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 Pests1 (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

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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.

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.

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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 $\pi_{\text{pest}}$ 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 $\Delta t^{pb}$ or a longer delay without pre-breeding $\Delta t^{nopb}$ 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 $\Delta t^{pb}$. Alternatively, the breeding investment response with no pre-breeding is initially a period of high investment at $I^{\text{max}}$ (Figure 1b) towards fast-track pre-breeding for the pest. Once varieties are established after $\Delta t^{nopb}$, 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](image_url)

**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, $\pi_{\text{no pest}}$ prior to incursion, $\pi_{\text{pest}}$ with no control or resistance, $\pi_{\text{pest, spray}}$ with chemical use, and $\pi_{\text{pest, resist}}$ variety with resistance. (b) Investment options into pre-breeding, $0 = \text{no investment}, I^* = \text{invest in pre-breeding}, I^{\text{max}} = \text{fast-track breeding response}.$
2.1. Production revenue and costs

The term $\pi^j$ 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:

$$
\pi^j = \begin{cases}
\sum_s \sum_{t=1}^{T} \left( a_{st}(p_{st}y_{st} - c_{st}) \right) \delta^t, & t < t_i \\
\sum_s \sum_{t=t_i}^{T} \left( a_{st}'(p_{st}y_{st} - c_{st}) + \sum_{k \in R_{st}^{j,i}} \omega_{st}^k a_{st}^i((p_{st}\theta_{st}^k) (y_{st}\phi_{st}^k) - c_{st} - c_{st}) \right) \delta^t, & t_i \leq t < t_i + \Delta t^j \\
\sum_s \sum_{t=t_i+\Delta t^j}^{T} \left( a_{st}'(p_{st}y_{st} - c_{st}) + \sum_{k \in R_{st}^{j,i}} \omega_{st}^k a_{st}^i((p_{st}\theta_{st}^k) (y_{st}\phi_{st}^k) - c_{st} - c_{st}) \right) \delta^t, & t \geq t_i + \Delta t^j
\end{cases}
$$

(1)

where subscript $s$ ($s = 1, \ldots, S$) gives the wheat or barley producing regions, $t$ ($t = 1, \ldots, T$) is the year, and $T$ the end of the planning horizon. The variables are defined as follows: $a_{st}$ is the total production area, $a_{st}'$ 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 $\delta^t$ 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 ($0 \leq \phi_{st}^k \leq 1$); and (ii) a price reduction ($0 \leq \theta_{st}^k \leq 1$). The variable cost of the management option is given by $c_{st}$. The proportion of the area subject to management option $k$ is $\omega_{st}^k$. Here $R_{st}^{j,i}$ is the set of all management options available at time $t$ across the infested/infected area. The sum of $\omega_{st}^k$ 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:

$$I_t \sim \text{Poisson}(n_t)$$

(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:

\[
\frac{da_{st}}{dt} = \rho_s a_{st} \left( 1 - \frac{a_{st}}{a_{st}} \right)
\]

where \( \rho_s \) 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 \((\psi_{st})\), is given by a binomial distribution:

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

where \( \psi_c \) 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:

\[
h_{st} = \frac{\sum_{s' \neq s} w_{s,s'} a_{st}}{A}
\]

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:

\[
w_{s,s'} = e^{\vartheta d_{s,s'}} \quad \vartheta = \ln(w_{min}) d_{max}
\]

The parameter \( \vartheta \) 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 \( C_{nop} \). For any pest the option value of pre-breeding is:
\[ J = E[\pi^{pb} - \pi^{nopb} - C^{nopb}] \] (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 ($c_{st}$), 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 ($\lambda$) 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.
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 ($\phi_k$) 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](image)

**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 ($\rho_s$) within the statistical area, it can jump to another statistical area. The probability of jump ($\psi_{st}$) 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](image)

**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
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 (GIa), generated from the weekly Growth Index (GIw) 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 GIw 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 El equal to zero and a GI, 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.](image)

(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 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 GIₐ 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 GIₐ 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 GIₐ 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.

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

**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.
White et al. (2016) Should we invest in cereal pre-breeding now for biosecurity threats? SARE Working paper

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.

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

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.

<table>
<thead>
<tr>
<th>Pest</th>
<th>EWSR</th>
<th>RWA</th>
<th>HF</th>
<th>SP</th>
<th>BSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>KB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EWSR</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RWA</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>HF</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KB</th>
<th>EWSR</th>
<th>RWA</th>
<th>HF</th>
<th>SP</th>
<th>BSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline mean return to pre-breeding ($ million)</td>
<td>0.0003</td>
<td>36.2</td>
<td>18.0</td>
<td>0.2</td>
<td>1.3</td>
<td>16.7</td>
</tr>
<tr>
<td>Percent change relative to the baseline:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delay pre-breeding +1 years (6 years)</td>
<td>-6.5</td>
<td>-2.7</td>
<td>-3.1</td>
<td>-3.0</td>
<td>-6.2</td>
<td>-5.5</td>
</tr>
<tr>
<td>Delay pre-breeding -1 years (4 years)</td>
<td>3.5</td>
<td>1.2</td>
<td>1.6</td>
<td>1.4</td>
<td>3.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Discount rate +0.03 (8%)</td>
<td>-42.4</td>
<td>-37.7</td>
<td>-44.5</td>
<td>-58.8</td>
<td>-44.1</td>
<td>-39.0</td>
</tr>
<tr>
<td>Discount rate -0.03 (2%)</td>
<td>91.6</td>
<td>71.8</td>
<td>97.6</td>
<td>189.4</td>
<td>99.4</td>
<td>78.6</td>
</tr>
<tr>
<td>Probability of incursion +30% (various)</td>
<td>7.1</td>
<td>14.2</td>
<td>31.0</td>
<td>-49.5</td>
<td>15.4</td>
<td>7.6</td>
</tr>
<tr>
<td>Probability of incursion -30% (various)</td>
<td>-28.2</td>
<td>-19.0</td>
<td>-27.7</td>
<td>-75.7</td>
<td>-22.5</td>
<td>-25.9</td>
</tr>
<tr>
<td>Adoption of resistant variety +40% (100%)</td>
<td>66.7</td>
<td>65.1</td>
<td>65.5</td>
<td>29.5</td>
<td>66.7</td>
<td>63.4</td>
</tr>
<tr>
<td>Adoption of resistant variety -40% (20%)</td>
<td>-66.7</td>
<td>-65.1</td>
<td>-65.5</td>
<td>-29.5</td>
<td>-66.7</td>
<td>-63.4</td>
</tr>
<tr>
<td>Elasticities²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delay pre-breeding +1 years (6 years)</td>
<td>-0.09</td>
<td>-0.04</td>
<td>-0.04</td>
<td>-0.04</td>
<td>-0.09</td>
<td>-0.08</td>
</tr>
<tr>
<td>Delay pre-breeding -1 years (4 years)</td>
<td>-0.04</td>
<td>-0.01</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.03</td>
<td>-0.02</td>
</tr>
<tr>
<td>Discount rate +0.03 (8%)</td>
<td>-0.29</td>
<td>-0.25</td>
<td>-0.31</td>
<td>-0.45</td>
<td>-0.31</td>
<td>-0.26</td>
</tr>
<tr>
<td>Discount rate 0.03 (2%)</td>
<td>-0.24</td>
<td>-0.20</td>
<td>-0.25</td>
<td>-0.36</td>
<td>-0.25</td>
<td>-0.21</td>
</tr>
<tr>
<td>Probability of incursion +30% (various)</td>
<td>0.06</td>
<td>0.11</td>
<td>0.22</td>
<td>-0.55</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>Probability of incursion -30% (various)</td>
<td>0.27</td>
<td>0.18</td>
<td>0.27</td>
<td>1.02</td>
<td>0.21</td>
<td>0.25</td>
</tr>
<tr>
<td>Adoption of resistant variety +40% (100%)</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.16</td>
<td>0.31</td>
<td>0.30</td>
</tr>
<tr>
<td>Adoption of resistant variety -40% (20%)</td>
<td>0.62</td>
<td>0.60</td>
<td>0.61</td>
<td>0.22</td>
<td>0.63</td>
<td>0.58</td>
</tr>
</tbody>
</table>

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) |
|------|-------------------------|----------------|-------------------------|----------------------|-------------|-------------------------------------------------------------------------------------------------
| KB   | Propiconazole           | 13.50          | 0.5                     | 1                    | 19.75       | 0                                                                                               |
| EWSR | Propiconazole           | 13.50          | 0.5                     | 1                    | 19.75       | 185.7                                                                                          |
| RWA  | Chlorpyrifos            | 10.00          | 0.9                     | 1                    | 22.00       | 179.5                                                                                          |
| HF   | Not recommended         | -              | -                       | -                    | -           | -                                                                                               |
| SP   | Fenitrothion            | 33.92          | 0.65                    | 2                    | 70.09       | 12.8                                                                                           |
| BSR  | Propiconazole           | 13.50          | 0.5                     | 1                    | 19.75       | 86.0                                                                                           |

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); Carbophuran 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.

![Chemical use graphs](image1)

**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.
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Appendix A Table 6. Analysis assumptions.

<table>
<thead>
<tr>
<th>Number</th>
<th>Section</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2. Investment return model</td>
<td>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.</td>
</tr>
<tr>
<td>2</td>
<td>2. Investment return model</td>
<td>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.</td>
</tr>
<tr>
<td>3</td>
<td>2. Investment return model</td>
<td>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.</td>
</tr>
<tr>
<td>4</td>
<td>2. Investment return model</td>
<td>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.</td>
</tr>
<tr>
<td>5</td>
<td>2. Investment return model</td>
<td>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.</td>
</tr>
<tr>
<td>6</td>
<td>2. Investment return model</td>
<td>At present there is no resistance to the pest in current or ready for release varieties in Australia.</td>
</tr>
<tr>
<td>7</td>
<td>3.1 Pre-breeding costs, time delays and adoption</td>
<td>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.</td>
</tr>
<tr>
<td>8</td>
<td>3.4 Region specific pest suitability and yield losses</td>
<td>Climate is the only factor determining the presence of the pest.</td>
</tr>
<tr>
<td>9</td>
<td>3.4 Region specific pest suitability and yield losses</td>
<td>Climatic suitability determines the damage and yield loss expected.</td>
</tr>
</tbody>
</table>
## Appendix B Table 7. Cereal breeding summary.

<table>
<thead>
<tr>
<th>Pest</th>
<th>Type of resistance</th>
<th>Markers available</th>
<th>Yield penalty</th>
<th>Resistance breakdown</th>
<th>Comment</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karnal bunt</td>
<td>Quantitative genes</td>
<td>Yes</td>
<td>No</td>
<td>Limited evidence</td>
<td>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.</td>
<td>Sharma et al., 2012, R. Bowden pers. comm.</td>
</tr>
<tr>
<td>Exotic wheat stem rust</td>
<td>Single gene resistance replaced by multiple genes and gene pyramiding, increases costs</td>
<td>Yes for major genes</td>
<td>Yes</td>
<td>Common</td>
<td>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.</td>
<td>Murray and Brennan, 2009</td>
</tr>
<tr>
<td>Russian wheat aphid</td>
<td>Single gene resistances, some biotype specific, and less specific.</td>
<td>Yes</td>
<td>No</td>
<td>Ten years between Dn4 resistance to Biotype 1 and appearance of Biotype 2.</td>
<td>Development of locally adapted pre-breeding material, through the GRDC funded project UMU00029.</td>
<td>GRDC and Cakir, 2011</td>
</tr>
<tr>
<td>Hessian fly</td>
<td>Genes are available (for example H24 and H26) which confer broad resistance. Breeding with these may take more time, with 'pyramiding' recommended.</td>
<td>Yes</td>
<td>5%</td>
<td>Biotypes</td>
<td>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.</td>
<td>Botha et al., 2005, M. Francki, pers. comm.</td>
</tr>
<tr>
<td>Sunn pest</td>
<td>The genetic nature of resistance is unknown</td>
<td>No</td>
<td>Unknown</td>
<td></td>
<td>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 <em>Aestivium umbellulatum</em> Zhuk.. These factors will make pre-breeding and breeding for resistance to sunn pest difficult, costly and time consuming.</td>
<td>Boussssin et al., 2013, 2009</td>
</tr>
<tr>
<td>Barley stripe rust</td>
<td>Single gene resistance</td>
<td>Yes</td>
<td>No</td>
<td>Unknown</td>
<td>Some resistance in Australian varieties.</td>
<td></td>
</tr>
</tbody>
</table>
### Appendix C Table 8. Illustrative steps in pre-breeding for an exotic pest or disease.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Comment</th>
<th>Total cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>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.</td>
<td>Costs $250,000 per annum over three years. (Probably only required for Sunn pest as source of resistance not identified).</td>
<td>750,000</td>
</tr>
<tr>
<td>2.</td>
<td>Confirm that Australian varieties are susceptible to the pest/pathogen – presumably requires phenotyping overseas and/or in containment in Australia.</td>
<td>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.</td>
<td>195,000</td>
</tr>
<tr>
<td>3.</td>
<td>Cross it with a susceptible Australian variety and develop progeny populations. The costs depend on whether or not crossing is done overseas.</td>
<td>$30 per line, 3 resistance sources, 2 adapted lines per GRDC region, 18 populations in total.</td>
<td>540</td>
</tr>
<tr>
<td>4.</td>
<td>Extract DNA. Using AGRF services.</td>
<td>$5 per sample, 18 lines including 100 plants.</td>
<td>9,000</td>
</tr>
<tr>
<td>5.</td>
<td>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.</td>
<td>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.</td>
<td>90,000</td>
</tr>
<tr>
<td>6.</td>
<td>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.</td>
<td>Two weeks’ time from a postdoc. Assume $110,000 per annum including on-costs.</td>
<td>4,231</td>
</tr>
<tr>
<td>7.</td>
<td>Increase the seed.</td>
<td>Glasshouse space and services.</td>
<td>1,000</td>
</tr>
<tr>
<td>8.</td>
<td>Phenotype the population overseas.</td>
<td>Assumes 100 lines in one country.</td>
<td>65,000</td>
</tr>
<tr>
<td>9.</td>
<td>Quarantine clearance through AQIS.</td>
<td>$80 per line for 18 populations Greg Grimes (Australian Winter Cereal Collection) (2014, pers. com.).</td>
<td>144,000</td>
</tr>
<tr>
<td>10.</td>
<td>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.</td>
<td>Two weeks of a postdoc.</td>
<td>4,231</td>
</tr>
<tr>
<td>11.</td>
<td>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.)</td>
<td>Two weeks of a statistician. As for postdoc.</td>
<td>4,231</td>
</tr>
<tr>
<td>12.</td>
<td>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.</td>
<td>$10,000 plus 3 weeks for a technician. $80,000 per annum including on costs.</td>
<td>14,615</td>
</tr>
<tr>
<td>13.</td>
<td>Reanalyse the data and pick the best ones. Start using them in marker-assisted germplasm development.</td>
<td></td>
<td>1,000</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Notation</th>
<th>Details</th>
<th>Units</th>
<th>KB</th>
<th>EWSR</th>
<th>RWA</th>
<th>HF</th>
<th>SP</th>
<th>BSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta t^{nopb}$</td>
<td>Delay resistant variety release - no pre-breeding</td>
<td>years</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$\Delta t^{pb}$</td>
<td>Delay resistant variety release - pre-breeding</td>
<td>years</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Net present value of the cost of pre-breeding over the planning horizon</td>
<td>$</td>
<td>$1,259,773</td>
<td>$1,259,773</td>
<td>$1,259,773</td>
<td>$1,259,773</td>
<td>$2,009,773</td>
<td>$1,259,773</td>
<td></td>
</tr>
<tr>
<td>$r$</td>
<td>Discount rate</td>
<td>%</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$c^{k}_{st}$</td>
<td>Additional pest control costs following incursion</td>
<td>$/ha per year</td>
<td>19.75</td>
<td>19.75</td>
<td>22.00</td>
<td>0</td>
<td>70.09</td>
<td>19.75</td>
</tr>
<tr>
<td>Pest control effectiveness against yield losses</td>
<td>%</td>
<td>n/a</td>
<td>80</td>
<td>80</td>
<td>n/a</td>
<td>80</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>$q^{k}_{st}$</td>
<td>Maximum yield loss without control</td>
<td>%</td>
<td>0.2</td>
<td>45</td>
<td>82.9</td>
<td>15</td>
<td>90</td>
<td>50</td>
</tr>
<tr>
<td>Minimum yield loss without control</td>
<td>%</td>
<td>0.001</td>
<td>10</td>
<td>25</td>
<td>2</td>
<td>50</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Modal yield loss without control</td>
<td>%</td>
<td>0.1</td>
<td>20</td>
<td>42.5</td>
<td>7.5</td>
<td>70</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>$\lambda$</td>
<td>PERT shape parameter</td>
<td>10</td>
<td>20</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$\theta^{k}_{st}$</td>
<td>Proportion of commodity price with disease/pest</td>
<td>%</td>
<td>80</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>$n_t$</td>
<td>Probability of established incursion (Poisson)</td>
<td>year$^{-1}$</td>
<td>0.011</td>
<td>0.057</td>
<td>0.011</td>
<td>0.011</td>
<td>0.011</td>
<td>0.044</td>
</tr>
<tr>
<td>Minimum area of initial infestation/infection</td>
<td>ha</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>Intrinsic spread rate of pest area (logistic)</td>
<td>ha per year</td>
<td>0.69</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$\psi_{st}$</td>
<td>Jump probability (binomial)</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>$d^{max}$</td>
<td>Maximum distance of spread</td>
<td>km per year</td>
<td>300</td>
<td>2000</td>
<td>1000</td>
<td>45</td>
<td>250</td>
<td>2000</td>
</tr>
<tr>
<td>$\omega^{k}_{st}$</td>
<td>Proportion of infested area adopting resistant variety</td>
<td>%</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

**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/L (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-Bowdler, 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% (PBRC, 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).


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 $a_{st}^{\text{max}} \rightarrow 0$, 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 infected/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^W. 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. *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).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mnemonic</th>
<th>Details</th>
<th>Value</th>
<th>Units$^a$</th>
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<td>2</td>
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<tr>
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<td>-</td>
</tr>
<tr>
<td>Cold stress</td>
<td>THCS</td>
<td>stress accumulation rate</td>
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<td>-</td>
</tr>
<tr>
<td>Cold stress</td>
<td>DTCS</td>
<td>degree-day threshold$^\dagger$</td>
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</table>

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

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