Foresight

Infectious Diseases: preparing for the future

OFFICE OF SCIENCE AND INNOVATION

T8.11: The benefits of potato ring rot exclusion from the United Kingdom

David C. Cook
CSIRO Entomology, and the Australian National University
(email: david.c.cook@csiro.au, GPO Box 1700, Canberra, ACT 2601, Australia)

Jeffery K. Waage, John D. Mumford, Rob W. Fraser
Imperial College London

Andy Wilby
University of Reading

Abstract:

This review discusses the economic benefits the potato industry in the United Kingdom can expect to enjoy if potato ring rot can be prevented from entering the region in the next 30 years. It presents a stochastic bioeconomic model in which producer management behaviour changes with the presence of the disease, but is unable to prevent the loss of export markets, reduced crop yields and additional production costs. The avoidance of these on-farm cost and revenue effects can be interpreted as the benefits of exclusion. The model estimates that benefits of around £2.6 million per year will accrue to the potato industry if regional freedom can be maintained over a period of 30 years.

1 Introduction

In this review, we apply a stochastic bioeconomic model to an important biosecurity issue facing the United Kingdom: the exclusion of potato ring rot (PRR). This disease causes severe losses throughout several potato-growing regions of the world, but remains absent from the UK. Using the model, we simulate expected spread and impact of this disease as it may occur in the region in future. If no eradication campaign were to be mounted against PRR after it entered and became established in the UK, spread would continue until it became naturalised. Naturalisation is complete when a pest or disease spreads to its full capacity within an environment, in such way that, over time, it becomes a permanent, non-spreading feature of that environment (Mack 1989; Mack and Lonsdale 2001). The model further estimates the economic costs throughout the naturalisation process by making simple predictions about the behaviour of affected producers, and what cost will be associated with this behavioural change.

The uncertainty and variability surrounding many of the model parameters means that we are only able to place a broad estimate on the likely benefits of maintaining freedom from PRR over time. Expressing results as an annual average benefit of exclusion, we estimate that the process of PRR naturalisation would cost UK potato producers up to £10.9 million per year over the next 30 years if no response were mounted after an incursion. On average, the annual benefit of exclusion is estimated to be £2.6 million. Being a ‘do nothing’ scenario (where there is no government response to an incursion), this result can serve as a base case against which future biosecurity risk management and mitigation strategies relating to PRR can be compared. We perform scenario analyses to show the effects of changing key parameter estimates according to perceived future circumstances and examine the ramifications of these changes on the model results.

This review is structured as follows. Section 2 provides a background to the PRR issue and explains just what we mean by ‘exclusion benefits’. Section 3 outlines the model, and Section 4 presents parameters used in impact simulations. The results are presented in Section 5, along with sensitivity and scenario analyses, and the review concludes with a brief summary and discussion in Section 6.

2 Background

PRR is caused by the bacterium *Corynebacterium sepedonicum* and is one of the most serious potato diseases in Asia, North America, and central and northern European countries. The disease causes the early death of plants, rotting of progeny tubers and extensive yield reduction. A yellowing of the lower leaves on one or more stems is followed by progressive wilt and the eventual death of plant stems. The infection spreads to tubers by way of the stolons, causing a cheesy, odourless rot of the vascular ring. Tangible negative impacts of PRR result from a loss of seed certification and requirements for disinfection of equipment and stores. The disease is spread to seed tubers by mechanical planters, elevators, dressers and other handling machinery, and so is generally a more severe problem in highly mechanised potato-growing operations (Stansbury et al. 2001). If PRR spread to the UK, it is expected to severely damage the domestic host industries through the need for disinfection procedures, and through yield losses and export market losses.

Biosecurity has become a major concern for trading nations.[1] The establishment of new and lucrative trade routes provides a myriad biological organisms with the opportunity to colonise areas of the world previously impossible to reach unaided. In this sort of environment, a system of targeting quarantine effort towards those pests and diseases capable of producing the greatest amount of damage to an economy forms an important tool for policy makers. If advanced warning of pest threats can be provided, along with an indication of their potential means of entry and the damage to be expected from them, it may be possible to cost-effectively tailor a biosecurity system to minimise losses from exotic pest outbreaks. With this in mind, this review puts forward a method of estimating the potential economic benefits of keeping PRR out of the UK.

For every time period we are successful in maintaining areas free from a pest or disease such as PRR, we receive a notional benefit by avoiding the costs of managing the disease. We must assume that the probability of entry and establishment in each time period is positive (since zero risk is technically unachievable), the expected benefits of exclusion must be positive as we track them throughout time.

Consider Expected Benefit Stream A in Figure 1 and assume the invasive species represented is PRR. Beginning at time zero, the expected benefits accruing to potato producers from maintaining area freedom increase as we move along the time axis towards t. The further out in time we project this benefit stream, the higher the chance is that in reality we will have had an outbreak of the disease. So, if we can successfully exclude PRR for an extended period of time, we will have earned a considerable benefit for potato growers in potentially affected areas.

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[1] The term ’biosecurity’ generally applies to any method of non-indigenous pest damage mitigation, be it preventing introductions, detecting incursions and eradicating resultant populations, or managing new species as long-term problems, curtailing their impact and preventing their further spread (Waage et al. 2005).

If we were to invest in risk mitigation technologies in time zero and lower the likelihood of a PRR outbreak occurring over time, we may face a stream of benefits like Expected Benefit Stream B. This curve lies everywhere below Stream A, since the consequences of living with PRR have not changed, only the probability of it entering and becoming established in susceptible areas. It follows that the vertical distance between these curves forms the expected returns from the new technology. The benefits of exclusion over time fall, since the technology is effective in preventing outbreaks, meaning that PRR is no longer as capable of causing damage to the economy over time. The difference in the resultant benefit stream from that of the original status quo or 'control case' represents the extent to which potato growers benefit from the reduction in entry and establishment probability.

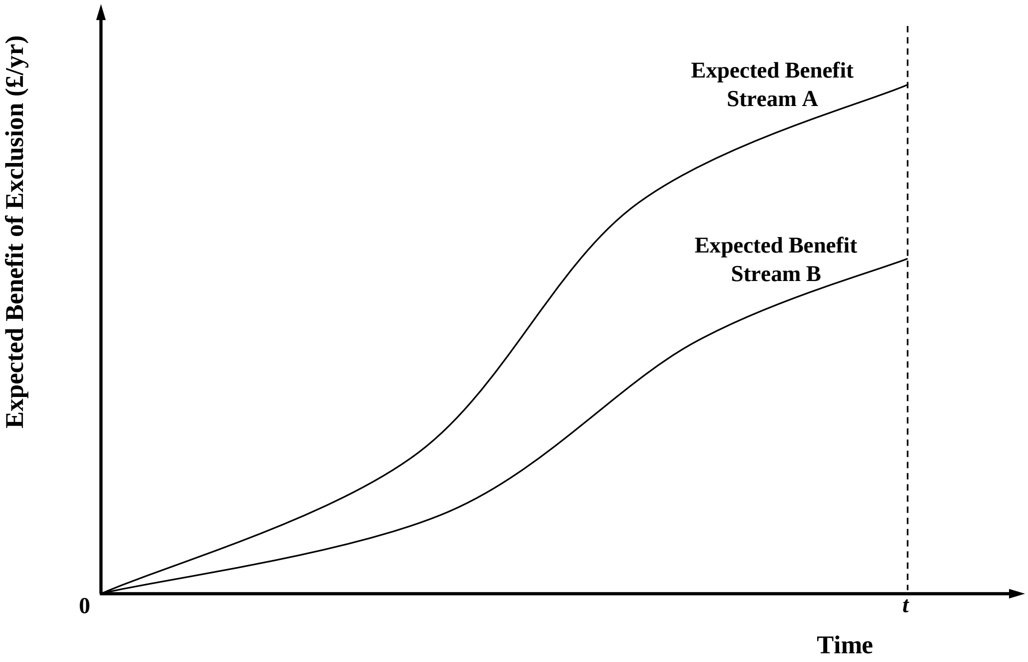

Figure 1: *Expected benefits from exclusion*

Using a simulation model to form the base case enables a virtually endless number of scenario comparisons to be performed. We will demonstrate how such comparisons can be made in Section 5, but the main purpose of the review is to elicit the base case. This is essentially a reference point for future scenario analyses.

3 The model[2]

Invasive species incursions are inherently uncertain. An incursion may be unlikely within an immediate timeframe and almost certain to occur in the medium or longer term (Beare et al. 2005). The objective of the model used in

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[2] Much of this section has been taken from Cook et al. (2005).

this review is to assess the size of the threat posed by PRR by determining the total *expected* (or probability-weighted) benefit of exclusion over a specified period of time. The use of stochastic simulation models is becoming common in risk analysis modelling systems with parameter uncertainty and variability. This is the approach adopted here. Monte Carlo simulation with Latin Hypercube sampling is used to extract values from specified distributions.[3] Each parameter is expressed as a probability distribution, and then 10,000 iterations of the model are run. In each iteration, one value is randomly sampled across the range of each distribution, and the results are tallied at the end of the process to give an indication of the spread of potential benefits of exclusion.

Arrival and establishment are approximated in the simulation model as the simple probabilities of entry (P_{ent}) and establishment (P_{est}). For any pest y, these are combined to give a probability of invasion p_y:

$$p_y = p_{ent} \cdot p_{est} \qquad (1)$$

where

$$0 < p_y < 1.$$

Since we are concerned with a single pest, the 'y' subscript is dropped hereafter.

The transition between a 'with pest' and 'without pest' state is described as a Markov process. The probability of a PRR invasion (call it event a) occurring in a time period, $t+1$, conditional on its absence (event b) in time period t, is denoted p_{ab}. There is also a probability attached to event a occurring in both time periods. All possible outcomes for time period $t+1$ are arranged in a transition matrix, $\boldsymbol{P}$, where a defines the row and b the column, i.e.:

$$\boldsymbol{P} = \begin{pmatrix} p_{aa} & p_{ab} \\ p_{ba} & p_{bb} \end{pmatrix}. \qquad (2)$$

The elements in the matrix are conditional probabilities indicating the likelihood of being in a 'with pest' (i.e. invasion) state defined by the row, given that we were in the state indicated by the column in the previous time period (i.e. either 'with pest' or 'without pest'). By specifying the initial probabilities of being in either state, we can determine the likelihood of being in a certain state in any future time period.[4]

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[3] The *@Risk* software package (Palisade Corporation) was used to carry out simulations.

[4] The transitional probability p_{ab} represents p_y in equation (1). Similarly, p_{aa} is given by p_{est}. We discuss specific values for these probabilities below. The remaining transitional probabilities are $p_{ba} = (1 - p_{aa})$ and $p_{bb} = (1 - p_{ab})$.

If we denote the probabilities of the events a and b occurring at any time t by $p_a(t)$ and $p_b(t)$, the probability of a occurring in $t+1$, given that b has occurred in t, can be expressed as:

$$p_a(t+1) = \sum_b p_{ab} p_b(t) . \qquad (3)$$

If $\boldsymbol{p}(t)$ is a column vector with elements $p_a(t)$ and $p_b(t)$, we can use the transition matrix to express (3) as:

$$p_a(t + 1) = \boldsymbol{Pp}(t). \qquad (4)$$

By applying this previous equation repeatedly, we obtain:

$$\boldsymbol{p}(t) = \boldsymbol{P^t p}(0). \qquad (5)$$

If our Markov chain is regular, the vector $\boldsymbol{p}(t)$ will converge to a unique vector $\boldsymbol{p}$ as t increases (Moran 1984; Hinchy and Fisher 1991).[5] Independent of the state of the world in t, we can accurately predict the probability of being in either state a or b after several time periods, $t+n$. Hence, the probability of event a occurring in any given time period will reduce to a constant value after several time periods. Since we are only concerned with event a, we will denote $p_a(t)$ as p_t in the text to follow.

So, what happens when PRR successfully enters the UK and begins to spread (i.e. event a above)? As a base case scenario, assume no centrally co-ordinated response plan is to be invoked in the event of an outbreak. The reasoning for this 'unrealistic' assumption is that response policies should be guided by a standardised control case assessment of potential damages, the most straightforward of which to form is 'no government response'. This is not to say that there will be no action taken on behalf of potato growers to protect their crops from PRR. In fact, the very opposite. If we make the assumption that they are profit maximisers in a perfectly competitive market structure, growers will use every technology at their disposal to minimise impact, as long as this doesn't inflate their average cost of production above the market price. Disinfectants such as quaternary ammonia, chlorine, iodine or phenol-containing compounds applied to equipment and other contaminated surfaces for a minimum of 10 minutes under low organic load are effective against *C. sepedonicum* (CABI/EPPO 2002).

Crop treatments such as *Chlorothalonil/Cyprocanazole* may also be applied by growers in an effort to minimise disease impact, although the effectiveness of this treatment is not expected to be high. Of far greater concern to potato

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[5] The initial probabilities attached to events a and b will be dependent on the effectiveness of quarantine and surveillance policies in place at the outset of the analysis. Changes to these policies will alter these probabilities as the likelihood of pre- and post-border detection changes (Hinchy and Fisher 1991). Analyses of policy effectiveness are easily accommodated using this framework, but are not undertaken in this paper.

growers are revenue effects, including export and yield losses. Potato exports account for around £25 million per year in export revenue (approximately 40% from raw, unprocessed potatoes and 60% from processed potatoes). It has been estimated that 20–95% of seed potato export markets, 10–50% of ware potato export markets and 0–5% of processed potato export markets would be lost if PRR were to become established in the UK (Pemberton 1988; Mumford et al*.* 2000).

In assuming a minimal response (or 'do nothing') scenario as our base case, the economic impact of PRR becomes a function of the cost and revenue implications for the potato industry as the naturalisation process takes place over time. Becoming a naturalised species involves an original site of introduction (i.e. entry and establishment), and a number of satellite sites that subsequently develop. Leaving the issue of entry and establishment probability to one side, the total damage (D) attributable to any one of these sites j in any time period t is given by:

$$\mathrm{D}_{jt} = \left(d_j.\mathrm{A}_j.\mathrm{N}_j\right)_t \qquad (6)$$

where

D_{jt} = total damage inflicted by site j at time t;

d_j = marginal damage cost of the pest in site j;[6]

A_j = area affected in site j;

N_j = pest density within site j.

Here, the marginal damage cost $d_j = c_j + r_j$, where c_j and r_j are the cost and revenue implications (respectively) for an affected industry (or industries as the case may be). Let us assume that each site involves a single crop, x, such that $d_j = c(x) + r(x)$. The relative size of the independent variables therefore depends on factors such as additional management activities (i.e. cost) and export losses (i.e. revenue).

After arrival, the spread of the outbreak to other susceptible areas is modelled in a relatively simple way. We assume that, once established, the population spread can be described using a reaction diffusion model descended from

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[6] Note that intuitively d_j, which represents the damage increment attributable to the addition of one unit of the fungus, will decline over time (i.e. $d_j' < 0$). However, let us assume $d_j' = 0$ in the interests of simplicity, so in effect d_j represents an *average* damage cost, rather than a marginal damage cost.

those employed by Fisher (1937) and Skellam (1951).[7] We assume that, once established in a site j, the population spreads by a diffusive process, such that the area occupied by the population (A) expands following the function (Hengeweld 1989; Lewis 1997; Shigesada and Kawasaki 1997):

$$\mathrm{A}_j = 4D\pi g t^2 \tag{7}$$

where

D = population diffusion coefficient;[8]

g = intrinsic rate of population growth;

t = time period after introduction and establishment.

We assume that, within each unit of area affected by the expanding PRR outbreak, the local infection density (N) within site j grows logistically to the carrying capacity of the environment, such that:

$$\mathrm{N}_j = \frac{\mathrm{K}}{1 + \left(\dfrac{\mathrm{K}}{\mathrm{N}_{\min}} - 1\right).e^{-gt}} \tag{8}$$

where

K = carrying capacity, or maximum density of infestation attainable per unit of area;

$\mathrm{N}_{\min}$ = pest density immediately on establishment (assumed as 1 hectare of affected crop).

The total number of component sites (s) making up an outbreak at any one point in time is also assumed as a logistic function:

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[7] These models are of the general form:

$$\frac{dn}{dt} = f(n) + \mathrm{D}\left(\frac{d^2n}{dx^2} + \frac{d^2n}{dy^2}\right) \tag{i}$$

where $f(n)$ is the population growth function and D is the diffusion coefficient. A generic result of these models is that a population diffusing from a point source will eventually reach a constant asymptotic radial spread rate of $2\sqrt{g\mathrm{D}}$ in all directions (Waage et al. 2005).

[8] D can be derived from the mean dispersal distance (MDD) (Andow et al. 1990):

$$\text{i.e. } \mathrm{D} = \frac{2\mathrm{MDD}^2}{\pi}. \tag{ii}$$

$$s_t = 1 + \frac{\mathrm{S}_{\max}}{1 + \left(\frac{\mathrm{S}_{\max}}{\mathrm{S}_{\min}} - 1\right).e^{-\mu \mathrm{A}_{t-1}}} \qquad (9)$$

where

$\mathrm{S}_{\max}$ = maximum attainable number of satellite sites;

$\mathrm{S}_{\min}$ = minimum number of satellite sites;

μ = intrinsic rate of satellite generation.

So, as the total area affected increases and the population density within that area increases, so too does the likelihood of a random satellite outbreak some distance from the original site.

Spread area, infection density and the number of sites can now be combined with the probability of entry and establishment in an expression of probability-weighted, or expected, benefits of exclusion over time. Assuming a discount rate α, the present value of expected damage after n time periods ($\mathrm{PV}(\mathrm{ED}_n)$) is:

$$\mathrm{PV}(\mathrm{ED}_n) = \sum_{t=0}^{n} (1+\alpha)^{-t} . \sum_{j=1}^{s_t} p.d.\mathrm{A.N} \, . \qquad (10)$$

Equation (10) provides us with a probability-weighted estimate of PRR-induced revenue losses and cost increases to potato growers over time. It is *not* a measure of what damage will be inflicted by PRR if it is introduced to the UK in the present time period (i.e. $p \neq 1$). Rather, it provides a measure of expected benefits of exclusion taking into account uncertainty in the time of arrival, and change in abundance and distribution over time after arrival.

4 Parameters

4.1 Probability of entry and establishment

Although there has been an increased level of quantitative research across many disciplines in recent years, this is often not the case in the biological and natural resource management fields. A lack of basic data prevents the same level of quantification being achievable in analytical work compared to other fields such as engineering (Nunn 2001). This places a major limitation on examining the potential impacts of invasive species when one considers that entry and establishment probabilities can be highly sensitive parameters (Cook 2005).

In the absence of a rigorous, quantitative risk assessment reporting the probability of species arrival, we have used the semi-quantitative categorisation system outlined in AFFA (2001). This involves uniform (or rectangular) distributions being used to represent uncertainty in the probability of entry and establishment. The probability of PRR entering the UK is estimated as *very low*, which according to this categorisation system can be represented by a uniform distribution with a minimum value of 0.001 and a maximum value of 0.05, i.e. Uniform(0.001, 0.15). The choice of risk category in this analysis is completely subjective.[9] The probability of establishment conditional on entry already having taken place is categorised as *high*, represented as Uniform(0.7, 1.0). Hence, the combined probability of entry and establishment is given by Uniform(0.0003, 0.05).

4.2 Revenue loss and cost increments

Only the potato industry is assumed to be affected by PRR. Between 1999 and 2003, the gross value of the UK potato industry averaged approximately £596.8 million per year (6,570,000 tonnes grown on roughly 160,000 hectares). Throughout this period, an average of 383,000 tonnes of potatoes were exported, around 40% of which were ware potatoes, 40% processed (raw equivalent) potatoes and 20% seed potatoes. Prices received (quoted for all growers) averaged £100.90 per tonne between 1999 and 2003 (DEFRA 2005). We use the damage estimates of Mumford et al*.* (2000) and Pemberton (1988), and assume that a PRR establishment in the UK would cause a 10–48% reduction in ware potato exports revenue, a 0–5% reduction in processed potato export revenue, and a 20–95% reduction in seed export revenue.

The gross value of these losses is incurred by affected growers in the first time period of infection. Average yield (for all potatoes) between 1999 and 2003 are approximately 40.9 tonnes per hectare, so the gross value of first-year losses are around £4,130 per hectare (DEFRA 2005). In subsequent years, only the gross margin (that is, the return growers would have received from affected areas had PRR not become established) is lost as producers divert resources away from export markets. The gross margin for seed export potatoes is used for all affected areas, and is estimated at £2,155 per hectare (Mumford et al*.* 2000).

It is difficult to speculate as to the likely costs of implementing necessary crop rotation, disinfection and other sanitation practices. Disinfectants such as quaternary ammonia, chlorine, iodine or phenol-containing compounds applied to equipment and other contaminated surfaces for a minimum of 10 minutes under low organic load are effective against PRR (CABI/EPPO 2002). However, estimating a likely cost on a ‘per hectare’ basis is somewhat difficult. It is therefore estimated in relatively broad terms (Pert(£9/ha,£18/ha,£27/ha)). The number of applications is equally difficult to estimate, and is represented as Discrete({0,1,2,3}{0.5,1,1,1}) (Waage et al*.* 2005).

Yield losses in affected areas are expected to be positive despite these measures. This is represented as a pert distribution with a minimum value of

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[9] We explore the sensitivity of the results to the probabilities of entry and establishment in Section 5.

1%, a maximum value of 3.0% and a most likely value of 1.5% per annum (Mumford et al. 2000).

4.3 Area, density and satellite generation

Table 2 provides details of the biological parameters used:

Table 1: *Parameterisation – potato ring rot*

Parameter	Assumed parameter value
P(entry)	Uniform(0.001, 0.05) (see AFFA (2001))
P(establishment)	Uniform(0.7, 1.0) (see AFFA (2001))
g	Pert(1.5,3.0,4.5) (Zadocks and Shein 1979)
N_{min}	1
K (N_{max})	Pert(10000,55000,100000) (Waage et al. 2005)
S_{min}	1
S_{max}	Pert(70,85,100)
μ	Pert(1.0×10^{-5},5.95×10^{-4},1.0×10^{-3}) (Waage et al. 2005)
D	Pert(0,0.25,0.5) (Waage et al. 2005)

5 Results, sensitivity analysis and scenario analysis

The expected benefits to the UK potato industry of remaining free from PRR over the next 30 years are estimated to be around £2.6 million per year (average). In the absence of the disease, potato growers would benefit from reductions in yield and export losses, and the costs associated with disinfection procedures. There is a 90% likelihood of benefits of up to £10.9 million per year accruing to the industry if regional freedom can be maintained. This broad estimate is indicative of the variability and uncertainty inherent in many of the key assumptions used in the simulation. Figure 2 presents a cumulative probability distribution of the expected exclusion benefits over time.

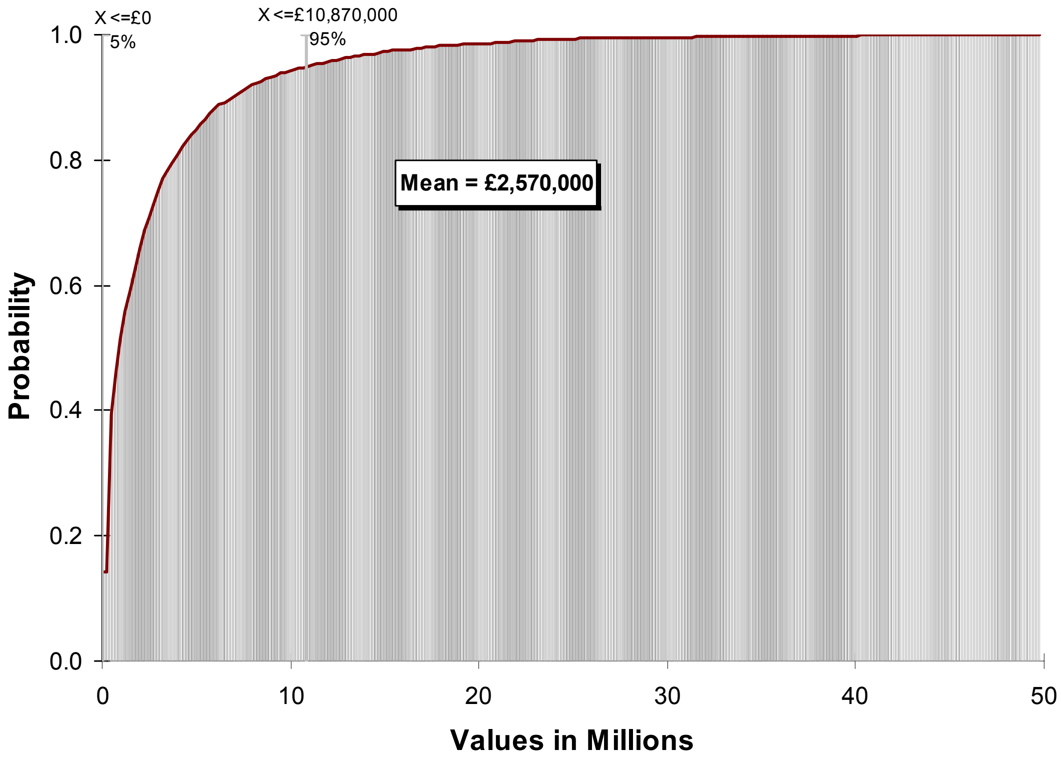

Figure 2: *Cumulative distribution of the expected benefits from PRR exclusion over 30 years*

The most significant variables in determining the expected benefits of exclusion are: the probabilities of entry and establishment; the discount rate; the intrinsic rate of growth; and expected loss of export revenue. This is shown in Table 2. Each parameter was changed by a factor of 50%, and the effect on the final result was then recorded. Hence, if the resultant change in the benefit of PRR exclusion changes by more than 50%, the parameter can be said to exert a relatively large influence on the model.

Table 2: *Sensitivity analysis*

Parameter	Change in parameter value (%)	Resultant change in expected benefit of exclusion (%)
P(entry) (p_{ent})	–50.0	–87.9
	+50.0	+62.4
P(establishment) (p_{est})	–50.0	–33.7
	+50.0	+26.9
Cost of fungicide application (c)	–50.0	–18.3
	+50.0	+13.1
Average total revenue loss – export losses (all potatoes) (r)	–50.0	–39.1
	+50.0	+39.5
Average total revenue loss – yield loss (r)	–50.0	–16.6
	+50.0	+11.2
Discount rate (α)	–50.0	+96.3
	+50.0	–47.1
Population diffusion coefficient (D)	–50.0	–17.7
	+50.0	+17.4
Intrinsic rate of growth (g)	–50.0	–49.5
	+50.0	+58.5
Maximum attainable infection density (K)	–50.0	–7.8
	+50.0	+5.6
Maximum number of satellite sites (S_{max})	–50.0	–2.6
	+50.0	+3.8
Intrinsic rate of satellite site generation (μ)	–50.0	–12.9
	+50.0	+12.3

The high sensitivity of results to both the discount rate and the intrinsic rate of growth indicates that the expected impact of PRR depends on the time over which it is simulated. Figure 3 plots cumulative average annual expected benefits from maintaining PRR freedom from the present to 30 years into the future. The diffusion model used in the analysis produces the pattern of spread (and subsequent impact) we observe in the plots for the mean value and the 5% and 95% confidence intervals. The expected damage avoided grows at an increasing rate until year 30. By year 20, when the mean expected benefit is £0.6 million, the variance associated with our estimate is expected, given the variability in parameter estimates. This uncertainty about the mean damage avoided increases with the period over which the simulation is run.

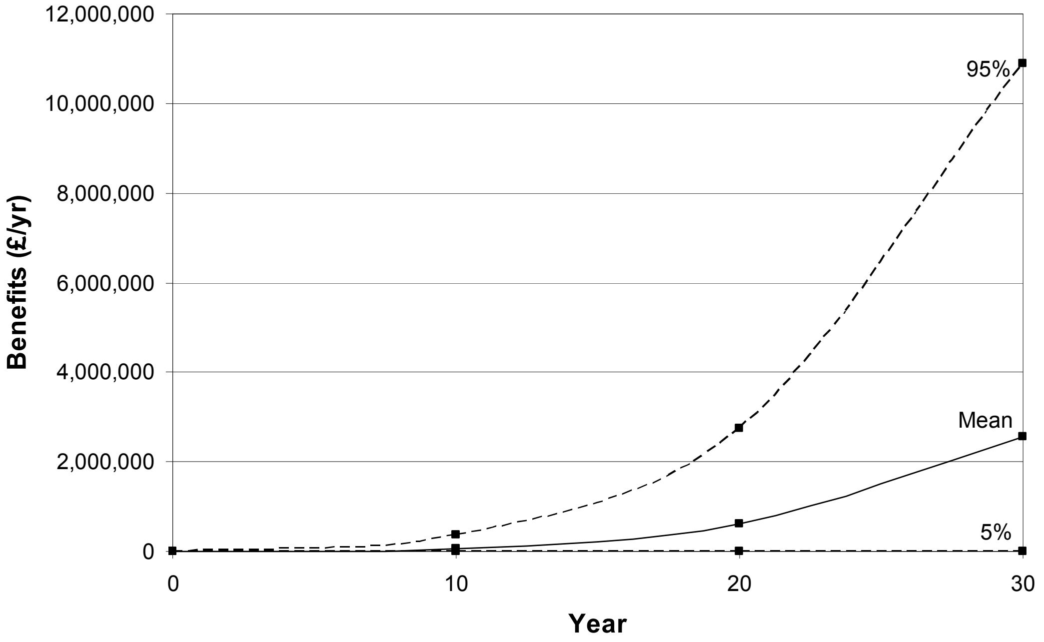

Figure 3: *Expected benefits from PRR exclusion*

Other points to note with regard to Figure 3 are, first, that it is representing 'expected' benefits of exclusion over time, not projected damages from an incursion at time zero. Second, all time periods after time zero have a positive expected benefit of exclusion, reflecting the fact that the probability of entry and establishment is greater than zero.

Sensitivity analysis is useful in that it highlights the parameters of the model with the largest influence on the benefits of exclusion, and so identifies areas where research effort might be invested in future. However, when we wish to look at scenarios in which a number of parameters change, it is of limited use since different parameters can act in different directions and magnitudes.

In this case, we may run the model for different scenarios, where we vary selected parameters to reflect possible future conditions, and compare these to our base case, or 'do nothing' scenario. Here we present scenarios which consider how the benefit of exclusion changes with (1) trade liberalisation and (2) improved disease control technologies.

Let us assume that trade liberalisation will increase the probability of PRR entering the UK, such that it increases to the 'Moderate' category according to AFFA (2001). That is, it increases from Uniform(0.001, 0.15) to Uniform(0.3, 0.7).[10] We might also expect the area of domestically grown potatoes to fall in the wake of increased international competition if the landed price of imported potatoes is lower than the minimum average variable cost of production for a

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[10] We might also expect an external factor like global warming to exert a positive influence on the probability of entry.

number of UK producers. We speculate that the extent of this area reduction may be 10%, so the area under potato cultivation in the UK falls from 160,000 hectares to 144,000 hectares.

The top curve in Figure 4 represents the results of a model simulation with these assumptions. It is immediately obvious that the trade liberalisation scenario produces higher expected benefits from exclusion, reaching a maximum of £10,510,280 by year 30, in spite of the reduction in potato hectarage. This compares to £2,566,160 by the same time in the control case, a rise of around 410%. Given the high sensitivity of the model to the probability of PRR entry, this is not surprising, and the difference between the scenario and control case increases with the length of time over which the estimation is made. We simply conclude that, if the likelihood of contracting PRR increases in the future, the benefits of keeping it out of the UK are set to rise. This implies that returns on investment in preventative measures are also set to increase.

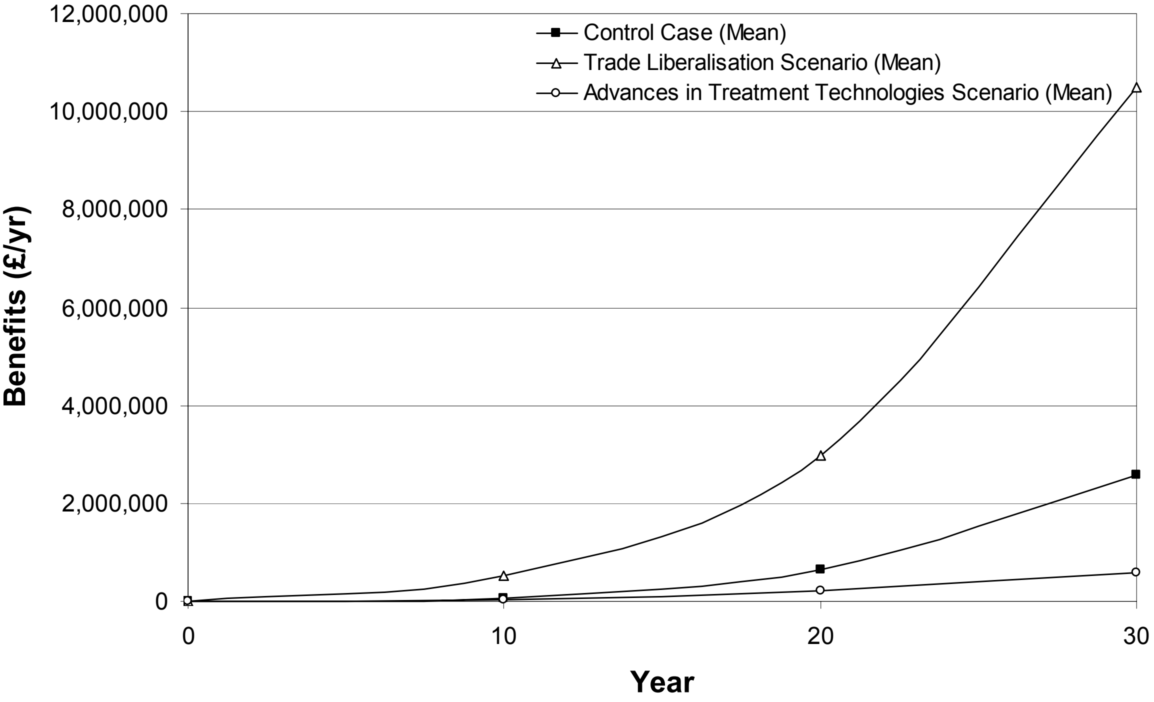

Figure 4: *Scenario analyses*

For a second scenario, consider the impact of improved PRR control technologies on-farm. Technologies that reduce the yield effects of PRR, and slow its spread, may become available in the future, reducing the severity of impact once the disease becomes established in the UK. These may take the form of fungicide treatments or the development of resistant varieties. Whatever the form of this technology, let us assume that yield reduction (despite treatment) falls from Pert(1.0%,1.5%,3.0%) (Mumford et al. 2000) to Pert(0.0%,1.0%,2.0%). Assume also that the new treatment employed on-farm reduces the spread of infection between growing areas, such that the intrinsic rate of growth of an outbreak (g) falls slightly from Pert(1.5,3.0,4.5) (Zadocks and Shein 1979) to Pert(1.0,1.5,3.0). Finally, the number of repetitions of the new control technology may fall from Discrete({0,1,2,3}{0.5,1,1,1}) to Discrete({0,1}{1,1}).

The bottom curve in Figure 4 plots the expected benefits of exclusion over time for our control case and the new technology scenario. As the new technology reduces the severity of the on-farm impact of PRR, the expected benefits of excluding the disease over time fall: preventing disease has less economic benefit when the cost of subsequently controlling it is reduced. But we can use this result in a different way – to estimate the value of that new control technology. By the 30th time period, the expected benefit of exclusion is £597,610, a reduction of almost 80%. This translates into expected returns from the new technology amounting to around £1.97 million per year by year 30. So, provided the costs of developing and adopting the technology are less than this amount, the benefit/cost ratio will be positive.

By estimating the expected benefits from exclusion as we have done here, it is straightforward for decision makers to evaluate investment decisions. Table 3 summarises the information provided in Figure 4, and shows the difference between the control case and both scenarios. Using Table 3, decision makers are provided with a quantitative prediction of the extent to which an exogenous factor such as trade liberalisation will increase the risk to domestic producers. Compared to the control case, the expected benefit of remaining free from PRR increases by £460,090 by 10 years into the future, and £7,944,120 by year 30. This represents the increased production risk domestic potato producers may be subjected to under trade liberalisation (and therefore the increased benefit of keeping PRR out of the UK over time). The economic effects of other exogenous factors such as climate change can be predicted in much the same way.

Table 3: *Comparing scenarios*

	Control case	**Trade liberalisation scenario**		**Advances in treatment technologies scenario**	
Year	Expected benefit of exclusion (mean)	Expected benefit of exclusion (mean)	Predicted increase in production risk	Expected benefit of exclusion (mean)	Predicted benefit of technology
10	£67,140	£527,230	£460,090	£26,600	£40,540
20	£631,280	£2,981,540	£2,350,260	£200,230	£431,050
30	£2,566,160	£10,510,280	£7,944,120	£597,610	£1,968,550

Decision makers can also make quantitative predictions about the benefits of technologies that will reduce the impact of PRR if it were to become established in the UK. Table 3 indicates that in the second of our scenarios, the expected benefits of PRR exclusion falls, relative to the control case, by £40,540 by year 10 of PRR-freedom preservation and by £1,968,550 by year 30. This difference in the expected benefit streams represents the predicted return on the new technological innovation, and therefore the benefit component of a cost–benefit analysis of the decision to invest in its development. Improvement in chemical treatments, resistant varieties, satellite outbreak prevention and the like can be analysed in this way.

6 Conclusions

We have demonstrated the substantial impact that PRR is expected to have on the UK economy if it were to become a naturalised species, and therefore the benefits of its continued exclusion. Expected benefits to the potato industry of remaining free from the disease over the next 30 years have been estimated at up to £10.9 million per year if regional freedom can be maintained. On average, the expected benefit of exclusion is estimated at around £2.6 million per year. The overall size of expected benefits implies that large expenditures could be made to either keep PRR out, or to reduce its effects once established, before the costs of these actions exceed the intertemporal benefits of maintained exclusion. The costs of risk mitigation and abatement activities can be compared to the benefits to determine if a net benefit will result from the expenditure over time. The model has been shown to be highly sensitive to changes in the probability of entry and establishment, the intrinsic rate of disease spread, total export losses and the discount rate. This suggests that returns on investment in detection and spread mitigation technologies are likely to be large.

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First published April 2006. Department of Trade and Industry. www.dti.gov.uk