De-Forestation of a Nation: Estimating the Economic Impact of Pitch Canker in Australia

David C. Cook and A. Colin Matheson[√]

This paper discusses the economic benefits selected Australian pine plantations can expect to enjoy if the Pitch Canker virus can be prevented from entering the country over the next 30 years. It presents a stochastic bioeconomic model in which producer behaviour changes with the presence of the pathogen as it enters the country and begins to spread, imposing additional production costs. The avoidance of these large cost and revenue effects can be interpreted as the benefits of exclusion. Our results indicate even delaying the process of entry and spread by a small amount will produce significant economic benefits over time.

Key Words: Biosecurity, pitch canker, risk assessment.

[√] David Cook is a Research Economist at CSIRO Entomology (GPO Box 1700, Canberra 2601, ACT, Australia, tel. +61(2) 6246 4093, email: david.c.cook@csiro.au) and a Visiting Fellow at the School of Resources, Environment and Society, The Australian National University; Colin Matheson is a Research Fellow at Ensis and Visiting Fellow at the School of Resources, Environment and Society, The Australian National University.

1. Introduction

The fungus *Fusarium subglutinans* (sometimes referred to as *Gibberella circinata*), which causes the condition known as pitch canker in Monterey pine or radiata pine (*Pinus radiata*), presents a serious biosecurity threat to Australia. 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). The process of allocating sufficient resources to threat abatement is hampered by a lack of understanding and information about the invasions process, particularly in the case of species like *F. circinatum* which have not previously been observed in Australia.

This paper addresses this lack of information using a process of invasion simulation to determine the likely costs to industry of living with *F. circinatum* in the production system. We use a stochastic bioeconomic model to simulate potential spread and impact as it may occur in radiata pine plantations future. Following introduction and establishment, spread of the fungus is assumed to continue until it becomes naturalised. Naturalisation is complete when a species spreads to its full capacity within an environment, such that descendents of the original specimens introduced into that environment become permanent, non-spreading members of the floral/fauna (Mack 1996, Mack and Lonsdale 2001). We adopt a *frequentist* framework (Kangas and Kangas 2004) for dealing with uncertainty in which a quantitative model is used to estimate the economic costs throughout the naturalisation process by making simple predictions about the behaviour of radiata pine producers, and what behavioural change is likely to cost.

Expressing results as an annual average, we estimate that the benefits of maintaining area freedom from *F. circinatum* may produce annual benefits to the Australian economy of around $1.62 million over the next thirty years. This result can serve as a base case against which future incursion response strategies, and present risk management and mitigation strategies, can be compared. By delaying arrival and/or establishment, our analysis indicates substantial returns to investment.

The paper is structured as follows. Section 2 provides a background to the *F. circinatum* issue. Section 3 outlines the model, and section 4 presents parameters used in impact simulations. The results are presented in section 5, and the paper concludes with a brief

summary and discussion in section 6.

2. Background

Pine Pitch Canker disease (PPC) was first described in the South-Eastern states of USA in 1946 (Hepting and Roth 1946) although it is also found elsewhere, including Chile (Wingfield *et al.* 2002), Haiti, Mexico (but not in the two island pine populations of Guadalupe and Cedros), South Africa and Spain (Dwinell 1999). It has not yet been identified in Australia or New Zealand. Pitch canker is known to infect many pine species (Gordon *et al* 2001, Hodge and Dvorak 2000) as well as Douglas-Fir (*Pseudotsuga menziesii* – Vogler *et al.* 2004), and species differ in their response.

PPC is a die-back disease of pines and Douglas-fir caused by the ascomycete fungus *Fusarium circinatum*, (synonym = *Fusarium subglutinans* (Wollenw. and Reinking) Nelson, Toussoun and Marasas f. sp. *pini* (Correll *et al.* 1991). Infection of mature trees by the fungus causes a resinous canker from which pitch flows (Gordon *et al.* 2001). Although bark is retained, the wood beneath is deeply resin-soaked. The fungus also causes mortality in bare-root nurseries (Gordon *et al.* 2001). PPC was first observed in California in 1986 (McCain *et al.* 1987) on planted *Pinus radiata* D.Don (radiata pine) near San Francisco and Santa Cruz, in natural stands at Año Nuevo and Monterey in 1992 and Cambria in 1994 (Matheson et al 2006). Mortality rates of about 30% have been predicted for radiata pine in the natural stands (Owen and Adams 1999).

The four recent discoveries of PPC (California, South Africa, Spain and Chile) suggest that *Fusarium circinatum* can be transmitted relatively easily and that the large exotic plantations of Australia (1m ha) and New Zealand (1.5m ha) are also at risk (Dick and Bain 1996). The IMPACT Project of CSIRO - Ensis (with support from the Australian Forest and Wood Products R & D Corporation, NZ Radiata Pine breeding Company, the Chilean Controlodora de Plagas Forestales and the US Forest Service) investigated the response of radiata pine elite genetic families from Australia, Chile and NZ to artificial inoculation by *Fusarium circinatum* (Matheson *et al*. 2006) and has planted a field trial in California to assess resistance in many of the same families. These and other studies (eg Hodge and Dvorak 2000) indicate that radiata pine and its relatives are particularly sensitive to PPC. It is therefore appropriate to investigate what the potential economic impact of an incursion by PPC into Australia would be. This might help inform decisions about appropriate resources

for quarantine exclusion or treatment, breeding for resistance or alternative species or other responses.

3. The Model

We adopt a frequentist probability theory approach using a model in which parameters are stated as probability distributions rather than point estimates (Kangas and Kangas 2004). The objective of the model is to assess the significance of the threat posed by *F. circinatum* by determining its total *expected* (or probability-weighted) damage over a specified period of time. The use of stochastic simulation models is becoming common in risk analyses modelling systems with a great deal of parameter uncertainty and variability. This is the approach adopted here. Monte Carlo simulation is used to sample from specified distributions. Each parameter is estimated as a probability distribution, and then 10,000 iterations of the model run in which one value is randomly sampled across the range of each distribution.

Arrival and establishment are formalised 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:

$$p_y = p_{ent} \cdot p_{est} \tag{1}$$

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 *F. circinatum* 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, $\boldsymbol{P} = \begin{pmatrix} p_{aa} & p_{ab} \\ p_{ba} & p_{bb} \end{pmatrix}$, where *a* defines the row and *b* the column. The elements in the matrix are conditional probabilities indicating the probability 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. 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 in section 4.1. 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 $p_a(t+1) = \sum_b p_{ab} p_b(t)$. 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 this as $p_a(t + 1) = \boldsymbol{P}\boldsymbol{p}(t)$. Applying this equation repeatedly, we obtain:

$$\boldsymbol{p}(t) = \boldsymbol{P}^t \boldsymbol{p}(0). \tag{2}$$

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). 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). 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 *F. circinatum* successfully enters Australia and begins to spread throughout radiata pine plantations (i.e. event *a* above)? As a base case scenario, assume no centrally coordinated response plan is to be invoked in the event of an outbreak. This is not to say there will be no action taken on behalf of foresters to protect their trees from *F. circinatum*. On the contrary. If we make the assumption that they are profit maximisers in a perfectly competitive market structure they will use every technology at their disposal to minimise impact as long as this does not inflate their average cost of production above the market price. Unfortunately, in the case of pitch canker there does not appear to be an effective treatment other than the removal of affected stands, so any treatment undertaken by growers is expected to have a minimal effect on the spread of the fungus.

In assuming a minimal response (or "do nothing") scenario as our base case, the economic impact of the pest becomes a function of the cost and revenue implications for pollination-

dependent industries 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 time period t is given by:

$$\mathrm{D}_{jt} = \left(d_j.\mathrm{A}_j.\mathrm{N}_j \right)_t \tag{3}$$

Where D_{jt} is the total damage inflicted by site j at time t, d_j is the marginal damage cost of the pest in site j [1], A_j is the area affected in site j, and N_j is pest density within site j. Here, $d_j = c_j + r_j$, where c_j and r_j are the cost and revenue implications (respectively) for host industries. Costs may be borne in the form of additional fungicide treatments, while revenue may decline as a result of yield losses. This is a partial equilibrium model, so the flow-on effects to other industries using the outputs of affected plant industries as inputs into their production functions are not included in the impact assessment.

After an arrival, the spread of the outbreak to other susceptible areas is modelled in a relatively simple way. Modelling of species invasions has been an active sector of ecological theory for many years. Skellam (1951) employed reaction diffusion models, originally developed by Fisher (1937) to model the spread of mutant genotypes in populations, to the spread of muskrat populations in Europe (Waage et al. 2005). These models are of the general form $\frac{dn}{dt} = f(n) + D\left(\frac{d^2n}{dx^2} + \frac{d^2n}{dy^2} \right)$, 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 $2\sqrt{rD}$ in all directions, where r is the population's intrinsic growth rate. We have adopted this well-studied model of spread to simulate the local post-establishment population spread of a non-native species (Waage et al. 2005). Hence we assume that naturalisation occurs via a

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

diffusive process where the area occupied by the invading organism expands following the function (Hengeweld 1989, Lewis 1997, Shigesada and Kawasaki 1997):

$$A_t = 4D\pi r t^2 \qquad (4).$$

Where A_t is the area occupied at time t; D is the population diffusion coefficient; r is the intrinsic rate of population growth. It is assumed that the population is in a homogenous environment and expands at an equal rate in each direction (Waage et al. 2005).

Equation (3) allows prediction of the spread of a species on the basis of an estimated intrinsic rate of population growth, while an estimate of D can be derived from the Mean Dispersal Distance (MDD) (Andow et al. 1990, Waage et al. 2005):

$$\text{i.e.} \qquad D = \frac{2MDD^2}{\pi} \qquad (5).$$

The model also assumes that in each unit of area affected by the expanding *F. circinatum* population, the local population density (N) within site j grows logistically to the carrying capacity of the environment such that (Cook et al. in press):

$$N_j = \frac{K}{1 + \left(\dfrac{K}{N_{min}} - 1\right).e^{-gt}} \qquad (6)$$

where K is the carrying capacity of the environment, or maximum density of infestation attainable per unit of area, and N_{min} is the pest density immediately upon 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 (Cook et al. in press):

$$s_t = 1 + \frac{S_{max}}{1 + \left(\dfrac{S_{max}}{S_{min}} - 1\right).e^{-\mu A_{t-1}}} \qquad (7)$$

where S_{max} is the maximum attainable number of satellite sites, S_{min} is the minimum number of satellite sites, and μ is the 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, population 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 damage over time. Assuming a discount rate α, the present value of expected damage after n time periods ($PV(ED_n)$) is (Cook et al. in press):

$$PV(ED_n) = \sum_{t=0}^{n} (1+\alpha)^{-t} . \sum_{j=1}^{s_t} p.d.A.N .$$ (8)

The expression in (8) provides us with a probability weighted estimate of *F. circinatum*-induced revenue losses to selected crops over time. This is to provide a measure of the significance of the threat posed by the pest to Australia's biosecurity system. It is *not* a measure of what damage will be inflicted by *F. circinatum* if it is introduced to Australia tomorrow (i.e. $p \neq 1$). Rather, it provides a measure of expected damage taking into account uncertainty in the time of arrival, and change in abundance and distribution over time after arrival[2].

4. Parameters

4.1 Probability of Entry and Establishment

While an increased level of quantitative research has been witnessed across many disciplines in recent years, it 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 presents a major limitation when examining potential impacts of invasive species when one considers that entry and establishment probabilities can be highly sensitive parameters (Cook 2005). In the absence of quantitative risk assessments reporting the probability of species arrival, we have used the semi-quantitative categorisation system outlined in Biosecurity Australia (2001). This involves uniform (or rectangular) distributions being used to represent uncertainty in the probability of entry and establishment.

Gadgil et al. (2003) presents a semi-quantitative, pathway-specific risk assessment using the questionnaire-based EPPO Pest Risk Assessment Scheme (MacLeod and Baker 2003), which

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[2] Spatial characteristics of affected regions are not taken into account when modelling spread, so results will tend to overstate expected damage. In this simple framework, the relative isolation of individual units of *P. radiata* has no bearing on its susceptibility in the event of an outbreak.

we use to guide our choice of entry and establishment distributions from which to sample in model iterations. On a scale of one (not likely) to nine (very likely), Gadgil et al. (2003) scores the association of *F. circinatum* with seeds of *Pinus* spp. and *Pseudotsuga menziesil* for sowing as a five (p. 63). We subjectively determined this result to translate to the *low* probability of entry category in Biosecurity Australia (2001) represented by Uniform(0.05, 0.30). Similarly, Gadgil et al. (2003) scored the likelihood of the pest to be able to transfer from the pathway to a suitable host as a nine, which we interpreted as corresponding to the Biosecurity Australia (2001) *high* risk category represented by Uniform(0.7, 1.0). Hence, the combined probability of entry and establishment in our simulation is Uniform(0.035, 0.3).

4.2 Revenue Loss and Cost Increments

In simulating a naturalisation scenario we assume that growers will take drastic action in an effort to mitigate the spread of *F. circinatum*. This involved removing affected trees and not replacing them due to the persistence of the disease in the soil. The average age of radiata pine stands in Australia is assumed to be between 10 and 20 years (Forestry Technical Services 2000, Gadgil et al. 2003). The estimated cost of removing such stands is assumed to be between \$12,000/ha and \$15,000/ha (Gadgil et al. 2003). However, we assume this will form an imperfect containment strategy, and for yield losses to persist in remaining stands. We assume losses in average stands of around 15 per cent in the long term (i.e. if the disease becomes naturalised). Damage is expected to be up to 30 per cent in stands between 0 and 10 years of age, while damage to older stands (20-35 years) is likely to be negligible.

4.3 Area, Density and Satellite Generation

Even a simple diffusive model of spread is difficult to parameterise. Table 1 provides details of the biological parameters used, some of which can only be described as intuitive estimates:

Table 1 near here.

5. Results and Discussion

Taking the mean of the distribution of expected damage costs over a 30-year simulation, we estimate that the expected producer surplus losses avoided through successful exclusion are around \$1.62 million per year. However, due to the uncertainty and variability of the

parameter estimates used in the calculations our confidence intervals are broad, and we can only suggest that we are 90 per cent sure of avoiding damages between $0.07 million and $7.45 million per annum. These losses are comparable to previous estimates put forward (e.g. Gadgil et al. (2003), Beare et al. (2005)). Figure 1 presents the probability density function of expected damage avoided through the exclusion of *F. circinatum*, where damage is expressed as an annual average over a 30-year period (i.e. $\frac{\text{PV(ED}_n)}{n}$).

Figure 1 near here.

Our results indicate that if efforts to maintain area freedom from *F. circinatum* are successful the likely returns to the radiata pine industry are high enough to warrant a significant investment in preventative measures. For instance, if we were to take the a minimum-exclusion benefit scenario (i.e. 5 per cent confidence interval), risk mitigation and management activities could be approved up to a value of $0.07 million per annum before the ratio of benefits to costs becomes negative. If we were to take the maximum exclusion benefit scenario (i.e. 95% confidence interval), this breakeven level of investment would be as high as $7.45 million per year. The distribution of these benefits by State and Territory are provided in Figure 2, which indicates the largest proportion of benefits are set to accrue to New South Wales, Victoria and Queensland as the largest growers of radiata pine.

Figure 2 near here.

Sensitivity analysis of the model indicates the variables with the greatest influence on results are the probabilities of entry and establishment, the intrinsic rate of population growth and the discount rate. We therefore suggest that large reductions in expected incursion damage could be achieved by targeting these parameters. Using a hypothetical example to illustrate this point, if the probability of arrival can be lowered by 25% as a result of an additional $0.25 million invested in pre-border and border security measures to avoid *F. circinatum* incursions we predict a benefit/cost ratio of 1.9:1 would be achieved. Similarly, if the same investment did not affect the arrival probability but lowered the intrinsic rate of population growth to around , we predict a benefit/cost ratio of around 6.3:1.

In the absence of a hazard rate function relating expenditure in prevention measures to the arrival probability, or reduction in the rate of growth brought about by research and development activities to reduce spread, such a prediction remains open to question (Cook et al. in press). Extremely high levels of investment may be necessary to achieve a relatively

minor reduction in the probability of *F. circinatum*, particularly in relation to the seed pathway. Indeed, further efforts to tighten pre-border and border security measures may in fact raise compliance costs above the expected value of penalties for non-compliance, thereby increasing incentives to bypass regulated entry points (Department of Primary Industries and Energy 1988, Cook et al. in press).

It is also difficult to comment on an appropriate discount rate, which makes the fact that results are particularly sensitive to this parameter very important. In the absence of definitive information on opportunity costs relevant to a specific project like *F. circinatum* -exclusion, we use a standard discount rate of 8 per cent which consists of a margin of 3 per cent on top of a real risk free rate of 5 per cent (Department of Finance 1991). Figure 2 demonstrates the effects of both a higher discount rate and a lower discount rate. If, for example we were to apply a personal discount rate to model calculations (as opposed to a public/social discount rate) of 10 per cent the annual expected benefits of exclusion over 30 years would fall to approximately $1.0 million. On the other hand, if we were to adopt a much more precautionary approach to agricultural change and apply a discount rate of 5 percent, annual expected benefits over 30 years rise to over $3.2 million.

Figure 3 near here.

6. Conclusions

With the information currently available we have been able to demonstrate the substantial impact *F. circinatum* is expected to have on the economy if it were to become a naturalised species, and through this the benefits of maintaining Australia's area freedom from this pest. The expected benefits of remaining free from the pest over the next 30 years have been estimated using a stochastic impact simulation model. In total, we estimate that these benefits would be between $0.07 million and $7.45 million per year if area freedom could be maintained.

The overall size of expected benefits imply that large expenditures could be made to either keep *F. circinatum* out, remove its lethal effects or to eliminate outbreaks as they occur before the costs of these actions exceed the intertemporal benefits of maintained exclusion. In a sense we have provided one half of a benefit cost analysis, the benefit side. The costs of risk mitigation and abatement activities can easily be compared to the benefits to determine if a

net benefit will result from the expenditure. We have shown that results are highly sensitive to changes in the probability of arrival and rate of spread, which suggests the returns to investment in detection and spread mitigation technologies are in all likelihood very large. We have also shown that the discount rate decision-makers apply to the returns to *F. circinatum* may be critical in terms of determining an appropriate level of investment in risk mitigation efforts.

7. References

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Table 1 Biological parameters

| Parameter	Assumed Parameter Value
A_{min} (ha)	Pert(1,3,5)
A_{max} (ha)	750,000ha (Forestry Technical Services 2000, Gadgil et al. 2003)
r	Pert (0.5,0.75,1.0) (Zadocks and Shein 1979, Waage et al. 2005)
N_{min}	Pert(1,2,3)
K (N_{max})	Pert(10000,55000,100000) (Waage et al. 2005)
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)
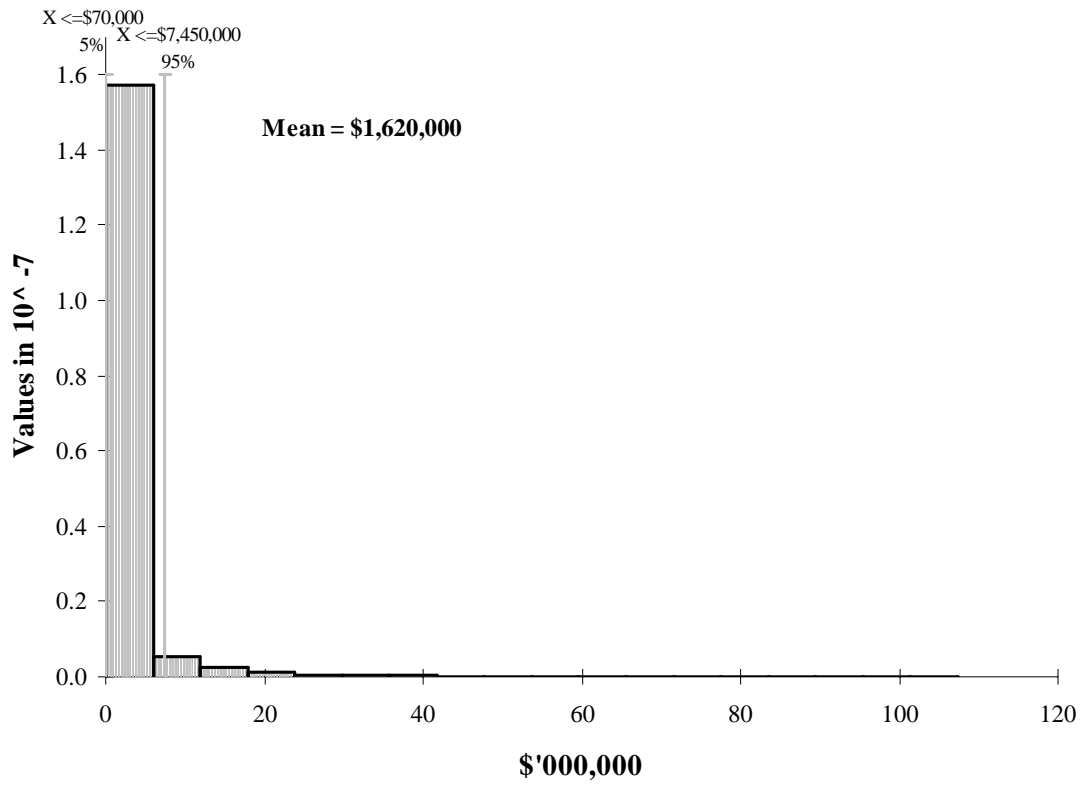
Figure 1 Average expected annual damage from *Fusarium circinata* over 30 years
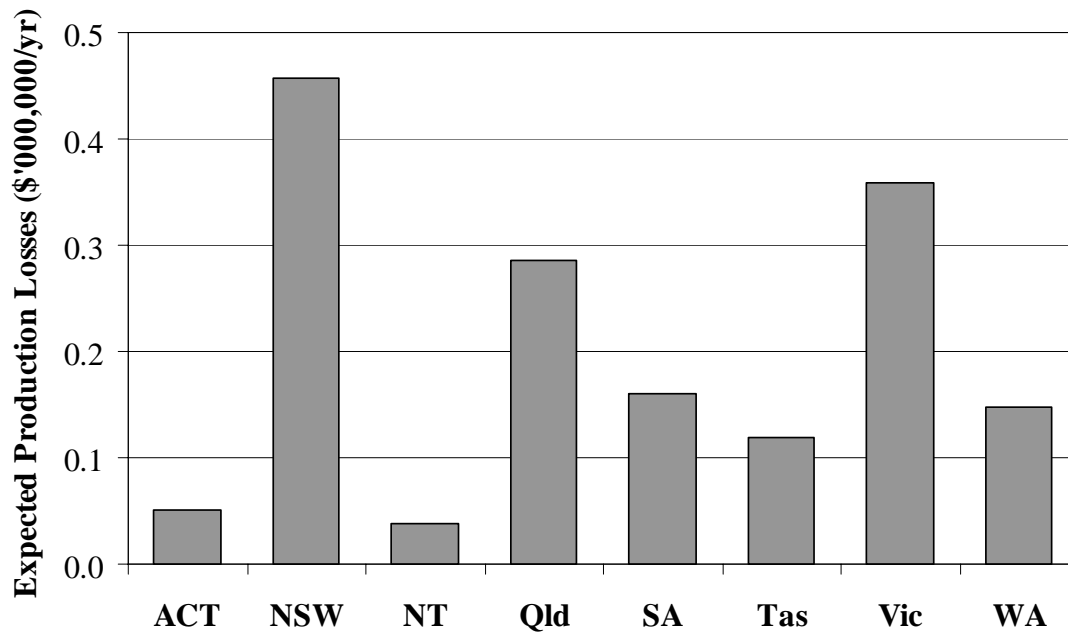
Figure 2 Distribution of exclusion benefits by State and Territory
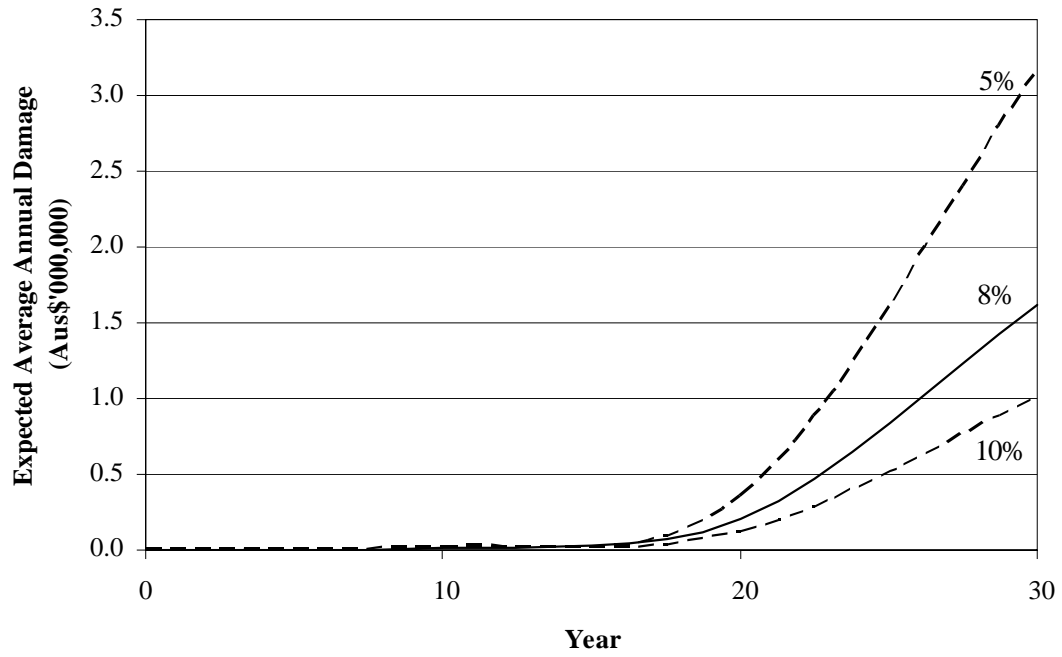
Figure 3 Discount rate sensitivity