year (although very unlikely)* (Malipatil and PHA, 2008b; Morgan *et al.*, 2005). *SP: Up to 250 kms* (Malipatil and PHA, 2008a).

11. *Evidence from the RWA outbreak in the US and the National Variety Trial data DAFWA* (Shackley *et al.*, 2014; Trainor *et al.*, 2015) *is that single varieties even conveying significant resistant genes rarely account for more than 50 to 60% of the crop.*

Appendix E Table 10. CLIMEX parameter values used to predict the geographical distribution of an exotic stem rust such as Ug99 *Puccina graminis* f. sp. *tritici* and Russian wheat aphid (RWA) *Diuraphis noxia*. The initial parameters were sourced from Beddow *et al.* (2013), Hughes and Maywald (1990) and Sutherst *et al.* (2007), and adjusted slightly to suit the known distribution. Each parameter is described in detail in Sutherst *et al.* (2007).

	Parameter		**Value**		**Units**[a]
	Mnemonic	**Details**	**EWSR**	**RWA**	
Temperature	DV0	lower threshold	4	2	°C
	DV1	lower optimum temperature	17	10	°C
	DV2	upper optimum temperature	25	25	°C
	DV3	upper threshold	32	35	°C
Moisture	SM0	lower soil moisture threshold	0.15	0.05	
	SM1	lower optimum soil moisture	0.20	0.10	
	SM2	upper optimum soil moisture	1.50	0.30	
	SM3	upper soil moisture threshold	2.50	0.80	
Cold stress	TTCS	damaging low threshold temperature	4	-	°C days
	THCS	stress accumulation rate	-0.01	-	Week^{-1}
	DTCS	degree-day threshold†	-	15	°C days
	DHCS	stress accumulation rate	-	-0.00012	Week^{-1}
Heat stress	TTHS	damaging high threshold temperature	34	35	°C
	THHS	stress accumulation rate	0.005	0.02	Week^{-1}
Dry stress	SMDS	soil moisture dry stress threshold	0.1	0.05	
	HDS	stress accumulation rate	-0.005	−0.01	Week^{-1}
Wet stress	SMWS	soil moisture wet stress threshold	-	0.80	
	HWS	wet stress rate	-	0.035	Week^{-1}
Hot-Wet stress	TTHW	hot wet temperature threshold	30	-	°C
	MTHW	soil moisture wet stress threshold	0.35	-	
	PHW	stress accumulation rate	0.03	-	Week^{-1}

[a] Where values are absent, units are a dimensionless index of available soil moisture, scaled from 0 (oven dry) to 1 (field capacity).

† Stress accumulates if the weekly number of degree-days above DV0 (2°C) is below this value.