Australian Government
Australian Bureau of Agricultural and Resource Economics and Sciences

AARES
Australian Agricultural and Resource Economics Society
9–11 February 2011, Melbourne, Victoria

11.02

The use of an integrated model of pest spread and commodity markets to estimate the cost of a pest outbreak

Ahmed Hafi

Abstract

There are significant benefits in integrating a biological spread model into economic assessment of the cost of pest incursions (such as varroa mite or Mexican feather grass) on agricultural industries.

To illustrate the potential usefulness of an integrated approach, a generic bioeconomic model is developed by linking a simple stochastic pest spread module, built around a set of logistic spread equations, and a partial equilibrium module of the market for an affected agricultural industry. The pest spread module estimates the damage over time, while the partial equilibrium module estimates the resultant effect of a reduction in supply on the commodity market. The estimated effects on market variables are then used to estimate the cost of a pest outbreak.

In this study, the cost of a hypothetical pest outbreak is estimated for three scenarios: (1) do nothing; (2) control actions to slow the spread; and (3) control actions aimed at eradication of the pest. The estimates are derived for a large number of random values of the spread rates specified in the logistic functions. The study also presents the frequency distribution of benefits of implementing the two control strategies.

Key words: pest spread, logistic functions and partial equilibrium model.

Acknowledgments

I am grateful to Paul Morris, Terry Sheales, Bruce Bowen, Peter Caley, Ben Buetre and Ali Abdalla for their comments and suggestions, and to Sally Thorpe for sharing her extensive knowledge of partial equilibrium modelling.

ABARES project: 43086

ISSN: 1447-3666

1 Introduction

Pest incursions can adversely affect agricultural industries and natural resources, imposing significant economic and environmental costs. Spread modelling simulations are increasingly being used to inform policy decisions on managing invasive species systems. Spread models can vary from a simple aggregate spread model, based on one or two linear or logistic equations, to complex, spatially explicit models representing the landscape as a lattice of a large number of square cells.

The probability of entry of a pest invader and its subsequent establishment and spread depends on the pest management options in place. For example, the probability of entry depends on the border control measures, and the probability of further spread depends on measures in place for surveillance, detection, subsequent treatment and containment. The actual detection and subsequent removal of an invader is determined by the border control, search or surveillance and containment efforts used. Spread models need to contain built-in features to accommodate the effect of these measures for checking the further spread of the invader. Models designed in this manner can be used to simulate the effect of a pest outbreak with alternative management options such as border controls, surveillance for detection and treatment and containment. These effects can then be used to estimate and compare the benefits of implementing alternative management options net of their implementation cost.

Most of the spread models treat in detail the spatial aspects of the spread of an invasive species but lack the capability to incorporate the effect of control actions on further spread of the species. However, a few models have managed to take this into account. The model of Cacho et al. (2010) incorporates cell attributes of detectability of the pest and search speed, which can be influenced through management actions. For example, the role of increased investment in surveillance in limiting the further spread of the invader can be modelled. The increase in detection rates resulting from such investment are modelled by specifying the detectability and search speed parameters as functions of the investment. Elliston et al. (2004) used an agent-based model in which the interface between the behaviours of the invasive species and the relevant agents—such as farmers, contractors and those involved in various tactical response efforts—was modelled, resulting in more realistic responses to management options.

A bioeconomic model linking a simple spread module to a partial equilibrium module of a commodity market is outlined in this paper. The spread module is designed so that specific actions to control the growth and spread of the pest can be introduced, enabling the economic benefits of such control actions to be readily estimated from the integrated model. The characteristics of the spread and partial equilibrium modules are initially outlined, followed by a discussion of some illustrative results, including the examination of the benefits of alternative pest management options.

2 Pest spread module

A generic conceptual model that can be applied to most pest species is presented below. It is an aggregate model that incorporates the general characteristics of a pest's growth and spread.

Assume that the pest population starts to grow from a single introduction to the most habitable area. The process of spatial spread of the pest is characterised by growth in numbers and dispersion. The fundamental equation that captures this spread process is given by Fisher (1937), as shown in equation (1).

$$\frac{\partial n}{\partial t} = D\left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2}\right) + (\varepsilon - \mu n)n \qquad (1)$$

Where: $\partial n / \partial t$ denotes change in population per unit of time; D is the diffusion coefficient that measures the rate of spatial dispersion of the pest; ε is the intrinsic rate of increase in population; μ is the effect of intra-species competition on reproduction; n is the population at a given point in time; and x and y are spatial coordinates.

Fisher's model states that, at a given point in time, the change in population per unit of time equals random diffusion (the first term on the right-hand side) plus the growth in the population in an already infested location (the second term on the right-hand side) during that unit of time.

The particular model employed in this paper has both diffusion and growth components. However, for simplicity, diffusion is assumed to occur by new satellite generation around the home focus rather than over a lattice of a large number of square cells as implied in Fisher's model. It is also assumed that the maximum size of the home focus is larger than that of satellite foci. The diffusion and growth are modelled as three different equations and later combined. In the model, the overall range expansion is assumed to occur from the area of the home range and the expansion of the areas of a large number of smaller foci or satellites originating from dispersions from the overall range.

Growth

The growth component of Fisher's model can be re-parameterised by considering the relationship between the growth rate, $\varepsilon - \mu n$ and the population itself *(n)*. This relationship shows that the growth rate declines as the population increases, indicating that there is a maximum environmental carrying capacity for growth. Following Shigesada and Kawasaki (1997), the environmental carrying capacity can be defined as equal to the ratio of intrinsic growth rate to the parameter measuring the effect of intra-species competition or $K = \varepsilon / \mu$. Substituting this relationship in the growth component of equation (1) and disregarding the diffusion component, which is handled separately, yields the widely used logistic growth model.

$$\frac{\partial n}{\partial t} = \varepsilon\left(1-\frac{n}{K}\right)n \tag{2}$$

For simplicity, the population at the end of a time period is assumed to be approximated by the corresponding area of spread denoted by a^m and a^s, respectively, for the home focus and the satellite foci. Equation (2) can then be further simplified by expressing it in the form of first order difference equations as given in (3) and (4), respectively, for the home focus and the satellite foci. The discrete time step used in equations (3) and (4) should be small enough to minimise the errors in approximating the continuous time differential equation (2). In this spread module a quarterly time step is assumed, while an annual time step is assumed in the partial equilibrium module.

$$a^m_{t+1} = a^m_t + \varepsilon\left(1-\frac{a^m_t}{K^m}\right)a^m_t - k \tag{3}$$

$$a^s_{t't+1} = \begin{cases} a^s_{t't} + \varepsilon\left(1-\frac{a^s_{t't}}{K^s}\right)a^s_{t't} & \text{for baseline and all } t' \text{ and } t < 30 \\ a^s_{t't} + \varepsilon\left(1-\frac{a^s_{t't}}{K^s}\right)a^s_{t't} & \text{for control strategies and all } t' \text{ and } t' < t' + 4 \\ 0 & \text{for control strategies } t' \text{ and } t' \geq t' + 4 \end{cases} \tag{4}$$

Where, a^m_t is the aggregate area of spread within the outermost boundary of the infested area of the home focus at the beginning of quarter t, $a^s_{t't}$ is the aggregate area of spread within the outermost boundary of the infested area of a satellite formed in quarter t' measured at the beginning of quarter t, k represents a fixed infested area removed each quarter from the home focus as part of control actions. With the control actions in place, the pest population that remains after control continues to grow and spread according to the logistic growth function in (3) and (4).

Dispersion by satellite formation

Following Moody and Mack (1988) and Cook et al. (2007), the number of new satellite foci at any quarter since $t=2$ grows following a logistic growth function of the form:

$$N_t = N_{\max}\left[1+\frac{N_{\max}-N_{\min}}{N_{\min}}e^{-\gamma A_{t-1}}\right]^{-1} \tag{5}$$

$$A_{t-1} = a^m_t + \sum_{t'} a^s_{t't}(N_t - N_{t-1}) \tag{6}$$

Where: N_t is the number of satellite foci at the end of quarter t with satellite generation starting from $t=2$; N_{max} and N_{min} are the maximum and minimum number of satellites, respectively; γ is the intrinsic growth rate of satellites; and A_{t-1} is the overall area of spread at the end of the previous quarter. This overall area of spread equals the area of the home focus plus the total area of all satellite foci (equation 6). The intrinsic growth rate in equation (4) is defined per unit area of the overall area occupied at the end of the previous quarter. These smaller satellite foci are assumed to grow as non-overlapping circles.

Control actions

Eradication and slow spread scenarios are simulated with the model. The eradication strategy involves a systematic approach to search, detect and destroy the infested areas of the home focus and all satellite foci. For the larger home focus, the strategy starts by working from the outermost ring of the infested area and moving inward, with the pest population being destroyed at a faster rate than the rate of increase. This process is considered to continue until no further detection of the pest is revealed. At the same time, smaller satellite foci are assumed to be detected and destroyed. If the rate of removal of infested area of the home focus and smaller satellite foci is less than the rate of increase, the control actions will slow the spread but will not be enough to eradicate the pest.

In this study, control actions to achieve eradication and control actions to achieve slow spread both have two specific activities: (1) removal of a constant area in each quarter from the home focus, starting from $t=5$; and (2) removal of 25 per cent of the remaining smaller satellites each quarter after being detected four quarterly time periods following their formation. It is implicitly assumed that satellites can be detected with certainty after they reach a critical age of four quarterly time periods from their initial presence. These satellites are subsequently destroyed. For simplicity, the control actions are assumed to be fully effective.

In the illustrative simulations, the constant area to be removed each quarter from the home focus to achieve eradication was determined through the model given the most likely value of its parameters. Half of this constant area was chosen for the illustrative slow spread scenario.

Control actions should combine the removal of a concentric area from the main focus with the detection and removal of any newly formed satellite foci. If satellites were ignored, any initial benefits of reducing the area of the main focus could be negated by the continuous generation and growth of satellite foci (Moody and Mack 1988). A slow spread or eradication is achieved as sustained controls introduced each time period retard the future growth and spread of the range.

Given that the intrinsic growth rates of logistic equations (3) to (5) are random variables, the success of control actions depends on the particular realisation of these parameters.

3 Partial equilibrium module

A partial equilibrium module is built around a supply and demand model of price determination for the affected industry. On the supply side, the module includes domestic and import supplies, and on the demand side, it includes domestic and export demands. The partial equilibrium module works on an annual time frame, compared with quarterly time steps used in the spread module.

Producers supply both domestic and export markets, while consumers demand both domestically produced and imported products of the same good. The domestically produced and imported products are treated as imperfect substitutes, with the rate of substitution being determined by the elasticity of substitution assumed (Armington 1969). The domestic price is solved by equating domestic supply to demand from both domestic and export markets. Export demand responds to domestic price, while domestic demand responds to the domestic and import share weighted price of the same product. Import prices are fixed based on the assumption that a change in Australian production has negligible effect on the landed prices of product (the world price).

For simplicity, this module excludes other variables that affect demand and supply. For example, it does not incorporate the price of substitute products and consumer income that affect demand and supply shifters such as technological improvements over time.

An algebraic representation of the partial equilibrium model is presented below.

Variables

qs	quantity supplied (tonnes/year)
qd	aggregate quantity demanded of both imported and domestically produced product (tonnes/year)
$qdom$	quantity of domestically produced product demanded (tonnes/year)
$qimp$	quantity imported (tonnes/year)
$qexp$	quantity exported (tonnes/year)
$pdom$	price of domestically produced product ($/tonne)
$pimp$	price of imported product ($/tonne)
pd	domestic and import value share weighted consumer price of product ($/tonne)

Parameters

α	scale term of the supply function
β	scale term of the domestic aggregate demand function
θ	scale term of the export demand function
μdom	scale term of the domestically sourced to total consumption share function
μimp	scale term of the imports to total consumption share function
εs	elasticity of supply
εd	elasticity of aggregate domestic demand
εx	elasticity of export demand

σ	elasticity of substitution in consumption between domestically produced and imported products
γ	proportion of reduction in production due to pest outbreak

Quantity supplied is a constant elasticity function of domestic price (equation 7), while aggregate demand is a constant elasticity function of the weighted average price of domestic and import prices (equation 8).

$$qs = \alpha \left(pdom \right)^{\varepsilon s} \times (1 - \gamma) \tag{7}$$

$$qd = \beta \, pd^{\varepsilon d} \tag{8}$$

In equation (7), γ denotes the proportion of reduction in production due to pest outbreak as, for simplicity, the 'do nothing' strategy chosen as the baseline scenario assumes there are no public or private actions to control pest spread. Alternatively, a pest spread scenario with no publicly funded control measures but with producers investing in pest control measures up to the point where marginal benefits of such investment equals the marginal cost can be chosen as the baseline.

Aggregate demand and the elasticity of demand specified in equation (8) are for a composite product that includes domestically produced and imported products that are treated as imperfect substitutes. The responsiveness in the demand for domestically produced and imported products to change in the domestic price could be different depending on the elasticity of demand for the composite product and the elasticity of substitution between the imported and domestically produced products.

Weighted average price of domestic and import prices is calculated by using quantity of domestically produced product consumed and imports as weights (equation 9).

$$pd = \frac{pdom.qdom + pimp.qimp}{qd} \tag{9}$$

The share of domestically produced products in aggregate consumption is a constant elasticity function of the ratio of domestic price to weighted average price (equation 10), while the share of imports in aggregate consumption is a constant elasticity function of the ratio of import price to weighted average price (equation 11).

$$\frac{qdom}{qd} = \mu dom \left(\frac{pdom}{pd} \right)^{-\sigma} \tag{10}$$

$$\frac{qimp}{qd} = \mu imp \left(\frac{pimp}{pd} \right)^{-\sigma} \tag{11}$$

Quantity of exports is a constant elasticity function of domestic price (equation 12). The domestic price is solved for by equating domestic supply to demand from both domestic and export markets (equation 13).

$$qexp = \theta \, pdom^{\varepsilon x} \tag{12}$$

$$qs = qdom + qexp \tag{13}$$

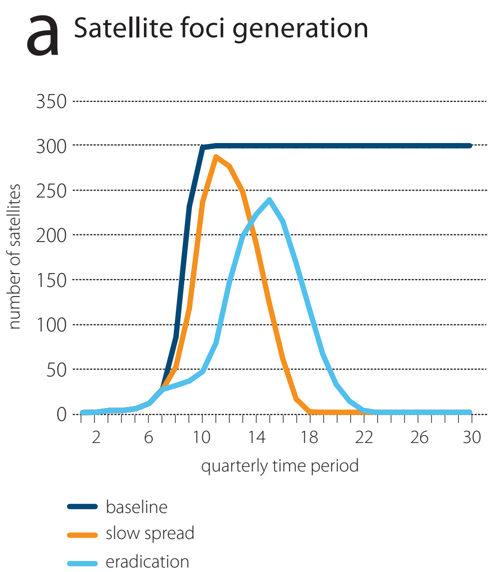
The integrated model is run over a planning horizon comprising 30 quarterly time periods. The equilibrium values for variables included in the commodity market module are determined endogenously in the process of solving the simultaneous equations (7) to (13). The market module is formulated as a Mixed Complementary Programming problem using the General Algebraic Modelling System (GAMS) and solved using the PATH solver.

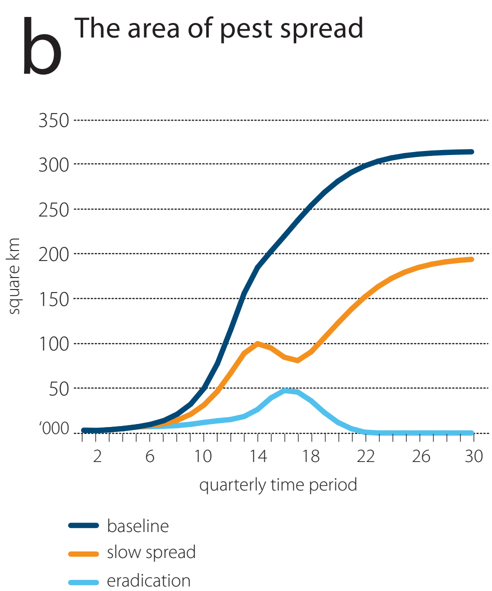
4 Illustrative results

The model is calibrated to a stylised data and parameter set presented in appendix a. Three scenarios are simulated: (1) a baseline where the pest spreads with no publicly and privately funded actions to control it; (2) an eradication strategy where 1200 km^2 of the area is removed each quarter from the home focus, starting from $t=5$ and a 25 per cent of the remaining satellite foci are removed each quarter after being detected at the age of four quarterly periods (note that the removal of satellites and infested area from the home focus starts at the same time as the satellite formation starts, from the second quarter onwards); and (3) a strategy to slow the spread that is similar to eradication except for the area removed each quarter, which is halved to 600 km^2. For simplicity, the control actions are assumed to be fully effective.

Pest spread

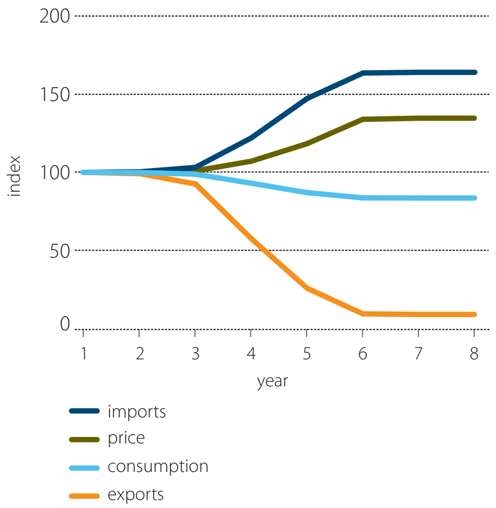
The overall range of pest spread consists of the expansion from the larger focus of the home range and the expansion of the areas of smaller foci. The satellite foci generation and the overall range expansion over time for all three scenarios are presented in figures a and b, respectively. For the eradication and slow spread scenarios, the satellite generation and area of spread at the end of each quarter is produced by the interaction of control actions and the growth and dispersion processes incorporated in the model. Compared with the baseline scenario, satellite formation is delayed in the eradication and slow spread scenarios, as infested areas are removed from the home focus. A larger area being removed in the eradication strategy results in the most delay. However, in the case of the slow spread and eradication scenarios, the simultaneously simulated satellite removals result in the eventual elimination of all satellites. In the slow spread scenario, it is assumed that continuing surveillance will ensure that any satellite formed is promptly detected destroyed but the home focus grows at a slower rate.



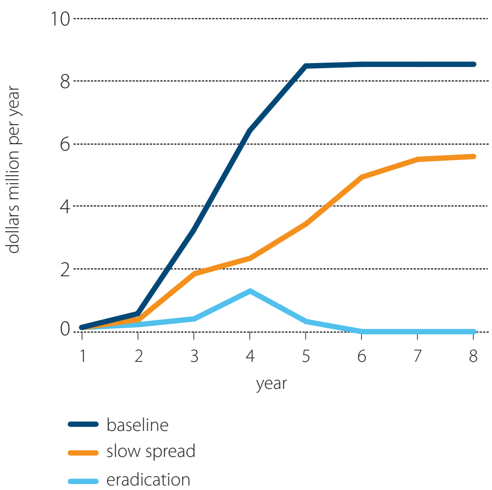


In the eradication scenario, as the infested area of the home focus is being removed at a rate faster than the rate of increase, along with the elimination of all satellite foci, the overall range is gradually reduced to zero by around quarter 21. In contrast, the slow spread scenario results in the range expansion being restricted to around 60 per cent of the baseline spread area estimated for quarter 30. The continued spread of the infested area reflects the fact that the rate of removal of infested area is slower than the rate of increase.

c Effect on market variables



d Direct economic cost of pest spread



Market and direct economic effects

Achieving a new model-based market equilibrium after a pest incursion involves several elements. A reduction in the supply of a domestic product because of a pest incursion and spread puts upward pressure on its market price. Buyers in both Australian and foreign markets respond by reducing the quantity demanded of the product. In Australia, consumers substitute cheaper imported product for the now more expensive domestically produced variety, thereby mitigating some of the negative effects of the increase in price of the Australian-produced product. These market effects increase over time as increasing quantities of production are lost with the pest spread. The time paths of the market variables for the baseline scenario are presented in figure c with yearly time step. They mirror the time path of pest spread (at every fourth quarter time step) in the baseline scenario presented in figure b.

The direct economic cost of the pest incursion to Australia includes the loss in producer surplus as a result of reduced sales of Australian products in both domestic and export markets and the loss in consumer surplus as a result of both a higher price for the domestic product and its reduced availability. The estimated losses in economic surpluses are determined by the effect of reduced production on exports, price, domestic demand and imports, and the responsiveness of these market variables to changes in price. The consumer losses would be higher if cheaper imports were not allowed to substitute for more expensive domestic product.

The annual economic cost from pest spread for the three scenarios are presented in figure d. The time paths of economic costs mirror the time paths of overall area of pest spread (at every fourth quarter time step) presented in figure b.

Gross benefits of control actions

For each control strategy, the gross benefits constitute the avoided losses measured against an appropriate baseline. A pest spread scenario with no publicly funded control measures, but with producers investing in pest control measures to mitigate the negative effects, can be chosen as the baseline. However, for simplicity and purely illustrative purposes, the 'do nothing' strategy illustrated here assumes there are no public or private actions to control pest spread. This scenario is chosen as the baseline.

In benefit–cost analysis of control strategies, the expected gross benefits or avoided losses are compared against cost of control. The avoided loss or gross benefit of a control strategy equals the economic loss of the baseline scenario less the economic loss estimated for that strategy. It should be noted that, in estimating avoided losses in this manner, it is implicitly assumed that the pest would establish and spread with probability 1 in the case of the baseline, slowing the pest would be successful with probability 1 and eradication would be successful with probability 1.

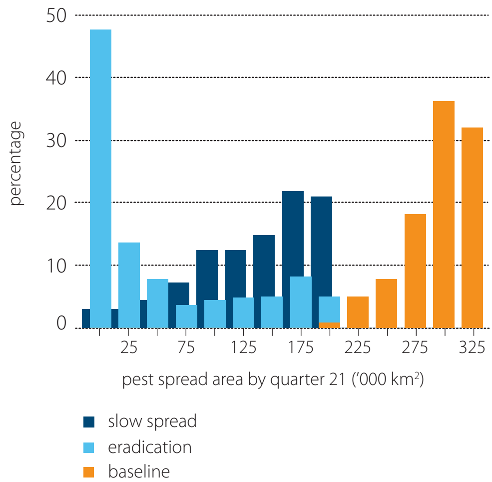
For each year, the gross benefit of eradication equals the difference in losses between the baseline and eradication scenarios, while the gross benefit of the slow spread scenario equals the difference in losses between the baseline and slow spread scenarios. Based on these assumptions, information presented in figure d suggests that the largest avoided losses or gross benefits are obtained from eradication. However, eradication is not necessarily the most cost-effective option for a range of reasons. For example, the cost of eradication could quickly exceed the gross benefits if the pest is not detected early enough and there is significant uncertainty around its success.

Moreover, the direct economic costs presented in figure d are derived by assuming the most likely values for the intrinsic growth rates specified in equations (3) to (5). However, because of uncertainty surrounding these growth rates, the pest spread process, both with and without control strategies, is highly stochastic, resulting in variability in these costs and therefore in the estimated benefits of control strategies.

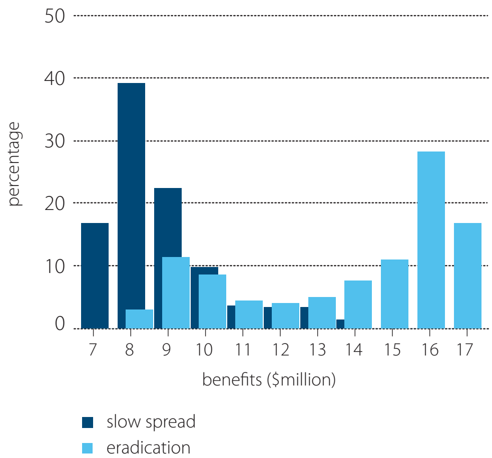
To estimate this variability in economic costs, the probability distributions of spread rate parameters are needed. In pest spread modelling, the probability distributions of spread parameters are normally constructed using expert opinions on lower bound, most likely and upper bound estimates. The Program Evaluation and Review Techniques (PERT) suggested by Vose (2000) are normally used in such situations to construct the probability distributions. This method is employed in the present process, and the three values used for each parameter are given in Appendix A.

The model was run repeatedly to conduct 500 Monte Carlo simulations, with values for the intrinsic growth rates randomly drawn from PERT probability distributions. For each control

e Frequency distribution of spread area by control strategy



f Frequency distribution of gross benefits



strategy (baseline with no control, slow spread and eradication), the time paths of the overall area of pest spread are generated for all 500 simulations. To be consistent with the discussion around figure b, the extent of pest spread at the end of quarter 21 observed in these simulations is then summarised in the form of frequency distributions presented in figure e.

Once the uncertainty surrounding the spread rates is incorporated, the probability of success in slowing the spread and eradication would both be less than one. For example, the eradication strategy has only succeeded in 48 per cent of the Monte Carlo simulations, while it has only achieved a slower spread in the remaining simulations as the pest has spread at a faster rate than the removal of the infested area (figure e). With fast growth rates, the strategy to slow the spread could also fail to achieve the intended outcome. In 3 per cent of Monte Carlo simulations done for the slow spread scenario, the strategy to slow the spread had actually achieved eradication (figure e).

For each Monte Carlo simulation and control strategy, the present value of gross benefits is estimated assuming a discount rate of 6 per cent. Results obtained for all 500 simulations are summarised in the form of frequency distributions presented in figure f. It shows that, despite a wider variability in gross benefits, the expected value of gross benefits from eradication is larger than for slow spread. However, these expected gross benefits need to be compared with cost of controls to determine which control strategy is more cost effective. In the absence of estimates on such costs, these expected gross benefits provide upper bounds on the public expenditure to be invested if it is to be cost effective.

5 Conclusions

This paper serves to demonstrate how a model integrating a stochastic pest spread module, incorporating growth and dispersion of the pest, and a partial equilibrium module of the commodity market, incorporating domestic supply and demand and foreign trade, can be used to develop information required by policymakers to make decisions on the management of a pest outbreak.

An integrated approach has an advantage in that specific actions to control the growth and spread of the pest can be directly introduced and the probability distribution of economic benefits of such control actions can be readily obtained as model outputs.

When applied for real pest incursion situations, such as a potential incursion of varroa mite or Mexican feather grass, the model could be used to inform policymakers on alternative management decisions.

The usefulness of the model can be improved by incorporating the implementation cost of control actions as a function of specific activities introduced in the model to control the stochastic process of the pest spread. This improvement will enable comparison of expected benefits with costs.

Appendix A: Stylised data used in the model

Item	Description	Value
Variable a		
qs	quantity supplied (tonnes/year)	7 500
qd	aggregate quantity demanded of both imported and domestically produced product (tonnes/year)	9 500
qdom	quantity of domestically produced product demanded (tonnes/year)	5 000
qimp	quantity imported (tonnes/year)	4 500
qexp	quantity exported (tonnes/year)	2 500
pdom	price of domestically produced product ($/tonne)	1 000
pimp	price of imported product ($/tonne)	750
Parameters b		
εs	elasticity of supply	1.2
εx	elasticity of aggregate domestic demand	–2
εd	elasticity of export demand	–8
σ	elasticity of substitution in consumption between domestically produced and imported products	10
ε	Intrinsic growth rate used in equations (3) and (4)	(0.2,0.35,0.5) c
γ	Intrinsic growth rate used in equation (5)	(0.0001,0.0005,0.001) c

a Base-year levels used to calibrate the model. **b** Values for scale parameters used in the partial equilibrium model are not shown as they are derived using base year values for variables and the other market parameters. **c** Lower bound, most likely and upper bound values, respectively. These values are used to draw parameter values from PERT (Program Evaluation and Review Technique) distribution (Vose 2000).

References

Armington, PS 1969, A *theory of demand for products distinguished by place of origin*, IMF Staff Papers, 16, pp. 159–178.

Cacho, OJ, Spring, D, Hester, S and MacNally, R 2010, 'Allocating surveillance effort in the management of invasive species: A spatially-explicit model', *Environmental Modelling and Software*, vol. 25, pp. 444–454.

Cook, DC, Thomas, MB, Cunningham, SA, Anderson, DL and De Barro, P 2007, 'Predicting the economic impact of an invasive species on an ecosystem service', *Ecological Applications*, vol. 17(6), pp. 1832–1840.

Elliston, L, Hinde, R, Beare, S and Yainshet, A 2004, *The Exotic Incursion Management (EIM) Model – technical documentation and user manual*, ABARE report for Plant Health Australia, Canberra, June.

Fisher, RA 1937, 'The wave of advance of advantageous genes', *Annals of Eugenics*, vol. 7, pp. 255–369.

Moody, ME and Mack, RN 1988, 'Controlling the spread of plant invasions: The importance of Nascent Foci', *The Journal of Applied Ecology*, vol. 25, no.3, pp. 1019–1021.

Shigesada, N and Kawasaki, K 1997, *Biological invasions: Theory and practice*, Oxford University Press.

Vose, D 2000, *Risk analysis: a quantitative guide*, second edition, John Wiley, Chichester, UK.