The Australian Journal of
Agricultural and
Resource Economics

Journal of the Australian
Agricultural and Resource
Economics Society

The Australian Journal of Agricultural and Resource Economics, 55, pp. 599–620

Estimating the social welfare effects of New Zealand apple imports

David C. Cook, Luis R. Carrasco, Dean R. Paini and
Rob W. Fraser[†]

International trade of agricultural products not only generates wealth but is also responsible for the introduction of invasive pests beyond their natural range. Comprehensive bioeconomic modelling frameworks are increasingly needed to assist in the resolution of import access disputes. However, frameworks that combine welfare analysis attributable to trade and invasive species spread management are lacking. This study provides a demonstration of how a comprehensive economic framework, which takes into account both the gains from trade and the costs of invasive species outbreaks, can inform decision-makers when making quarantine decisions. We develop a partial equilibrium trade model considering international trade and combine it with a stratified dispersal model for the spread and management of potential outbreaks of an invasive species. An empirical estimation is made of the economic welfare consequences for Australia of allowing quarantine-restricted trade in New Zealand apples to take place. The results suggest the returns to Australian society from importing New Zealand apples are likely to be negative. The price differential between the landed product with SPS measures in place and the autarkic price is insufficient to outweigh the increase in expected damage resulting from increased fire blight risk. As a consequence, this empirical analysis does not support the opening up of this trade.

Key words: biosecurity, fire blight, import risk assessment, SPS measures.

1. Introduction

1.1. Economics and biosecurity risk

In many ways, the use of economic models in the analysis of market access requests represents a new innovation in policy research. In Australia, these models have only been used in a handful of cases, all dealing with long-standing, high-profile cases. This is perhaps because, until recently, quarantine has been considered solely an area of scientific interest. In modern

---

[†] David C. Cook (email: david.cook@agric.wa.gov.au) is in the Department of Agriculture and Food Western Australia, Bunbury, Western Australia 6231, Australia; Cooperative Research Centre for National Plant Biosecurity, Bruce, Australian Capital Territory 2617, Australia; and Australian Centre for Biosecurity and Environmental Economics, The Australian National University, Canberra, Australian Capital Territory 0200, Australia. Luis R. Carrasco is at the National University of Singapore, Singapore 119077. Dean R. Paini is in the Cooperative Research Centre for National Plant Biosecurity, Bruce, Australian Capital Territory 2617, Australia; and CSIRO Ecosystem Sciences, Canberra, Australian Capital Territory 2601, Australia. Rob W. Fraser is at The University of Kent, Canterbury, Kent CT2 7NZ, UK; and The University of Western Australia, Crawley, Western Australia 6009, Australia.

doi: 10.1111/j.1467-8489.2011.00558.x

times, with the coming into being of the World Trade Organisation (WTO) and an ever-increasing emphasis being placed on quantitative and semi-quantitative risk assessments, economics is set to play a key role in quarantine policy formulation and justification as a supplement to scientific methodology. With this in mind, this study attempts to promote a definitive role for economic analysis by reconciling welfare analysis because of trade and invasive species impact simulation in the same modelling framework. The framework is applied to the much-talked-about case study of apples imported to Australia from New Zealand (NZ) growers.

The modelling framework, in considering a proposal to allow imports of a product, reconciles the benefits of trade in this product with the potential costs of an outbreak of invasive species as a consequence of the trade in the product.

This reconciliation is significant because import risk analyses typically exclude the benefits of trade in favour of either quantitative or qualitative assessments of possible invasive species impacts. This is the case in most WTO Member countries, including Australia. Article 5 of the WTO Agreement on the Application of Sanitary and Phytosanitary Measures, commonly referred to as the SPS Agreement, identifies the factors considered paramount from a WTO perspective in assessing the extent of quarantine risks. But a conspicuous omission from this list of relevant factors is *consumer gains from trade*. This becomes highly important when attempting to use measures of societal welfare to examine the impact of market access requests because consumers constitute a large proportion of society.

Reconciling the benefits and costs of trade is also important in terms of the economic modelling of invasive species invasions. Modelling efforts have been devoted to the prevention of invasive species introductions from international trade (Horan *et al.* 2002; Costello and McAusland 2003) or to the control of already established invasive species (Eiswerth and Johnson 2002; Olson and Roy 2002). Recently, more integrative approaches where the trade-offs between prevention and control of invasive species are considered have been developed (Kim *et al.* 2006; Finnoff *et al.* 2007). However, these studies rarely include a welfare analysis where the benefits of trade to consumers are considered. A further necessary step to broaden the bioeconomic analysis is to integrate the analysis of the benefits of trade with spread and control bioeconomic models.

In particular, if the economic benefits of importation can be clearly demonstrated to be above and beyond the quantifiable increase in pest damage risk, trade will result in a net gain to society. This being the case, the prohibition of these imports is effectively costing society. However, if the benefits of importing are insufficient to offset increased risk of pest damage, prohibition is justified on the grounds that it will prevent a net social welfare loss (Cook and Fraser 2008).

1.2. Case study: New Zealand apples importation request to Australia and the risk of fire blight introduction

The issue of importing New Zealand apples into Australia, and the analysis of potential consequences, has considerable history to it. Specifically, Hinchy and Low (1990) addressed a New Zealand request made in 1989 to import apples into Australia, where the major disease transference concern was (and remains) fire blight. Fire blight is a disease caused by the bacteria *Erwinia amylovora* that affects plants from the family *Rosaceae*, including apples and pears. Once established, the bacteria cannot be eliminated from an orchard, but costly measures such as an aggressive pruning regime can be taken to limit the extent of infection (Buckner 1995). The disease originated in the United States, but has spread to most apple growing areas of the world with the exception of Australia. It was first discovered in New Zealand in 1919, and apples have been refused entry to Australia since 1921 (BA 2004).

Australia's detailed response to NZ's 1989 request, coordinated by the Australian Quarantine and Inspection Service (AQIS), was partly motivated by the so-called 'Lindsay Review' of Australian quarantine (DPIE 1988) that recommended moves away from 'zero risk' policies towards 'acceptable' quarantine risk. The economic component provided by Hinchy and Low (1990) was accompanied by a biological component (Roberts 1991). The former took the form of a benefit-cost analysis comparing the expected consumer and producer surplus changes resulting from relaxing quarantine laws protecting the apple industry. In 1995, New Zealand made another request to access the Australian apple market. This time the economic analysis came in the form of Bhati and Rees (1996), which was quite different in approach to that of Hinchy and Low (1990). Expected consumer surplus change was not discussed. The analysis only considered possible producer surplus losses to fruit growers if a fire blight outbreak were to occur.[1] Both import access requests were denied. Viljoen *et al.* (1997) presents evidence that the import ban was indeed justified given that the pear industry in Australia could collapse in the event of a fire blight outbreak.

NZ again submitted an application to Australia to access the apple market in 1999 in which it asked specifically for management procedures that might be applied to reduce the risk of biological contamination below Australia's Appropriate Level of Protection (ALOP). Following the release of a draft import risk analysis in February 2004, which recommended that market access be granted subject to strict pre-entry quarantine measures, mistakes were identified in the spreadsheet models used to ascertain the risks associated with certain pests. When these mistakes were corrected and the final import risk analysis released in late 2006, market access was still deemed to

---

[1] Like Hinchy and Low (1990), Bhati and Rees (1996) base their assumptions about the impact of the fire blight disease on the information contained in Roberts (1991).

present a sub-ALOP level of risk, but only if an even more stringent set of SPS measures were applied.

These restrictions were considered by NZ to be inconsistent with Australia's obligations under the SPS Agreement, and in early 2007 NZ requested consultations with Australia using the WTO's Dispute Settlement Process (DSP). Subsequently, the European Union and the United States requested to join the consultations. Despite the DSP initially targeting a completion date of June 2009, it was not until August 2010 that the Panel handed down its verdict and declared Australia's restrictions to be in breach of the SPS Agreement. Australia has subsequently appealed this decision.

Given this controversial background, this study applies a partial equilibrium model that includes trade with a stratified dispersal model for the spread and control of fire blight in Australia. This represents a coherent economic framework of analysis of such trade decisions, to the empirical context of importing NZ apples with the aim of evaluating the social welfare consequences of allowing this trade.

The structure of the article is as follows. Section 2.1 briefly outlines the theoretical background for analysing the social welfare consequences of allowing new international trade using a static analysis. In Section 2.2, the bioeconomic model that links dynamically the spread of the invasive pest with the partial equilibrium model is described. Empirical estimates of the potential welfare gains from trade from relaxing Australia's import ban on NZ apples appear in Section 3.1, and estimates of the potential costs of outbreaks of fire blight in domestic apple crops appear in Section 3.2. The article ends with a brief discussion that integrates these findings to produce an overall estimate of the social welfare consequences of allowing trade in NZ apples and briefly discusses the associated policy and modelling implications.

2. Methods

2.1. Theoretical model for welfare analysis

The theoretical partial equilibrium model is based on the model developed by Cook and Fraser (2008). The choice facing the decision-maker is whether or not to import a homogenous good from another country. This good has the potential to act as a pathway for a harmful host-specific pest or disease that the source country has but the importing country does not. Assume that in the absence of price-inflating SPS measures, the landed price of imported product (p^{**}) is below that of a domestic equivalent (p_0) and that the domestic market is small relative to the rest of the world in terms of its influence on the world price. The domestic market for the product is characterised by a downward sloping demand curve, $f(q)$, and an upward sloping supply curve, $g(q)$. This situation is depicted in Figure 1, the details of which are explained below.

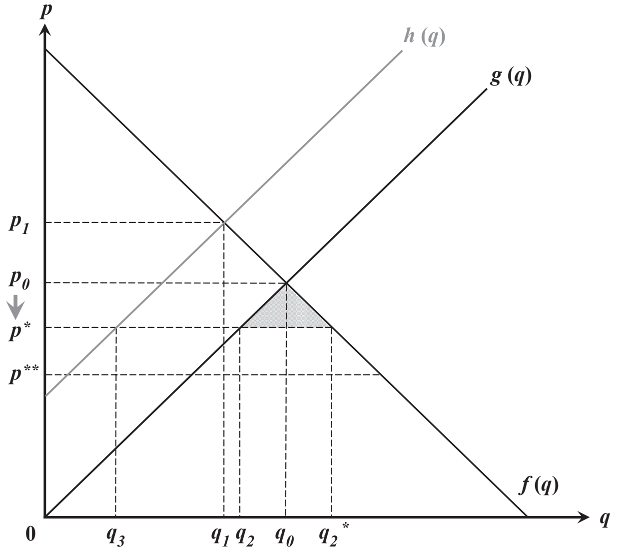

Figure 1 The quarantine-restricted trade decision from a closed economy position.

The domestic losses that could result from an exotic pest or disease outbreak resulting from contaminated imports can be estimated as the total expected change in producer surplus brought about by an incursion-induced (negative) supply shock, plus the cost of controlling the species (be it eradication or suppression). The probability of arrival (γ) is most likely an increasing function of the quantity of imported product, q^*, and a decreasing function of the preborder and border SPS measures the good is subjected to in the process of importation with cost c_{import} [i.e. $\gamma(q^*, c_{\text{import}})$]. To simplify the effects of uncertainty, it is useful to assume a deterministic change in the probability of arrival with SPS compliant imports from abroad (γ^*) relative to the probability of arrival without imports (r) (i.e. $\gamma^* > \gamma$).

As a starting point, a closed economy involves domestic producers with a supply schedule $g(q)$ providing the total supply (q_0) to the domestic market at a price p_0. If an incursion were to occur (despite there being no trade pathway), the supply curve will shift inwards to $h(q)$ and the new equilibrium price will rise to p_1, at which q_1 will be demanded. Note that even when no trade takes place, $0 < \gamma < 1$. Note also that for clarity of exposition we use a static model and thus describe the shifts of the supply curve as an instantaneous process. In reality, the shift of the supply curve is dynamic and linked to the spatial spread of the invasive pest. The bioeconomic model described in the next section accounts for the dynamic interaction between spread and the modifications of the domestic supply curve.

If the market were to move from a closed to a quarantine-restricted trade situation, the prevailing market price will fall to the world price (p^{**}) plus c_{import} (i.e. $p^* = p^{**} + c_{\text{import}}$ where c_{import} is sufficiently low to ensure that $p_0 > p^*$). Domestic producers will remain suppliers to the domestic market as long as p^* remains above the minimum average variable cost of production, supplying a lower quantity q_2. However, if trade takes place, the probability of contaminated product reaching Australia via the trade pathway provided by $q_2^* - q_2$ imports increases from γ to γ^*. In the event that a pest or disease incursion does result the supply curve will shift inwards to $h(q)$, further reducing the quantity supplied by domestic producers to q_3.

Following an incursion, a co-ordinated control campaign is mounted against the invasive species to either eradicate it or restrict its abundance and distribution. Assume the total cost of control will depend only on the size of the outbreak upon detection (s) and the total reduction in abundance and distribution sought by the campaign (a), and is denoted c (s, a) (Olson and Roy 2005). Total control costs are assumed to be increasing in both a and s, while marginal control costs are increasing in a and nonincreasing in s.

On this basis, *expected impact* of the invasive species if no trade takes place ($\mathrm{EI_A}$) is given by:

$$\mathrm{EI_A} = \gamma \cdot \left[\left(p_0 - \int_0^{q_0} g(q) \right) \cdot dq - \left(p_1 - \int_0^{q_1} h(q) \right) \cdot dq \right] + \gamma \cdot c(s,a). \quad (1)$$

Equation (1) states that $\mathrm{EI_A}$ is equal to the expected difference between the producer surplus under autarky if no outbreak occurs and the producer surplus under autarky if an outbreak occurs, plus the expected cost of control.

Secondly, the decision-maker needs to know the expected impact of the invasive species if trade takes place ($\mathrm{EI_Q}$):

$$\mathrm{EI_Q} = \gamma^* \cdot \left[\left(p^* - \int_0^{q_2} g(q) \right) \cdot dq - \left(p^* - \int_0^{q_3} h(q) \right) \cdot dq \right] + \gamma^* \cdot c(s,a). \quad (2)$$

Equation (2) states that $\mathrm{EI_Q}$ is the expected difference between the producer surplus with trade if SPS measures are 100 per cent effective and the producer surplus if an outbreak occurs, plus the expected cost of control. Note that the prevailing market price in the event of a disease incursion is assumed to be p^* (rather than p^{**}) because of the nonspecificity of SPS measures. The imported commodity will in general entail a risk of introduction of multiple pests and, even if one of them becomes naturalised, we assume c_{import} still applies.

Despite the risk of pests and disease hitchhikers, the importation of goods from abroad also brings with it potential gains from trade by placing downward pressure on prices. Imports provide a greater quantity of the good to consumers at a lower price, p^*, compared to the closed economy (autarky) situation which, as shown in Figure 1, imposes costs to consumers and provides gains to domestic producers. Therefore, the decision of whether to import a commodity subject to SPS measures must be made relative to a closed economy situation and must also establish the consumer benefits achieved and producer costs imposed by permitting trade.

In moving from a closed economy to a quarantine-restricted trade situation, the prevailing market price would be expected to fall to p^* at which domestic producers are willing to supply q_2 of the total quantity demanded, q_2^*. The total consumer surplus gained by allowing quarantine-restricted trade is given by:

$$\Delta\mathrm{CS} = \left(\int_0^{q_2^*} f(q) - p^*\right) \cdot dq - \left(\int_0^{q_0} f(q) - p_0\right) \cdot dq. \tag{3}$$

This change in consumer surplus is the difference between the postquarantine trade consumer surplus and autarkic consumer surplus. This gain comes at the cost of competition-induced producer surplus losses to domestic producers:

$$\Delta\mathrm{PS} = \left(p_0 - \int_0^{q_0} g(q)\right) \cdot dq - \left(p^* - \int_0^{q_2} g(q)\right) \cdot dq. \tag{4}$$

This producer surplus change is calculated as the difference between the autarkic producer surplus and post-trade producer surplus. The resultant net gains, termed *traditional gains from trade* in Snape and Orden (2001), are simply the difference between consumer surplus gain and producer surplus loss ignoring the possibility of an invasive species incursion. That is, the traditional gains from trade here represent the change in producer and consumer surplus as a result of price differentials between the domestic equilibrium and landed price of imports:

$$\mathrm{GT} = \Delta\mathrm{CS} - \Delta\mathrm{PS}. \tag{5}$$

This is represented as the shaded region in Figure 1.

However, as shown previously, these traditional trade effects do not take into account the effects on producers of the increase in invasive species risk (EI^*) brought about by trade (i.e. $\mathrm{EI}^* = \mathrm{EI}_\mathrm{Q} - \mathrm{EI}_\mathrm{A}$). Therefore, the total gains to consumers resulting from trade must be sufficiently high to offset all the expected losses to domestic producers for there to be a net gain from moving from a closed economy to a quarantine-restricted trade setting.

More specifically, combining the changes in consumer and producer surplus with the expected impact of an invasion on producers, the expected net gains from trade (NG_E) can be stated as:

$$\mathrm{NG}_\mathrm{E} = \mathrm{GT} - \mathrm{EI}^* \tag{6}$$

It follows that the decision of whether or not to import the potentially contaminated product is either:

1. If $\mathrm{GT} - \mathrm{EI}^* > 0$, allow trade to occur or
2. If $\mathrm{GT} - \mathrm{EI}^* < 0$, do not allow trade to occur.

The model used in this analysis to estimate GT is a simple comparative static spreadsheet model based on the theoretical model developed above. It determines the likely changes in consumer and producer surplus brought about by different levels of competition from external suppliers. To incorporate uncertainty in parameter estimates, the *@Risk* software package is used (Palisade-Corporation 2010). In all, 5000 iterations of the model were used to simulate the multitude of possible scenarios and to reveal the likely economic effects of apple imports.

2.2. Bioeconomic model to estimate the net impact of fire blight invasion

To estimate the invasion costs in both the autarkic and the quarantine-restricted trade scenarios, a biological model is used to simulate the arrival, spread and impact of fire blight in Australian apple orchards over a 30-year time period. This model is then combined with a measure of the marginal damage cost of invasion and periodic eradication attempts.

The biological model generates fire blight entry events using a Poisson process, which is often used to model the entry of invasive species and diseases to new environments (Vose 2000). The Poisson stochastic process implicitly assumes that each introduction is independent of another. The single parameter used to define the Poisson distribution is the expected number of introductions per time step (i.e. in our case 1 year), λ. With the exception of well-known, high-profile invasive species, quantitative arrival estimates are difficult to come by and often are poorly specified. We use an estimate put forward in Cook (2003) for the likelihood of fire blight arrival, which in turn uses Australian government guidelines for risk analysis (BA 2001) to represent λ using a uniform distribution. From Cook (2003) we assume that, on average, one introduction event would occur every 2 years under an SPS-restricted trade scenario. However, this may be as high as one introduction event every year or as low as one every 3 years. We therefore define λ under SPS-restricted trade using a uniform distribution with a minimum value of 0.3 and a maximum value of 0.7 [i.e. uniform (0.3, 0.7)]. Under autarky, we assume λ falls to uniform (0.001, 0.05). Table 1 summarises these and other parameter estimates used in the model that are explained below.

In iterations of the model in which the Poisson process predicts a successful introduction, the probability of that event leading to successful establishment is estimated as uniform (0.7, 1.0). This indicates that although introduction does not necessarily lead to establishment, in the case of fire blight there is a high probability that it will. Indeed, the likelihood of establishment in Australia has recently been shown to be very high using self-organising map (SOM) analysis, which is a type of artificial neural network. This technique uses worldwide species associations to determine which species have the highest likelihood of establishing (Worner and Gevrey 2006). A SOM analysis was performed on the worldwide distribution of 131 bacterial pathogens (CABI/EPPO 2003), of which 71 are currently absent from

Table 1 Parameters and their assumed values

Parameters	Quarantine-restricted trade	Autarkic trade
Biological		
Probability of entry[a]	Uniform (0.3, 0.7)	Uniform (0.05, 0.3)
Probability of establishment[b]	Uniform (0.7, 1.0)	Uniform (0.7, 1.0)
Detection probability	Binomial (1.0, 0.6)	Binomial (1.0, 0.6)
Probability of successful eradication in a single time step given an infected area, A, and a maximum area considered for eradication, A_{erad} (see below)	Binomial $\left(1, \frac{A}{A_{\mathrm{erad}}}\right)$	Binomial $\left(1, \frac{A}{A_{\mathrm{erad}}}\right)$
Infection diffusion coefficient, D (ha/year)[c]	Pert (1.0, 1.5, 2.0)	Pert (1.0, 1.5, 2.0)
Minimum area infected immediately upon entry, A_{min} (ha)	1	1
Maximum area infected, A_{max} (ha)[d]	32,760	32,760
Intrinsic rate of infection and density growth, r[e]	Pert (1.0, 1.25, 1.5)	Pert (1.0, 1.25, 1.5)
Minimum infection density, N_{min} (#/ha)	1	1
Maximum infection density, K (#/ha)[c]	Pert (1.0×10^6, 5.5×10^6, 1.0×10^7)	Pert (1.0×10^6, 5.5×10^6, 1.0×10^7)
Minimum number of satellite sites generated in a single time step, S_{min}	1	1
Maximum number of satellite sites generated in a single time step, S_{max}[c]	Pert (50, 60, 70)	Pert (50, 60, 70)
Intrinsic rate of new foci generation per unit area of infection, μ[c]	Pert (0.01, 0.03, 0.05)	Pert (0.01, 0.03, 0.05)
Economic		
Discount rate	0.08	0.08
Supply elasticity[f]	Pert (0.2, 0.5, 0.5)	Pert (0.2, 0.5, 0.5)
Demand elasticity[f]	Pert (−0.8, −0.6, −0.4)	Pert (−0.8, −0.6, −0.4)
Farm gate price of apples ($/T)	1190 (ie p^*)	1200 (ie p_0)[g]
Wholesale marketing margin	Pert (0.1, 0.2, 0.3)	Pert (0.1, 0.2, 0.3)
Retail marketing margin	Pert (0.3, 0.45, 0.6)	Pert (0.3, 0.45, 0.6)
Volume supplied by Australian producers (T)	Mean = 287,650 (ie q_2)	290,300 (ie q_0)[d]
Volume imports from New Zealand (T)	2650	0
Maximum area considered for eradication (ha)	500	500
Increased chemical cost ($/ha)[h]	1000	1000
Increased pruning expenses ($/ha)[h]	400	400

Table 1 (*Continued*)

Parameters	Quarantine-restricted trade	Autarkic trade
Yield loss despite control (%)[h]	Pert (0, 10, 20)	Pert (0, 10, 20)
Cost of eradication ($/ha)[i]	Pert (20,000, 30,000, 40,000)	Pert (20,000, 30,000, 40,000)

[a]Based on Cook (2003); [b]Paini *et al.* (2010); [c]Derived from Waage *et al.* (2005); [d]ABS (2004); [e]Zadocks and Shein (1979) and Waage *et al.* (2005); [f]Derived from Valdes and Zietz (1980) and Bhati and Rees (1996); [g]HAL (2004); [h]Cook (2003) and McElwee (2000); [i]Assumes zero compensation following tree removal, average density of planting of 600 trees/ha and removal, transport, destruction and chemical costs amounting to $16.70 per tree. This is inclusive of labour (team of three at $35/h each), bulldozing equipment ($100/h at 15 h per hectare), truck hire ($75/h), incendiaries ($60/ha for green waste) and creation of a circular chemical buffer zone approximately 10 hectares in diameter around previously infected sites. We assume a Bordeaux mixture (copper sulphate crystals and hydrated spay lime dissolved in water at a rate of 8-8-100) is used at a cost of $2.50/kg applied at 4 kg/ha in high water volumes to achieve a washing action on bark surfaces, taking approximately 2 h per hectare to apply.

Table 2 The gains from trade resulting from apple imports from New Zealand

	Mean	Standard deviation
Change in consumer surplus (ΔCS)	$46,343,200	$1,573,340
Change in producer surplus (ΔPS)	−$30,731,670	$400,150
Gains from trade (GT)	$15,611,530	$1,604,560

Australia. The analysis ranked fire blight 17th in this list (Paini *et al.* 2010). Thus, we considered a high probability of establishment with a median of 0.85 (Table 2).

Once entry and establishment have occurred, spatial homogeneity is assumed in the sense that different host plantings across the country are assumed equally susceptible to infection. If uncontrolled, fire blight will continue to spread to the point where 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, nonspreading members of the flora/fauna (Mack 1996; Mack and Lonsdale 2001).

The area of infection is generated by a reaction diffusion model derived from Fisher (1937). This form of model has since been expanded for more general use (Skellam 1951; Britton 1986) and has been shown to approximate the spread of a diverse range of organisms (Dwyer 1992; Holmes 1993; McCann *et al.* 2000; Okubo and Levin 2002). A generic result is that an infection 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 infection's intrinsic rate of growth. Hence, we assume that once established, the infection spreads by a diffusive process such that area affected expands following the function (Hengeweld 1989; Lewis 1997; Shigesada and Kawasaki 1997):

$$A_t = \pi\left(2t\sqrt{rD}\right)^2 = 4D\pi rt^2. \tag{7}$$

Here, A_t is the area of hosts infected with fire blight at time t, D is the infection diffusion coefficient and r is the intrinsic rate of infection growth.[2] In each unit of area infected, the local infection density $N(t)$ grows over time following a logistic function until the carrying capacity of the environment (K) is reached:

$$N(t) = \frac{K}{1 + \left(\frac{K}{N_{\min}} - 1\right)\mathrm{e}^{-rt}}. \tag{8}$$

Here, $N_{\min}$ is the size of the original infection.

The area and density functions of (7) and (8) are combined with a logistic function generating changes in the number of nascent foci (or *satellite* sites) as the process of infection continues. These are events that 'jump' the expanding infection beyond the invasion front and are attributable to causes external to the invasion itself such as weather events, animal or human behaviour. The number of new satellites created in each unit of time [$s(t)$] is:

$$s(t) = \frac{s_{\max}}{1 + \left(\frac{s_{\max}}{s_{\min}} - 1\right)\mathrm{e}^{-\mu t}}. \tag{9}$$

Here, μ is the intrinsic rate of new foci generation, $s_{\max}$ is the maximum number of satellite sites generated in a single time step (i.e. 1 year) and $s_{\min}$ is the minimum number of satellite sites generated per time step (Moody and Mack 1988). Once a satellite site is established, the infection begins to expand in the same manner as the original site. The total combined area of infection grows until $A_t = A_{\max}$ (maximum habitable area), at which point total area remains constant. This point represents the *carrying capacity* of the environment. Environmental and demographic stochasticity leading to non-uniform invasion is not considered in the model.

The complete model uses a relatively small number of parameters to estimate the ecological processes of arrival, establishment, spread and impact. The values and statistical distributions assigned to each appear in Table 1.[3]

---

[2] For analyses performed at higher spatial resolutions, a relatively simple modification can be made to constrain the rate of spread according to area and shape of potentially suitable habitat, or the distribution of the host. In our simple case, Equation (7) allows prediction of spread on the basis of a constant rate of infection. An estimate of D can be derived from the mean dispersal distance ($\bar{d}$) where $D = 2\left(\bar{d}\right)^2$ (Andow *et al.* 1990).

[3] Due to the uncertainty surrounding some of these parameters, a range of distributional forms are specified in Table 1. They include: (i) pert – a type of beta distribution specified using minimum, most likely (or skewness) and maximum values; (ii) uniform – a rectangular distribution bounded by minimum and maximum values; (iii) binomial – returning a zero (failure) or one (success) based on a number of trials and the probability of a success.

In terms of preventing naturalisation, eradication is the only government management activity simulated in the model. It involves the complete removal of infested trees and the creation of intensive buffer zones (using fungicide treatments) around infested sites (WAQIS 1999). Fire blight is a listed species under the Emergency Plant Pest Response Deed (EPPRD) (PHA 2005), which states that in the event of an incursion a pre-agreed cost sharing arrangement for eradication is activated.[4] This aids in the early reporting of an incursion, minimises the response time and capitalises on the opportunity to minimise the size and impact of an incursion. Eradication is the only management activity covered under the EPPRD and is conditional on results of a technical feasibility study and a benefit-cost analysis (PHA 2001). If eradication is deemed infeasible or likely to result in a net loss, the Deed no longer applies and much of the management responsibility falls to affected industries. However, once an eradication campaign has begun, it is largely technical and logistical factors that determine whether it will continue in the long-term.

We assume that eradication is immediately commenced once industry and government have been alerted to the presence of fire blight in Australia. The detection that triggers the EPPRD is, on average, assumed to occur in 60 per cent of incursion events simulated by the model using a binomial distribution [i.e. binomial (1.0, 0.6)]. The probability that the eradication attempt will successfully remove an infestation is proportional to the area of host plants occupied at the time of detection (see Table 1). If this does not occur before infection has spread to a predefined maximum area, A_{erad}, which we have arbitrarily assumed is 500 ha, the eradication attempt is aborted.[5]

If detection does occur sufficiently early, eradication entails the complete removal of all infected trees and the creation of a chemical buffer zone around the area where the infection occurred. Infected trees are bulldozed and removed from quarantined properties by truck for incineration. This involves expenses of approximately $10,000 per hectare of trees removed. It is assumed that no compensation is offered to affected orchardists. After infected trees have been destroyed, the area is immediately re-planted to apples and effectively re-enters production 6 years from the time of re-planting. In present value terms, the cost of replanting one hectare of apples and waiting for the trees to mature to the point of yielding fruit is approximately $55,000.

---

[4] Listed species fall in to one of four cost sharing categories relating to their potential impacts on public and private resources. The category chosen dictates an appropriate split of eradication funding between government and private funding sources. Currently, fire blight is classified as a category two species, indicating a 20 per cent private and 80 per cent government/public funding contribution PHA (2005).

[5] In reality a range of factors will affect this decision including the number and location of sites, proximity to alternative hosts, industry size and the number of simultaneous eradication programs for other species.

When detection does not occur early in an outbreak or when an eradication attempt fails to prevent infection reaching the 500 hectare threshold level, eradication is aborted. This does not mean that fire blight now spreads unimpeded within the virtual world of the model because we assume there are certain on-farm management strategies orchardists can adopt to reduce the impacts of the disease. For instance, aggressive pruning to remove infected spurs, shoots and limbs can greatly reduce fire blight incidence. Copper sprays can be applied in conjunction with the manual removal of fire blight cankers. Antibiotics can also be used to prevent fire blight infection on host flowers' stigma surfaces, although it is unlikely that they will be effective if applied more than 24 h post-infection, so the timing of applications is critical. All of these techniques involve a cost to producers and are not guaranteed to be 100 per cent effective. Yield losses despite control are estimated to average around 10 per cent per annum [represented in the model as Pert (0.0, 0.1, 0.2) (McElwee 2000)].

The spread of fire blight is connected dynamically with the costs of eradication and on-farm control by simply multiplying the area infested by a constant marginal damage cost (or an average damage cost). For outbreaks involving <500 hectares, area is multiplied by eradication and replanting costs (see Table 2). When infection spreads beyond 500 hectares, the remaining area is multiplied by an average on-farm disease management cost comprising of additional chemical and application costs (\$1000 per hectare), pruning costs (\$400 per hectare) and yield losses [Pert (0, 10, 20 per cent) (McElwee 2000; Cook 2003)].

By summing the production losses over each time step and assuming fixed costs are zero, we estimate the present value of producer surplus losses attributable to fire blight incursions over a 30-year period. We do this for both an autarkic and a quarantine-restricted trade scenario by altering the parameter λ, which is higher under the latter scenario, as explained above. The difference between estimated damages in each scenario indicates the change in expected impact of the disease over time as a result of granting NZ access to the Australian market for fresh apples, EI*. To determine the expected net gains from trade, NG_E, we must first calculate the traditional gains, GT (i.e. Eqn 6). To do this, we require some additional model parameters as outlined in Section 2.1 and Table 1. These parameters and the data used to represent them in the model are detailed below:

Elasticity of supply – Estimated using a pert distribution with a minimum value of 0.2, a most likely value of 0.5 and a maximum value of 0.8 (approximated using Valdes and Zietz (1980) and Bhati and Rees (1996) as guides);

Elasticity of demand – Estimated using a pert distribution with a minimum value of −0.4, a most likely value of −0.6 and a maximum value of −0.8 (approximated using Valdes and Zietz (1980) and Bhati and Rees (1996) as guides);

Closed economy quantity supplied (q_0) – The closed economy quantity supplied was estimated at 290,300T (ABS 2004; HAL 2004).[6]

Closed economy, or Autarkic price (p_0) – \$1200/T (HAL 2004).

Free trade price (p^{**}) – This represents the price at which apples from external sources can be supplied to the Australian market with no quarantine treatments required. O'Rourke (2007) ranked Australia 16th in a study of the production efficiency of 28 of the world's apple producing countries, while NZ was ranked 2nd. Given the relatively close proximity of NZ apple producers to the Australian market, this suggests that the landed price of NZ apples is a reasonable proxy for the world price. Using figures from Cook (2008) as a guide, we assume that shipping costs (including loading and road freight costs) involved in transporting product from NZ to Australia are in the order of \$400/T. Data from FAO (2009) from 2002 to 2006 were used to construct a linear time-series to project a 2008 NZ farm gate price of \$680/T. This implies a landed price of NZ apples in Australia of around \$1080/T.

Post-quarantine or import price (p^*) – In the absence of time-series price differentials in a closed and quarantine-restricted market, an approximate quarantine-induced price rise of 10 per cent above the free trade price is assumed (i.e. \$1190/T), at which 2650T will be imported.

Wholesale and retail marketing margins – Wholesale margins are specified as a pert distribution with a minimum value of 10 per cent, a most likely value of 20 per cent and a maximum value of 30 per cent. Retail margins are estimated using a pert distribution with a minimum value of 30 per cent, a most likely value of 45 per cent and a maximum value of 60 per cent (Cook 2008). Both wholesale and retail-marketing margins are assumed constant in percentage terms.

3. Results

3.1. Welfare analysis: benefits from trade

The parameterised model was used to calculate the net gains from trade resulting from the import of NZ apples (subject to quarantine treatments) into Australia. This represents a movement from a closed economy situation (autarky) to one of quarantine-restricted trade. Results are presented in Table 2.

As the variability of parameters has been incorporated in the analysis, results are probability distributions rather than point estimates. They are described in the table simply by using the mean and standard deviation. With the demand and supply curve specifications used in this exercise, the results indicate that the net gains from trade to the Australian

---

[6] The Australian Bureau of Statistics Catalogue No. 7121.0.55.002 is collected on behalf of the peak industry body, Apple and Pear Australia Limited.

economy from allowing NZ apples into the country subject to quarantine treatments (rather than excluding them completely) are expected to average around \$15.6 million per year with a standard deviation of approximately \$1.6 million. Figure 2 shows the flow of these gains from trade over a 30-year period, showing the average present value ± 1 standard deviation from the mean. The discount rate used in these calculations is 8 per cent. This relatively high rate consists of a margin of 3 per cent on top of a real risk-free rate of 5 per cent (Commonwealth of Australia 2006).

The calculated gains from trade are responsive to changes in the landed price of NZ apples under both a free trade and quarantine-restricted scenario, as we would expect. All other things being equal, if freight and transport costs are as low as \$300/T the landed price of apples may be as low as \$980/T. This would mean net gains from quarantine-restricted trade of \$17.3 million, and therefore, a higher break-even level of invasive species risk. On the other hand, if rising oil prices continue to increase the cost of freight to the point where they reach \$600/T, the landed price of apples may be as high as \$1280/T. This would mean the cost of quarantine restrictions to Australian consumers would be negligible. Likewise, if SPS measures imposed on imported apples increase the landed price of NZ apples by more than 20 per cent (above the base case level of \$1080/T), the gains to Australian consumers are negligible as the post-quarantine price would be equivalent to an autarkic price.

3.2. Invasion costs: spread, control and sensitivity analysis

The total invasion costs over a 30-year period were calculated for both the quarantine-restricted trade and the Autarkic trade, and then, the difference between them was taken to give the change in expected impact. The present value of annual damages expected to result from fire blight incursions over

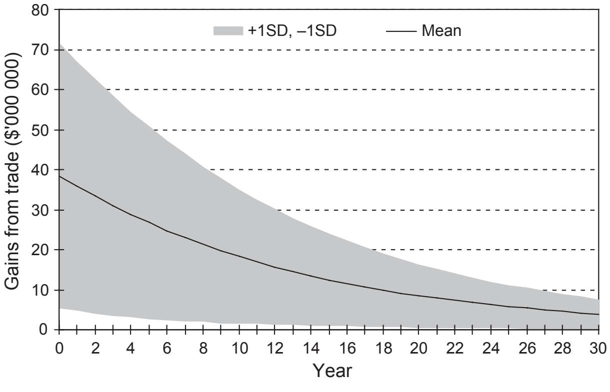

Figure 2 Present value of gains from trade over 30 years.

the simulation period is given in Table 3. These results are obtained using the parameter values from Table 1.

The average present value from 5000 iterations of the model ± 1 standard deviation from the mean is shown in Figure 3. The increase in expected losses from fire blight incursions will be relatively small until about year 6, after which they increase dramatically. This lag period is attributable to the SPS measures imposed on apple imports being relatively effective. Under the SPS-restricted trade scenario, the model predicts an incursion event is roughly four times more likely to occur than under an autarky scenario. However, despite the difference in expected impact occurring well into the future (and hence being subject to the erosive effects of an 8 per cent discount rate), the damage caused is on a very large scale relative to consumers' gains.

Given the uncertainty surrounding several parameters used to describe the invasion process, the sensitivity of the change in expected impact (i.e. EI*) to the key biological assumptions of the model was tested. Parameters were sampled from a uniform distribution with a maximum (minimum) of + 50 per cent (−50 per cent) of the original values entered in to the model using Monte Carlo simulation with Latin Hypercube sampling (once again, see Table 1 for the initial value of the parameters). The Spearman's rank

Table 3 Expected damage per year from fire blight incursions

	Mean	Standard deviation
Expected impact under autarky (EI_A)	\$17,282,810	\$14,242,790
Expected impact under quarantine-restricted trade (EI_Q)	\$40,803,290	\$9,813,510
Change in expected impact (EI*)	\$23,783,540	\$15,058,590

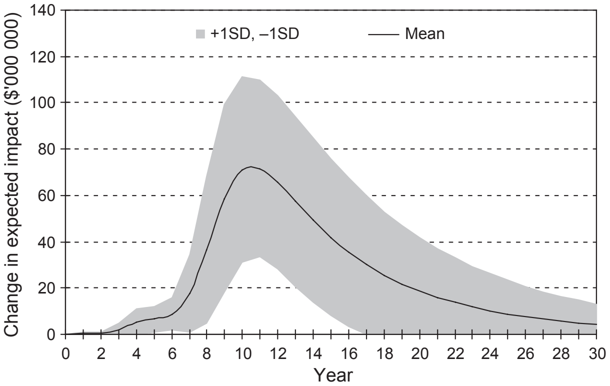

Figure 3 Increase in the expected net present value of fire blight damage costs in a scenario with quarantine-restricted trade with respect to a no trade scenario. Impacts are composed of costs of eradication attempts, on-farm management efforts and market revenue losses.

correlation coefficients relating the sampled model parameter values and the change in expected impact were then calculated. The results appear as a tornado graph in Figure 4.

The sensitivity tests indicate that the incursion simulation model is highly sensitive to changes in four of the 25 parameters listed in Table 1 (15 of which are shown in Figure 4). These parameters and their correlation with the model output are as follows: probability of entry under autarky (−0.399); yield loss despite control (0.289); discount rate (−0.195); and the probability of establishment under autarky (−0.184).

3.3. Expected net change in social welfare

The overall welfare effects on the economy can be seen by plotting the change in expected impact with the gains from trade, as in Figure 5. Here, the mean net change in social welfare represented by changes in consumer and producer surpluses under the Autarkic and SPS-restricted trade scenarios is also plotted. Net social welfare is likely to be improved substantially by opening up trade to NZ apples for the first 7 years. After this point, the increase in fire blight damages resulting from an increased likelihood of incursion will be such that net welfare is expected to become negative. This is despite the effects of discounting on future values using a high discount rate of 8 per cent.

Given the intertemporal nature of trade benefit and cost accrual, it is difficult to make comparisons as a great deal hinges on the time frame being considered by decision-makers. Assuming this to be 30 years and taking the mean present annual value of gains from trade and change expected impact resulting from a move from autarky to SPS-restricted trade, the net impact

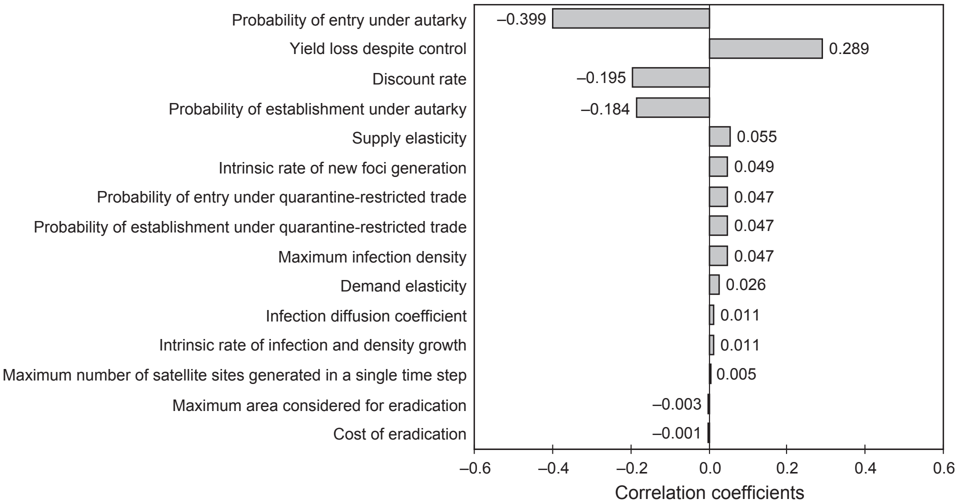

Figure 4 Sensitivity test of the expected net gains from Australia's importation of New Zealand apples to key model parameters showing Spearman rank correlation coefficients.

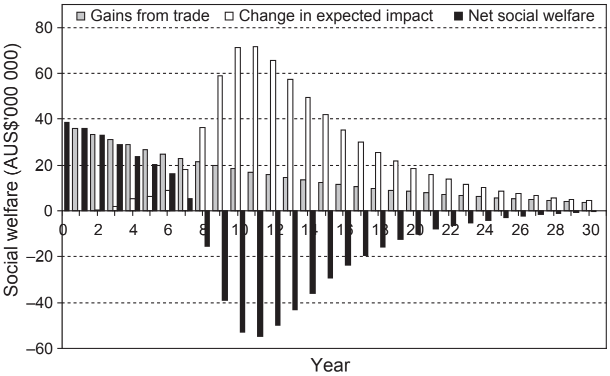

Figure 5 Change in social welfare over time.

on social welfare is likely to be negative. Over this time period, the ratio of trade benefits to expected costs is approximately 0.7–1. However, we should again point out the uncertainty in projecting this far into the future, as reflected in high standard deviations for both GT and EI*, making it difficult to draw definitive conclusions.

Note also that if we were to apply a personal discount rate of 10 per cent to the mean or average model calculations, as opposed to a public/social discount rate of 8 per cent, EI* would fall to $18.8 million. GT would also decrease to $13.2 million, meaning that the ratio of trade benefits to expected costs would remain 0.7–1. On the other hand, if we were to adopt a more precautionary approach to agricultural change and apply a discount rate of 5 per cent, EI* would increase to $34.6 million and GT to $20.7 million, reducing the ratio of benefits to costs to 0.6–1.

4. Discussion

The use of economic analysis in the assessment of import requests remains ‘new ground’ in many ways. While examples have been provided in the past, there has yet to be a consistent and generally accepted approach to quarantine policy analysis. This study has provided a demonstration of how a comprehensive economic framework, which takes into account both the gains from trade and the costs of invasive species outbreaks, can inform decision-makers when making quarantine decisions. In particular, this study has utilised the framework developed in Cook and Fraser (2008) and extended it with a stratified dispersal model of invasive pest spread and control to make an empirical estimation of the economic welfare consequences for Australia of allowing quarantine-restricted trade in NZ apples to take place.

Based on the theoretical model outlined in Section 2.1, it is shown in Section 3.1 that liberalising trade to allow apples to be imported from NZ subject to quarantine restrictions is expected to increase net economic welfare (primarily in terms of benefits to consumers) by approximately $15.6 million with a standard deviation of around \$1.6 million per year. However, in opening up the market to trade, the domestic apple industry is exposed to a higher level of biosecurity risk because of the presence of potentially harmful pests and diseases in external apple sources. In Section 3.2, an economic assessment of the potential impact of fire blight if introduced via NZ apple imports reveals an overall increase in likely annual damage (assessed over a 30-year period) of approximately \$23.8 million per year with a standard deviation of around \$15.1 million. Such a large dispersion is reflective of the uncertainty involved in predicting future impacts of fire blight on the Australian apple industry.

Combining the results of the estimations in Sections 3.1 and 3.2 suggests the returns to Australian society expected to result from importing apples from New Zealand are marginal. The price differential between the landed product with SPS measures in place and the autarkic price is insufficient to outweigh the increase in expected damage resulting from increased fire blight risk. As a consequence, this empirical analysis does not support the opening up of this trade.

The modelling framework developed can be extended to be used for the resolution of other import request disputes involving other invasive species. The application to other invasive species would demand ad hoc changes, e.g different market or control characteristics. However, the framework provides for a solid foundation over which other comprehensive economic analysis can be developed.

Future extensions to the model could range from (i) the consideration of the flow-on effects of the entry of the invasive species to the rest of the economy using a general equilibrium model (Wittwer *et al.* 2005); (ii) the adoption of an ecosystems approach within the bioeconomic model to study the interactions between the invasive and native species (Hulme 2006); (iii) the importance of potential economic costs of non-market (e.g impact on native biota, environmental costs resulting from the use of pesticides) and indirect market (e.g impacts on fertiliser sale after a major industry is devastated by an invader) impacts are acknowledged. However, it is difficult to incorporate these costs due to a high level of uncertainty. Our model only captures impacts on market goods. If the environmental costs of the use of pesticides to control for fire blight were included, the benefits from opening up trade would be further reduced; (iv) the use of more complex biophysical modelling of susceptibility and resilience to infection (e.g Hester and Cacho 2003). Using a general equilibrium model or using an ecosystems approach may improve the investigative power of the analysis at the cost of substantially increasing the demand for information for model construction and parameterisation.

Previous invasive species economic modelling has focussed mainly on the study of the introductions because of trade or on the management of established invasive species. Economic frameworks where the benefits of trade to consumers and bioeconomic modelling of invasive species spread and control are reconciled are increasingly needed to solve import trade disputes. This reconciliation allows for a comprehensive estimation of the costs and benefits of opening a new trade pathway.

References

ABS (2004). *AgStats Integrated Regional Database, Catalogue No. 1353.0*. Australian Bureau of Statistics, Canberra.

Andow, D.A., Kareiva, P., Levin, S.A. and Okubo, A. (1990). Spread of invading organisms, *Landscape Ecology* 4, 177–188.

BA (2001). *Guidelines for Import Risk Analysis*. Agriculture, Fisheries and Forestry Australia/ Biosecurity Australia, Canberra.

BA (2004). Importation of Apples from New Zealand – Revised Draft IRA Report, in Australia, B. (ed.), Department of Agriculture, Fisheries and Forestry, Canberra, 533 pp.

Bhati, U.N. and Rees, C. (1996). *Fireblight: A Cost Analysis of Importing Apples from New Zealand*. Australian Bureau of Agricultural and Resource Economics, Canberra, 21 pp.

Britton, N.F. (1986). *Reaction-Diffusion Equations and their Applications to Biology*. Academic Press, London.

Buckner, S. (1995). Reducing Fireblight, *The Grower*, 8 pp.

CAB International (2003). *Crop Protection Compendium – Global Module*. CAB International, Cayman Islands.

Commonwealth of Australia (2006). *Handbook of Cost-Benefit Analysis*. Department of Finance and Administration, Canberra, 180 pp.

Cook, D.C. (2003). *Prioritising Exotic Pest Threats to Western Australian Plant Industries*, Discussion Paper. Government of Western Australia – Department of Agriculture, Bunbury, 185 pp.

Cook, D.C. (2008). Benefit cost analysis of an import access request, *Food Policy* 33, 277–285.

Cook, D.C. and Fraser, R.W. (2008). Trade and invasive species risk mitigation: reconciling WTO compliance with maximising the gains from trade, *Food Policy* 33, 176–184.

Costello, C. and McAusland, C. (2003). Protectionism, trade, and measures of damage from exotic species introductions, *American Journal of Agricultural Economics* 85, 964–975.

DPIE (1988). *Australian Quarantine Requirements for the Future: Report of the Quarantine Review Committee*. Department of Primary Industries and Energy, Canberra.

Dwyer, G. (1992). On the spatial spread of insect pathogens – theory and experiment, *Ecology* 73, 479–494.

Eiswerth, M.E. and Johnson, W.S. (2002). Managing nonindigenous invasive species: insights from dynamic analysis, *Environmental & Resource Economics* 23, 319–342.

FAO (2009). *FAOSTAT Database*. Food and Agriculture Organization of the United Nations, Rome.

Finnoff, D., Shogren, J.F., Leung, B. and Lodge, D. (2007). Take a risk: preferring prevention over control of biological invaders, *Ecological Economics* 62, 216–222.

Fisher, R.A. (1937). The Wave of Advance of Advantageous Genes, *Annual Eugenics* 7, 353–369.

HAL (2004). *The Australian Horticulture Statistics Handbook*. Horticulture Australia Limited, Sydney.

Hengeweld, R. (1989). *The Dynamics of Biological Invasions*. Chapman and Hall, London.

Hester, S.M. and Cacho, O. (2003). Modelling apple orchard systems, *Agricultural Systems* 77, 137–154.

Hinchy, M.D. and Low, J. (1990). *Cost-Benefit Analysis of Quarantine Regulations to Prevent the Introduction of Fire Blight into Australia: Report to the Australian Quarantine and Inspection Service*. Australian Bureau of Agricultural and Resource Economics, Canberra.

Holmes, E.E. (1993). Are diffusion-models too simple – a comparison with telegraph models of invasion, *American Naturalist* 142, 779–795.

Horan, R.D., Perrings, C., Lupi, F. and Bulte, E.H. (2002). Biological pollution prevention strategies under ignorance: the case of invasive species, *American Journal of Agricultural Economics* 84, 1303–1310.

Hulme, P.E. (2006). Beyond control: wider implications for the management of biological invasions, *Journal of Applied Ecology* 43, 835–847.

Kim, C.S., Lubowski, R.N., Lewandrowski, J. and Eiswerth, M.E. (2006). Prevention or control: optimal government policies for invasive species management, *Agricultural and Resource Economics Review* 35, 29–40.

Lewis, M.A. (1997). Variability, patchiness, and jump dispersal in the spread of an invading population, in Tilman, D. and Kareiva, P. (eds), *Spatial Ecology: The Role of Space in Population Dynamics and Interspecific Interactions*. Princeton University Press, Princeton, NJ, pp. 46–74.

Mack, R.N. (1996). Predicting the identity and fate of plant invaders: emergent and emerging approaches, *Biological Conservation* 78, 107–121.

Mack, R. and Lonsdale, W. (2001). Humans as global plant dispersers: getting more than we bargained for, *BioScience* 51, 95–102.

McCann, K., Hastings, A., Harrison, S. and Wilson, W. (2000). Population outbreaks in a discrete world, *Theoretical Population Biology* 57, 97–108.

McElwee, H. (2000). *Economic Impact Assessment of Fireblight (Erwinia Amylovora) in Western Australia*, Unpublished Draft Report. Government of Western Australia – Department of Agriculture, Bunbury.

Moody, M.E. and Mack, R.N. (1988). Controlling the spread of plant invasions: the importance of nascent foci, *Journal of Applied Ecology* 25, 1009–1021.

Okubo, A. and Levin, S.A. (2002). *Diffusion and Ecological Problems: Modern Perspectives*. Springer, New York.

Olson, L.J. and Roy, S. (2002). The economics of controlling a stochastic biological invasion, *American Journal of Agricultural Economics* 84, 1311–1316.

Olson, L. and Roy, S. (2005). On prevention and control of an uncertain biological invasion, *Review of Agricultural Economics* 27, 491–497.

O'Rourke, D. (2007). *World Apple Review*. Belrose Inc., Pullman.

Paini, D.R., Worner, S.P., Cook, D.C., Barro, P.J.D. and Thomas, M.B. (2010). Using a self-organizing map to predict invasive species: sensitivity to data errors and a comparison with expert opinion, *Journal of Applied Ecology* 47, 290–298.

Palisade-Corporation (2010). *@Risk 5.0*. Newfield, NY.

PHA (2001). *Funding and Compensation for Emergency Eradication of Exotic Plant Pests and Diseases: A Discussion Paper*. Plant Health Australia, Canberra.

PHA (2005). *Government and Plant Industry Cost Sharing Deed in Respect of Emergency Plant Pest Responses*. Plant Health Australia, Canberra.

Roberts, W. (1991). *Consequences of Establishment of Fireblight in Australia, Information Paper No. IP/1/91*. Bureau of Rural Resources, Canberra.

Shigesada, N. and Kawasaki, K. (1997). *Biological Invasions: Theory and Practice*. Oxford University Press, Oxford.

Skellam, J.G. (1951). Random dispersal in theoretical populations, *Biometrika* 38, 196–218.

Snape, R.H. and Orden, D. (2001). Integrating import risk and trade benefit analysis, in Anderson, K., McRae, C. and Wilson, D. (eds), *The Economics of Quarantine and the SPS Agreement*. Centre for International Economic Studies and the Department of Agriculture, Fisheries and Forestry – Australia/Biosecurity Australia, Adelaide, pp. 174–182.

Valdes, A. and Zietz, J. (1980). *Agricultural Protection in OECD Countries: Its Cost to Less Developed Countries*, IFPRI Research Report 21. International Food Policy Research Institute, Washington, D.C.

Viljoen, J., McGillivray, M., Orton, T. and Oliver, G. (1997). *The Potential Impact of Fire Blight on the Australian Apple and Pear Industry: A Socio-Economic Study*. Corporate Strategy Consulting, Camberwell.

Vose, D. (2000). *Risk Analysis: A Quantitative Guide*. John Wiley & Sons, Chichester.

Waage, J.K., Fraser, R.W., Mumford, J.D., Cook, D.C. and Wilby, A. (2005). A new agenda for biosecurity. *Horizon Scanning Programme*. Department for Food, Environment and Rural Affairs, London, 198 pp.

WAQIS (1999). *Operations Manual, Western Australian Quarantine and Inspection Service*. Agriculture Western Australia, South Perth.

Wittwer, G., McKirdy, S. and Wilson, R. (2005). Regional economic impacts of a plant disease incursion using a general equilibrium approach, *The Australian Journal of Agricultural and Resource Economics* 49, 75–89.

Worner, S.P. and Gevrey, M. (2006). Modelling global insect pest species assemblages to determine risk of invasion, *Journal of Applied Ecology* 43, 858–867.

Zadocks, J. and Shein, R. (1979). *Epidemiology and Plant Disease Management*. Oxford University Press, Oxford.