The Optimal Time to Remove Quarantine Bans Under Uncertainty: the Case of Australian Bananas*

Anke D. Leroux
School of Economics and Finance, La Trobe University
(a.leroux@latrobe.edu.au)

Donald MacLaren
Department of Economics, University of Melbourne

Abstract

Import restrictions on biological materials are used widely as protection against exotic invasive pests and pathogens. While a scientific risk assessment is needed to justify an import ban under the WTO SPS Agreement, economics plays little role in determining the choice of import regime. Using a real option framework, we model the uncertain and irreversible costs from lifting an import ban and derive decision rules about the optimal timing, when ex ante research and development yields positive but uncertain benefits. The insights gained are applied to Australia's current import policy for bananas.

*The authors thank two anonymous referees for their comments and thank Roberto Raimondo and Vance L. Martin for helpful discussion and suggestions. This paper has also benefited from comments by conference participants at the Annual Conference of the Society for Risk Analysis, Melbourne, 2006 and the 2007 annual conference of the European Association of Environmental and Resource Economics in Thessaloniki. All remaining errors are ours.

1 Introduction

Biological invasions by exotic species[1] can cause significant damage to human health, domestic agricultural production and the natural environment. Australia's default position on quarantine, since the Quarantine Act 1908, has been to ban imports of biological material unless it is shown to be safe to do otherwise. This trade-policy stance continues to create tension with Australia's trade partners in the World Trade Organization (WTO). Members of the WTO are bound by the rules defined by the Agreement on the Application of Sanitary and Phytosanitary Measures (hereafter, the SPS Agreement) which, in general, requires greater flexibility with respect to quarantine policy than an outright import ban (WTO, 1995)[2]. However, economics is allowed to play only a very limited role in defining a Member's quarantine policy (see Article 5:3 for details) and it has been argued in Anderson et al. (2001) and by MacLaren (2001) that this constraint creates a profound weakness in determining a Member's SPS policy.

The trade tensions created by Australia's default position on quarantine policy can be illustrated by the decade-long interaction between the Commonwealth government and the government of the Philippines on bananas. In 2000, after a formal request from the Philippines, an import risk assessment (IRA) was initiated by the Commonwealth and a draft report issued in 2002 (The Senate, 2009). By this time, discussions were taking place on not just bananas but on fruits and vegetables of export interest to the Philippines. When these consultations failed to satisfy the latter government, it made a request in the WTO for the formation of a dispute panel and in 2003 a panel was established with six Members having third-party rights, a reflection of Members' concerns about Australia's quarantine policy (WTO, 2006). However, the panel was never composed and the Australian government instituted a review of import risk assessments for a number of fruits, including bananas. In 2008, a report was published on the findings from the IRA (Biosecurity Australia, 2008).

In summary, the IRA revealed that of the 122 species of pests and diseases that had the potential to cause damage if imported, 21 had an unacceptable level of risk if no risk management protocols were put in place (Biosecurity Australia, 2008, p.16). The probabilities of unrestricted entry, establishment and spread for these 21 ranged from 0.16 to 1.0 (Biosecurity Australia, 2008, Tables 4.1 and 5.4). On the basis of the analysis of probabilities and consequences, the recommendation made in the IRA was to permit imports of bananas from the Philippines, conditional on risk management protocols being put in place in that country for those pests and diseases that did not achieve the acceptable level of protection (ALOP) at unrestricted entry. An advice notice for this

[1] We follow the definition of exotic or invasive species given by Costello and McAusland (2003), but focus specifically on crop pests and pathogens that have been unintentionally moved beyond their natural range or zone of dispersal. We understand an invasion by these organisms to be their entry, establishment and spread in the new country, causing ecological or agricultural damage.

[2] See in particular Articles 2.1, 5.3, 5.6 and Annex A:4 for the rules with respect to defining a Member's WTO-consistent quarantine policy.

risk-mitigation strategy was issued in 2009 (Biosecurity Australia, 2009).

The import risk assessment on which this decision had been made was criticised on a number of grounds by a Senate Committee (The Senate, 2009). Amongst those criticisms, perhaps the most important was the doubt expressed that the risk management protocols that were required to be put in place in the Philippines before exports would be accepted, were judged largely to be impracticable. Therefore, if these risk management protocols do not allow exports to reach Australia's acceptable level of import protection, then Australian growers of bananas will not be exposed to the possible importation of exotic pests and pathogens; and, importantly, Australian consumers of bananas will continue to face higher prices, as well as risk of events similar to that which occurred in 2006.[3]

An alternative approach for Australia would be to put in place a set of import risk management protocols at the border. Within the economics literature on trade and invasive species, the focus has been on determining the usefulness of at-the-border policies. For example, single tariffs or trade volume restrictions are found to be less efficient in reducing the introduction and impact of invasive species (Costello and McAusland, 2003; Costello et al., 2007) than instruments combining tariffs with inspections (McAusland and Costello, 2004) and fines (Merel and Carter, 2008). A number of studies also conclude that the costs of driving invasive species risk to zero using mitigation actions, such as border inspections and treatment, can be prohibitive (Mumford, 2002; Shogren and Tschirhart, 2005).

As a third approach for Australia to manage the risk associated with importing invasive species, a case could be considered for investment, a priori, in bio-economic research and development (R&D) to develop effective adaptation strategies behind-the-border to manage the invasive species externality that accompanies trade. Behind-the-border adaptation strategies are designed to reduce the impact of biological invasions, while taking the probability of entry, establishment and spread of them as a given (Shogren and Tschirhart, 2005; Perrings, 2005). Adaptation measures include early detection systems, biological and chemical control options, as well as accommodative strategies but their development requires time and financial resources, and their duration is subject to uncertainty (Saphores and Shogren, 2005).

In this paper we investigate the trade-off between delaying the lifting of an import ban in order to conduct bio-economic research into the development of invasive species control measures behind the border, and the benefits from engaging in freer trade immediately. The optimal trade policy decision is modelled as an optimal stopping problem in continuous time.[4] We allow explicitly for the irreversibility of R&D expenditure on behind-the-border adaptive measures; for the irreversibility of invasion damage; for the uncertainty about the effectiveness

[3] In 2006, a cyclone reduced production by 90 per cent (Australian Banana Growers Council, 2006) and caused the retail price to increase by a factor of approximately five.

[4] This type of methodology is also adopted in Saphores and Shogren (2005), where the optimal timing decision relates to the application of a control measure to minimize the damage from an already present invasive species population.

of R&D expenditure on adaptation; and for the uncertainty about the timing of invasion by exotic pests and pathogens. However, we make no attempt to model the institutional arrangements that would be necessary to generate the scientific knowledge upon which practical adaptation strategies could be designed, while acknowledging that, in practice, these arrangements would be crucial to the discovery and implementation of successful adaptation strategies.

A technical departure in our paper is the invasion probability being modelled as a Poisson jump process in addition to the output from R&D following a geometric Brownian motion. The next section presents the development of a stochastic model of an import regime with exotic species invasion. We derive simple decision rules that govern the optimal timing of lifting the import ban as a function of invasion risk and damage, R&D investment and R&D uncertainty. In Section 3, the model is applied to the case of Australian banana imports. The numerical results obtained highlight the importance of accounting for uncertainty and irreversibility when developing economic decision rules to determine optimal quarantine policies. Section 4 concludes.

2 A Real Options Model of Import Regime

The problem of pursuing the optimal quarantine policy in the next instant is modelled as a real options problem in continuous time. In this framework, the welfare consequences of a freer trade policy are evaluated specifically against the risks and costs associated with importing exotic invasive pests and pathogens. It is assumed that the importing country is free of these commodity-specific pests and pathogens as long as a trade ban is maintained. The benefit of delaying the removal of import restrictions is linked to learning about the bio-economic parameters of these invasive organisms and to the development of an adaptation strategy, such as an efficient control measure, which is designed to minimize invasion damage.[5]

2.1 Objective Function

Let $F(u, C(t,u))$ be the total discounted welfare from the production and consumption of an agricultural product in a single country. It is a function of the prevailing trade regime, u, and the total costs associated with exotic species, $C(t,u)$. The decision to lift the import ban in the next instant is based on maximising the present value of the total net benefits

$$F\left(C\left(t,u\right)\right) = \max_{u} \int_{0}^{\infty} e^{-\rho dt} \left[\left(1+u\nu\right)N + \left(1-u\pi\right)P - C\left(t,u\right)\right] dt, \qquad (1)$$

where u is a continuous control variable,

$$u = \left[0,1\right]. \qquad (2)$$

[5] Such delays are permitted under Article 5:7 of the SPS Agreement.

A value of $u = 0$ represents the status quo of a complete and unconditional import ban, whereas $u = 1$ implies free trade and $0 < u < 1$ is some intermediate trade policy where imports are subject to specific regulations. The parameter $\rho > 0$ in equation (1) is the real rate of discount and N and P are the consumer and producer surpluses respectively. Lower domestic prices following the removal of the trade ban $(u > 0)$, benefit consumers by $0 \leq \nu$ and hurt producers by $0 \leq \pi \leq 1$. The total cost associated with exotic crop pests and pathogens, $C(t, u)$, varies with time (t) and the adopted trade regime (u).

It is assumed that the importing country conducts research into the development of an effective adaptation strategy while the import ban is in place. With a progressively open trade policy, expenditure on research and development is increasingly redirected towards another type of defensive expenditure, namely the implementation of adaptation actions, such as monitoring for signs of domestic outbreak and the application of control measures. As adaptive actions affect the extent but not the probability of biological invasions, the total cost $C(t, u)$, is the sum of two components,

$$C(t, u) = \phi\Omega(t, u) + \Omega(t, u), \tag{3}$$

where $\phi\Omega(t, u)$ is defensive expenditure, with ϕ being an exogenously determined proportion of invasion damage $\Omega(t, u)$.[6] Invasion damage is a stochastic dynamic variable, which depends on the adopted quarantine policy and defensive expenditure. Invasions can only occur, in the absence of invasions caused by travellers, with some degree of open trade and potential invasion damage decreases the more time and financial resources are dedicated to R&D. Over time, invasion damage, $\Omega(t, u)$, is assumed to follow the mixed geometric Brownian and Poisson process

$$\frac{d\Omega}{\Omega} = -(1-u)\,\alpha\phi dt + (1-u)^{1/2}\,\phi^{-1/2}\sigma dz + u\phi^{-1}dq, \tag{4}$$

where the mean, $-(1-u)\,\alpha\phi dt$, models the success from conducting R&D in terms of decreasing invasion damage at rate $\alpha\phi$, where $0 < \alpha < 1$, due to the development of effective adaptation measures. A relatively larger research and development budget, represented by a larger proportion ϕ, accelerates this process.[7] Uncertainty surrounding the success of R&D is assumed to be decreasing in ϕ, with ϕ reducing the variance of the expected invasion damage

$$var(d\Omega) = (1-u)\,\phi^{-1}\sigma^2,$$

and hence the standard deviation, $(1-u)^{1/2}\,\phi^{-1/2}\sigma$, in (4), where $\{z(t)\}_{t=0}^{\infty}$ is a standardized Wiener process such that $dz \sim N(0, dt)$. The variance parameter σ^2 is exogenous. The last term in equation (4) models the damage from random invasion events as a decreasing function in proportion to R&D expenditure, ϕ.

[6] In this model optimization occurs with respect to the quarantine policy adopted, where the expenditure on R&D is a fixed proportion of invasion damage. For an analysis of optimal expenditure on bioeconomic research see Saphores and Shogren (2005).

[7] We assume that the results of R&D are successfully implemented.

Invasion events follow the Poisson process dq in (4), which is normally and independently distributed of dz,

$$\begin{aligned} dq &= 0 \text{ with probability } 1-\lambda dt, \\ dq &= 1 \text{ with probability } \lambda dt, \end{aligned} \tag{5}$$

where λ is the joint probability of entry, establishment and spread (PEES) over the time interval dt. This probability λ is constant over time as it is not affected by behind-the-border adaptation measures and is assumed to be independent of previous introductions.[8] By definition, invasions by commodity-specific exotic pests and pathogens cause damage $\Omega(t,u)$ and can only occur where there is some degree of open trade $(u > 0)$.

Given (3) and (4), the stochastic differential equation for the total annual cost associated with invasive species, $C(t,u)$ is

$$\frac{dC}{C} = -(1-u)\,\alpha\phi dt + (1-u)^{1/2}\,\phi^{-1/2}\sigma dz + u\phi^{-1}dq. \tag{6}$$

The chosen trade policy, u, affects C in several ways. Under the current no-trade regime $(u = 0)$, the only costs are from bioeconomic research into the development of an efficient adaptation strategy to control known exotic pest or pathogens that could become established after trade bans are lifted. Equation (6) under a trade ban is thus

$$\frac{dC}{C}\,|_{u=0} = -\alpha\phi dt + \phi^{-1/2}\sigma dz.$$

At the other extreme case of free trade $(u = 1)$, expenditure on invasive species research is re-directed towards the implementation of the adaptation strategy that was developed while $u = 0$. The intuition is that unregulated free trade in a specific agricultural commodity requires confidence within the home country that potential outbreaks of exotic pests and pathogens, while still damaging, will be met by efficient strategic responses and adequate control options. Hence, under free trade, $C(t,u)$ is constant until the next random introduction and establishment of a new exotic pest and pathogen causes it to jump upwards. The extent of the jump is the damage from exotic species invasions, which is a function of resources that were allocated to R&D expenditure before trade bans were lifted.

$$\frac{dC}{C}\,|_{u=1} = \phi^{-1}dq.$$

In the intermediate case of restricted trade $(0 < u < 1)$, R&D is conducted while exotic species invasions are also experienced and hence dC follows (6).

[8] Assuming time constant probabilities aids the tractability of this model, where the emphasis is on new trade flows. In an analysis of long established trade flows Costello et al. (2007) relax this assumption and find marginal invasion risk by new exotic species to be decreasing in the duration and intensity of the trade flow.

This case describes a preferential trade policy, whereby only imports from high risk countries are banned. For the purpose of this paper, an exporting country is considered high risk, if the importing country has no adequate adaptation strategy in place to deal with the pests and pathogens that originate from that exporting country. On the other hand, imports from countries that are associated with less damaging pests and pathogens may proceed unregulated. Such discrimination is permitted by Article 6 of the SPS Agreement. As a result, the scope of R&D in the intermediate case $(0 < u < 1)$ is reduced to include only those exotic pests and pathogens that are associated with high risk exporting countries.

2.2 The Optimal Timing of Removing Quarantine Restrictions

Finding the optimal quarantine strategy involves maximising the objective function (1) with respect to the control variable u. As the objective function (1) and the constraints are not explicit functions of time, the problem is autonomous. In addition, given that the objective function has an infinite time horizon, the optimal solution is based on rewriting (1) as[9]

$$\rho F\left(C\left(u\right)\right) = \max_{u} \left\{ \left(1 + u\nu\right) N + \left(1 - u\pi\right) P - C\left(u\right) + \frac{1}{dt} E_t\left[dF\right] \right\}. \tag{7}$$

The conditional expectation, $\frac{1}{dt}E_t\left[dF\right]$ in equation (7) is found using[10]

$$E_t\left[dF\right] = \lambda dt E_t^j\left[dF\right] + \left(1 - \lambda dt\right) E_t^{nj}\left[dF\right] + o\left(dt\right), \tag{8}$$

where E_t^j denotes the expectation at time t conditioned on the occurrence of the Poisson event and E_t^{nj} denotes the expectation conditioned on the Poisson event not occurring. The term $o\left(dt\right)$ collects higher order terms in dt. Expression (8) may be simplified to

$$E_t\left[dF\right] = E_t^{nj}\left[dF\right] + \lambda dt \left(E_t^j\left[dF\right] - E_t^{nj}\left[dF\right]\right) + o\left(dt\right), \tag{9}$$

where Ito's Lemma is used to derive

$$\begin{aligned} E_t^{nj}\left[dF\right] &= \frac{\partial F}{\partial C} E_t^{nj}\left(dC\right) + \frac{1}{2}\frac{\partial^2 F}{\partial C^2} E_t^{nj}\left(dC\right)^2 \\ &= \left(-\left(1-u\right)\alpha\phi C F_C + \frac{1}{2}\left(1-u\right)\phi^{-1}\sigma^2 C^2 F_{CC}\right) dt. \end{aligned} \tag{10}$$

Expression (10) is based on $E\left[dz\right] = 0$ and on the higher order terms in dt approaching zero as dt approaches zero. Similarly, (10) implies for (9) that $E_t^{nj}\left[dF\right]$ in the second term may be disregarded due to the higher order in dt.

[9] The notation (t) on time dependent variables is henceforth omitted to aid with the exposition of the model.

[10] See pp.121-124 in Malliaris and Brock (1982) for a more detailed exposition of the generalized Ito formula for jump processes.

The expected change in the value function conditional on the Poisson event occurring $E_t^j[dF]$, is

$$\lambda dt E_t^j[dF] = \lambda dt\left[F\left(C + u^*\phi^{-1}C\right) - F(C)\right], \tag{11}$$

since the higher order in dt implies that the terms $-(1-u)\alpha\phi C dt$ and $(1-u)^{1/2}\phi^{-1/2}\sigma C dz(t)$ may also be disregarded. The dynamic programming approach defines F as the optimal solution with respect to u, hence the control variable in equation (11) is the optimal trade policy, denoted u^*. Substituting (10) and (11) into (8) yields

$$\begin{aligned} E_t[dF] &= \left(-(1-u)\alpha\phi C F_C + \frac{1}{2}(1-u)\phi^{-1}\sigma^2 C^2 F_{CC}\right)dt \\ &\quad + \lambda dt\left[F\left(C + u^*\phi^{-1}C\right) - F(C)\right] \end{aligned}$$

and substitution into (7) yields

$$\begin{aligned} \rho F &= \max_u \Big\{(1+u\nu)N + (1-u\pi)P - C - (1-u)\alpha\phi C F_C \\ &\quad + \frac{1}{2}(1-u)\phi^{-1}\sigma^2 C^2 F_{CC} + \lambda\left[F\left(C + u^*\phi^{-1}C\right) - F(C)\right]\Big\} \end{aligned} \tag{12}$$

The value function F is obtained as the solution to the following second-order differential equation

$$\begin{aligned} \rho F &= (1+u^*\nu)N + (1-u^*\pi)P - C - (1-u^*)\alpha\phi C F_C \\ &\quad + \frac{1}{2}(1-u^*)\phi^{-1}\sigma^2 C^2 F_{CC} + \lambda\left[F\left(C + u^*\phi^{-1}C\right) - F(C)\right], \end{aligned} \tag{13}$$

where u^* is the solution to the maximisation problem in (7).

Equation (13) is linear in the control variable u, which implies that the solution is bang-bang, whereby the two possibilities for the optimal value of u are

$$u^* = \begin{cases} 0 & : \quad \text{no trade} \\ \\ 1 & : \quad \text{free trade.} \end{cases} \tag{14}$$

Hence equation (13) may be solved separately for the cases of no trade and free trade. To distinguish between the two solutions, let the value function corresponding to $u^* = 0$ be denoted F and the value function corresponding to $u^* = 1$ be denoted f. Comparison of $F(C)$ and $f(C)$ determines if maintaining import restrictions or lifting all restrictions immediately yields the greater net benefit.

The problem is further specified by the following boundary conditions

$$F(\infty) = 0, \tag{15}$$

$$F = f, \tag{16}$$

$$F_C = f_C. \tag{17}$$

Condition (15) states that in the limit, where costs associated with exotic pests and pathogens are infinite, the benefit from changing trade policies in the future is zero. The value matching condition (16) says that the switch from no trade to free trade is optimal when the net present value of expected benefits arising from no trade is exactly equal to those arising from free trade. A third, smooth-pasting condition (17), imposes further structure on the model, requiring first-order continuity with respect to the state variable C.

Finding the solution to F involves setting $u^* = 0$ in (13), which yields the ordinary differential equation (ode)

$$\rho F = N + P - C - \alpha\phi C F_C + \frac{1}{2}\phi^{-1}\sigma^2 C^2 F_{CC}, \tag{18}$$

with the general solution

$$F = A_1 C^{\beta_1} + A_2 C^{\beta_2}, \tag{19}$$

where A_1 and A_2 are unknown constants of integration. The constants β_1 and β_2 are respectively the positive and negative square roots of the fundamental quadratic, which is obtained by substituting the general solution and its partial derivatives

$$\begin{aligned} F_C &= \beta A C^{\beta-1}, \\ F_{CC} &= \beta(\beta-1) A C^{\beta-2}, \end{aligned}$$

into (18). The fundamental quadratic is

$$0 = -\rho - \alpha\phi\beta + \frac{1}{2}\phi^{-1}\sigma^2\beta(\beta-1),$$

which yields the expressions for β_1 and β_2

$$\begin{aligned} \beta_1 &= \frac{1}{2} + \frac{\alpha\phi^2}{\sigma^2} + \sqrt{\frac{2\phi\rho}{\sigma^2} + \left(\frac{\alpha\phi^2}{\sigma^2} + \frac{1}{2}\right)^2}, \\ \beta_2 &= \frac{1}{2} + \frac{\alpha\phi^2}{\sigma^2} - \sqrt{\frac{2\phi\rho}{\sigma^2} + \left(\frac{\alpha\phi^2}{\sigma^2} + \frac{1}{2}\right)^2}. \end{aligned}$$

Boundary condition (15) requires $\lim_{C\to\infty} F = 0$. With $\beta_1 > 0$, boundary condition (15) is only satisfied if $A_1 = 0$. Combining the homogeneous solution with the particular solution to (18) yields the total net present value of maintaining the current no-trade policy

$$F = AC^{\beta} + \frac{N+P}{\rho} - \frac{C}{\rho + \alpha\phi}, \tag{20}$$

where $AC^{\beta} = A_2 C^{\beta_2}$. The first term in equation (20) describes the benefits from restricting trade in terms of having time to develop an effective adaptive strategic response to invasion. The second term is the discounted level of consumer and producer surplus, and the third term is the discounted total cost.

The net present value of lifting the trade ban is obtained by substituting $u^* = 1$ in (13), which yields

$$\rho f = (1+\nu) N + (1-\pi) P - C + \lambda \left[f \left(C + \phi^{-1} C \right) - f(C) \right]. \tag{21}$$

Substituting the linear equation of the general form

$$f = aC + b \tag{22}$$

into (21) and simplifying yields expressions for the intercept

$$b = \frac{(1+\nu) N + (1-\pi) P}{\rho}, \tag{23}$$

and the slope coefficient

$$a = \left(\frac{\lambda}{\phi} - \rho \right)^{-1}, \tag{24}$$

which is the effective discount factor of the stochastic variable C. The solution of (21) is

$$f = \left(\frac{\lambda}{\phi} - \rho \right)^{-1} C + \frac{(1+\nu) N + (1-\pi) P}{\rho}. \tag{25}$$

Note that for (25) to be a decreasing function in C the term $\left(\frac{\lambda}{\phi} - \rho \right)^{-1} < 0$, which is the case when the probability of entry, establishment and spread is less than $\rho\phi$[11]

$$\lambda < \rho\phi. \tag{26}$$

The smooth-pasting condition (17) is used to solve for AC^{β} in (20), where

$$AC^{\beta} = \frac{1}{\beta} \left(\frac{1}{\rho + \alpha\phi} + \frac{\phi}{\lambda - \rho\phi} \right) C, \tag{27}$$

which, upon substitution into (20) yields

$$F = \frac{1}{\beta} \left(\frac{1}{\rho + \alpha\phi} + \frac{\phi}{\lambda - \rho\phi} \right) C + \frac{N+P}{\rho} - \frac{C}{\rho + \alpha\phi}, \tag{28}$$

which is now linear in C. Using the value matching condition (16) and substituting (28) for F and (25) for f in (16) gives

$$\frac{1}{\beta} \left(\frac{1}{\rho + \alpha\phi} + \frac{\phi}{\lambda - \rho\phi} \right) C + \frac{N+P}{\rho} - \frac{C}{\rho + \alpha\phi} = \frac{\phi}{\lambda - \rho\phi} C + \frac{(1+\nu) N + (1-\pi) P}{\rho},$$

[11] The value $a < 0$ in (22) implies that the cost function is increasing as marginal costs are positive.

which yields the expression for $C(T)$, the level of C where lifting the import ban is optimal

$$C\left(T\right)=\left(\frac{\beta}{\beta-1}\right)\frac{\left(\rho+\alpha\phi\right)\left(\rho\phi-\lambda\right)}{\lambda+\alpha\phi^{2}}\left(\frac{\nu N-\pi P}{\rho}\right). \tag{29}$$

$C\left(T\right)$ is the total cost associated with invasive species at the time when trade restrictions are lifted. With $\beta<0$ and $\nu N>\pi P$, the solution (29) also contains the parameter restriction from (26) of $\lambda<\rho\phi$. This restriction must be satisfied for $C\left(T\right)>0$. If (26) does not hold, then $C\left(T\right)<0$, which implies that import bans should be lifted immediately. The same conclusion results for $\lambda<\rho\phi$ and $F\left(C\left(0\right)\right)<f\left(C\left(0\right)\right)$, where $C\left(0\right)=\phi\Omega\left(0\right)$. In this case, the net present value from immediate free trade, $f\left(C\left(0\right)\right)$, outweighs the net present value from maintaining the import ban, $F\left(C\left(0\right)\right)$. The time it will take until lifting the import ban becomes optimal is impossible to predict with certainty due to the variance around R&D output. However, an expected time period may be derived from equation (6) as

$$T=-\frac{1}{\rho+\alpha\phi}\ln\left(\frac{C\left(T\right)}{C\left(0\right)}\right), \tag{30}$$

where $C\left(T\right)$ is given by (29). As long as $C\left(0\right)>C\left(T\right)$, the benefits from waiting and developing a more effective adaptation strategy while protecting the economy from the risk of costly biological invasions outweigh the benefits from lower prices of allowing import immediately. As a result, $T>0$ is the expected mean number of years it will take to develop an adaptation strategy capable of reducing the invasion impact to the optimal level, $\Omega\left(T\right)$.

3 Application to Australian Trade Policy Concerning Bananas

The stochastic model of the optimal timing of quarantine decisions developed in Section 2 is now applied to Australian import policy for bananas, as described in Section 1.

3.1 Background

James and Anderson (1998) were amongst the first to demonstrate the potential value of economics in quarantine decisions using the Australian banana market as a case study. In their study a static, partial equilibrium model is used to compare three situations with respect to imports, namely, an outright ban, a cost-free import risk management regime at the border, and unrestricted free trade. When the authors allow imports of bananas together with their associated exotic pests and diseases, the optimal policy is ambiguous a priori because of the unknown size of the shift in the domestic supply function caused by invasion damage. Using data on domestic prices (for 1996) measured at three levels in the supply chain (farm-gate, wholesale and retail) they conclude (with appropriate caveats) that the losses to Australian banana producers are more than outweighed by the gains to consumers. The latter could compensate the former and still leave the country better off than with the import ban, even if the industry were wiped out as a result of exotic species invasions.

Javelosa and Schmitz (2006) repeat the analysis of James and Anderson (1998) using data for the year 2003 and they also extend that study by calculating the welfare effects for the Philippines of a change in Australia's import regime. They too conclude from their static and deterministic analysis that, even if exotic pests and diseases were to wipe out the Australian banana industry, the country would still be better off by allowing the free importation of bananas than by continuing with the long-run practice of banning imports.

3.1.1 A Dynamic Stochastic Analysis

We now re-assess these conclusions by applying the dynamic stochastic model developed in Section 2. We therefore explicitly allow for: (i) the stochastic occurrence of invasion events under free trade; (ii) the irreversible environmental consequences of free trade; (iii) the economic benefits that arise from conducting research into the development of behind-the-border adaptive management strategies for invasive species during the period of time for which imports are banned; and (iv) the uncertainty surrounding the effectiveness of the adaptation strategies. The analysis is based initially on the parameter values shown in Table 1, where the static welfare effects were derived from estimates in Javelosa and Schmitz (2006).

The data on prices and quantities for 2003 given in Javelosa and Schmitz (2006, Table 1), together with their assumed values of the price elasticities of demand and supply (-0.5 and 1.0, respectively), allow us to calculate the parameters of the domestic demand and supply functions and the levels of consumer and producer surplus under both the import ban and under free trade. Assuming an own-price elasticity of demand of -0.5 for the base case seems reasonable (Clements, 2008) and an own-price elasticity of supply of 1.0 is consistent with the range of values estimated by Abdallah and Sheales (2005). Lifting all import restrictions on bananas is expected to benefit consumers by an estimated \$175m annually, resulting in a free trade consumer surplus of \$760m (Table 1). Producer surplus is estimated to fall by \$66m from \$135m. The resulting net gain in social welfare is \$109m, which exceeds the remaining producer surplus were the industry to be wiped out through the invasion of exotics, implying a welfare gain even if this extreme event should occur. However, this conclusion ignores the costs and benefits of developing an adaptation strategy.

Insert Table 1 about here.

The calculation of the costs of the adaptation strategy requires estimates of the parameters $\Omega(0)$, λ, ϕ, α, σ and ρ. The bio-economic parameters used in the base case were derived from the final import risk analysis report (Biosecurity Australia, 2008). Of the 122 pest species considered, 21 were characterised by unrestricted probabilities of entry, establishment and spread of between 0.16

and 1, which, combined with the potential expected consequences of invasion, exceeded ALOP and resulted in the notice given to the Philippines (Biosecurity Australia, 2009).

Given that the final IRA provided most information on the black Sigatoka fungus, we used the bio-economic characteristics of this pathogen as the basis for our analysis. The consequences of infection by black Sigatoka fungus were characterised as moderate, which requires for the restricted probability of entry, establishment and spread to be less than 0.05 to achieve ALOP (Biosecurity Australia, 2008, see Part A, Tables 4.1 and 5.4). The base case parameter value adopted in our analysis for PEES is $\lambda = 0.01$ or one invasion event in 100 years on average.[12] The parameter value for invasion damage if no prior R&D has been conducted is $\Omega(0) = 52$ or approximately 75% of free trade producer surplus. This figure is derived under the assumption that domestic banana producers experience yield losses of 38% as a result of infection (Biosecurity Australia, 2008, see Part B, p147), which translates into a loss of free-trade producer surplus of \$43m. In addition to production losses, it is further assumed that producers will bear 1/3 of the on-going control costs[13] from increased fungicide spraying and the public 2/3 of the costs, which yields a proportional defensive expenditure of $\phi = 0.33$ of total invasion damage, $\Omega(0)$.

The R&D process under base case assumptions is characterised by an expected return per dollar allocated to R&D of $\alpha = 0.15$ with an expected standard deviation of $\sigma = 0.1$. The value to choose for the risk-free, real social discount rate is one of unresolved debate (Stiglitz, 1988, see chapter 10 for a discussion). In particular, he argues that it is incorrect to increase the risk-free rate in the evaluation of risky projects. Harrison (2007) has proposed values for the risk-free rate in the range of 3–4 per cent, although he then proposes that an additional 3–4 percentage points should be added as a risk premium. Because our analysis explicitly models risk, we use the risk-free social discount rate (ρ) and choose a value for it of 4 per cent. The choice of these parameters satisfies the constraint imposed by equation (26) and provides conditions under which investment in R&D may be justified on the basis of economics.

The net social welfare gains from autarky and free trade under base case assumptions are reported in the third-last and second-last rows of Table 1 as \$19.2bn and \$18.9bn respectively. Making use of equations (29) and (30), the optimal time over which to conduct R&D, in the absence of free trade is 5.5 years (see Table 1, last line). This outcome differs from the conclusion of "free trade immediately" (as in James and Anderson (1998) and Javelosa and Schmitz (2006)), which is obtained when the analysis ignores the discounted and uncertain costs and benefits of developing a successful adaptation strategy behind the border.

[12] The probability $\lambda = 0.01$ corresponds to the PEES that results from a combination of designating areas of low pest prevalence and trash minimisation (Biosecurity Australia, 2008, see Part B, Tables 10.2 and 10.21).

[13] The total on-going control costs were estimated at \$36m for the autarky-size domestic industry (Biosecurity Australia, 2008, see Part B, p147). Evaluated for the free-trade case, this figure is proportionately less, \$26m, of which 1/3 is equal to approximately \$9m.

3.2 Sensitivity Analysis

The robustness of the case for delayed free trade is tested against variations in the values of base case parameters. The parameters that are varied are the price elasticities of supply and demand, the probability of entry, establishment and spread of an invasive pest or pathogen (λ), the damage from invasion ($\Omega(0)$), the proportional defensive expenditure (ϕ) and rate of discount (ρ), and the mean rate of reduction in invasion damage (α) and its standard deviation (σ).

3.2.1 Demand and Supply Elasticities

The importation of different varieties of Asian bananas could make the own-price elasticity of demand for Australian bananas more elastic. Table 2 shows the simulation results for a more elastic consumer demand, using an own-price elasticity of demand assumption of -0.75. This value is more elastic than the value of -0.6 chosen by Abdallah and Sheales (2005). For reference, the base case assumption of -0.5 is also reported. Similarly, the sensitivity of the base case result is tested with respect to the elasticity of supply by assuming a greater supply elasticity of 1.25, which was calculated by Abdallah and Sheales (2005). The analysis reveals greater sensitivity of the case for delayed free trade with respect to the supply elasticity assumptions than assumptions regarding the own-price elasticity of demand. While both the supply elasticity of 1.25 and the own-price elasticity of -0.75 reduce the optimal time in which to invest in R&D, only the combination of both leads to the conclusion that import bans should be lifted immediately without conducting R&D prior to permitting free trade.

Insert Table 2 about here

3.2.2 Real Social Discount Rate, PEES, and Invasion Damage

The relationship between the real rate of discount, ρ, the probability of entry, establishment and spread, λ, and the expected damage from an invasion event at time zero is complex and non-linear. Figures 1a-d show that for each rate of discount, there exists a range in $\lambda - \Omega(0)-$ space (plotted along the diagonal axes), for which delaying the importation of bananas in favour of conducting R&D is optimal. The optimal time of conducting R&D (plotted on the vertical axis) is represented by the fin-shaped forms for $\rho = 0.01$ (Figure 1a), for the base case $\rho = 0.04$ in Figure 1b, for $\rho = 0.07$ (Figure 1c), and for $\rho = 0.10$ (Figure 1d). The fin shifts towards higher PEES and becomes wider as the discount rate increases. This implies that the type of invasion threat that is targeted for R&D depends on the discount rate applied and that R&D is optimal for wider range of invasion threats when discount rates are high (Figure 1d). For each discount rate there is an upper threshold for PEES, beyond which the immediate lifting of import bans is optimal. The position of this threshold is determined exogenously by the parameter values of ρ and ϕ according to (26). Increasing ϕ for a given ρ increases the threshold for PEES and the range of invasion risks for which delays in free trade in favour of R&D are optimal.

Insert Figures 1a-d about here.

This point is further illustrated in Table 3, which reports the values for T for three cross-sections along the $\Omega-$ axis in Figure 1b at $\Omega(0) = 35$ (i.e. 50% damage), $\Omega(0) = 52$ (75% damage), and $\Omega(0) = 69$ (100% damage), whereby ϕ is adjusted to maintain the same margin greater than $\frac{\lambda}{\rho}$ as in the base case scenario thereby ensuring that restriction (26) is always satisfied. For example, an upward adjustment of the expected frequency of invasion events from one to three in one hundred years implies that a comparable annual defensive expenditure of 0.33 for the base case is $\phi = 0.99$. Table 3 shows that the probability and the extent of invasion damage has a significant impact on the optimal timing of free trade. Low invasion probabilities of up to five occurrences per one thousand years should result in an immediate lift of import bans. More frequent expected invasions, lead to increased periods of R&D of up to 13.2 years, provided the government is willing to invest sufficiently in invasive species research and development. These simulation results suggest that maintaining the current import ban in the short and medium run may be optimal in some cases in order to protect and prepare against invasions by exotic pests and pathogens with expected arrival probabilities of at least once in 100 years.

Insert Table 3 about here.

The simulation results reported in Table 3 suggest that defensive expenditure on invasive species research and management is important in determining the timing of free trade. This finding is further explored in Table 4, which reports optimal delays to free trade for variations in defensive expenditure ϕ as a proportion of invasion damage Ω. It is shown that the base case result of free trade being optimal after 5.5 years of R&D is very sensitive to the amount of defensive expenditure allocated to invasive species research and management. For the base case arrival probability of an invasion event of $\lambda = 0.01$ and the base case discount rate of $\rho = 0.04$, $\phi > 0.25$ if rule (26) is to hold. A minimum investment in R&D of $\phi = 0.251$ leads to extremely long waiting times before trade bans should optimally be lifted. However, increasing defensive expenditure by an additional eight percentage points reduces the optimal time to lift import bans significantly from 56.7 years to 5.5 years. Indeed if invasive species management budgets are sizeable relative to expected damages, it may be optimal to engage in free trade immediately.

Insert Table 4 about here.

3.2.3 Mean rate of reduction in damage and its standard deviation

Table 5 shows that the effect of the expected progress in R&D (α) on T is ambiguous, with the level of uncertainty about R&D success (σ) playing an important role.[14] With little uncertainty ($\sigma = 0.05$) and slow expected R&D progress ($\alpha = 0.01$), the benefit of delaying free trade is zero ($T = 0.0$). This benefit increases with uncertainty and R&D progress, hence T increases from 0 to 11.5 years for increases in σ from 0.05 to 0.2 and from 0 to 5.3 years for

[14] The nonlinear relationship between the moments of geometric Brownian motion and optimal decision thresholds has also been documented by Majd and Pindyck (1985).

increases in α from 0.01 to 0.25. The benefit of faster expected R&D progress in terms of reducing the optimal delay of free trade becomes more apparent in more uncertain environments, hence the reduction in T from 11.5 to 8.9 years in the last column of Table 5.

Insert Table 5 about here.

4 Conclusions

The threat of economic damage from biological invasions of pests and pathogens may be significant and it justifies the careful determination of the optimal trade policy to be adopted. While static economic net welfare benefit analyses support decisions in favour of unrestricted free trade in the presence of high-risk imports of agricultural commodities, scientific import risk assessments, mostly devoid of economics, do not.

The development of an effective behind-the-border-adaptation strategy takes time and is costly. In order to determine the optimal timing of when trade bans should be lifted in the face of invasion uncertainty and R&D uncertainty, a stochastic continuous-time model of optimal quarantine decisions was developed. In particular, the time dynamic characteristics of the costs associated with managing the invasion risk and its consequences were modelled as a combined Brownian motion and Poisson jump process.

Application to the case of banana imports into Australia showed that even when net economic welfare gains are to be realised from lifting import bans, it may still be suboptimal to do so immediately when a longer time horizon is considered. Where the benefits from investing time and money in learning about the specific risks and their effective management and control before lifting the import ban outweigh the opportunity cost of temporarily foregoing the welfare gains from free trade, the optimal strategy is to delay allowing free trade. Under the assumptions for Australia, used in Table 1, the optimal delay to free trade in bananas is 5.5 years from the time research into banana specific exotic pests and pathogens and the development of effective adaptive strategies commence. The expected optimal length of the delay is determined largely by the expected damage from invasion, the probability of an invasion occurring and the relative size of the defensive expenditure the government is willing to allocate to exotic pest and pathogen management. Larger expected damage, higher invasion probabilities and lower defensive expenditure all increase the expected delay to free trade. Moreover, the model suggests (Figure 1) that a threshold for high, unrestricted probabilities of entry, establishment and spread exists, which implies that the import risk is to too great to be cost-effectively reduced by behind-the-border adaptation measures. If this threshold is exceeded, the net social welfare maximising trade policy is immediate free trade.

References

Abdallah, A. and Sheales, T. (2005), Approximating supply response of a commodity with limited input data, *in* '49th Annual Conference of the Australian Agricultural and Resource Economics Society', Coffs Harbour, NSW.

Anderson, K., McRae, C. and Wilson, D., eds (2001), *The Economics of Quarantine and the SPS Agreement*, Centre for International Economic Sudies, AFFA Biosecurity Australia, Adelaide and Canberra.

Australian Banana Growers Council (2006), 'Cyclone Larry', http://www.abgc.org.au/pages/media/cyclonelarry.asp.

Biosecurity Australia (2008), 'Final import risk analysis report for the importation of Cavendish bananas from the Philippines, Part A'.

Biosecurity Australia (2009), 'Biosecurity policy determination - importation of bananas from the Philippines'.

Clements, K. W. (2008), 'Price elasticities of demand are minus one-half', *Economics Letters* **99**, 490–93.

Costello, C. and McAusland, C. (2003), 'Protectionism, trade, and measures of damage from exotic species introductions', *American Journal of Agricultural Economics* **85**(4), 964–975.

Costello, C., Springborn, M., McAusland, C. and Solow, A. (2007), 'Unintended biological invasions: Does risk vary by trading partner?', *Journal of Environmental Economics and Management* **54**(3), 262–276.

Harrison, M. (2007), Valuing the future: Choosing the discount rate in cost-benefit analysis, *in* 'OBPR Cost Benefit Analysis Conference'.

James, S. and Anderson, K. (1998), 'On the need for more economic assessment of quarantine/SPS policies', *Australian Journal of Agricultural and Resource Economics* **42**, 425–444.

Javelosa, J. and Schmitz, A. (2006), 'Costs and benefits of a WTO dispute: Philippine bananas and the Australian market', *The Estey Centre Journal for International Law and Trade Policy* **7**(1), 58–83.

MacLaren, D. (2001), Risk and protection for grains: analysis and quarantine, *in* D. Robertson and A. Kellow, eds, 'Globalization and the Environment: Risk Assessment and the WTO', Edward Elgar, Cheltenham, UK and Northampton, UK.

Majd, S. and Pindyck, R. S. (1985), 'Time to build, option value, and investment decisions', *NBER Working Paper* **1654**.

Malliaris, A. and Brock, W. (1982), *Stochastic Methods in Economics and Finance*, Vol. 17 of *Advanced Textbooks in Economics*, Elsevier Science B.V., Amsterdam.

McAusland, C. and Costello, C. (2004), 'Avoiding invasives: trade-related policies for controlling unintentional exotic species introductions', *Journal of Environmental Economics and Management* **48**(2), 954–977.

Merel, P. R. and Carter, C. A. (2008), 'A second look at managing import risk from invasive species', *Journal of Environmental Economics and Management* **56**(3), 286–290. doi: DOI: 10.1016/j.jeem.2008.02.002.

Mumford, J. (2002), 'Economic issues related to quarantine in international trade', *European Review of Agricultural Economics* **29**(3), 329–348.

Perrings, C. (2005), 'Mitigation and adaptation strategies for the control of biological invasions', *Ecological Economics* **52**(3), 315–325.

Saphores, J.-D. M. and Shogren, J. F. (2005), 'Managing exotic pests under uncertainty: optimal control actions and bioeconomic investigations', *Ecological Economics* **52**(3), 327–339.

Shogren, J. F. and Tschirhart, J. (2005), 'Integrating ecology and economics to address bioinvasions', *Ecological Economics* **52**(3), 267–271.

Stiglitz, J. E. (1988), *Economics of the Public Sector*, 2nd ed edn, W. W. Norton Company, New York.

The Senate (2009), 'Import risk analysis (ira) for the importation of Cavendish bananas from the Philippines'.

WTO (1995), *The Results of the Uruguay Round of Multilateral Trade Negotiations: The Legal Texts*, World Trade Organization.

WTO (2006), *Dispute Settlement: Dispute DS270, Australia - Certain Measures Affecting the Importation of Fresh Fruit and Vegetables*, World Trade Organization.

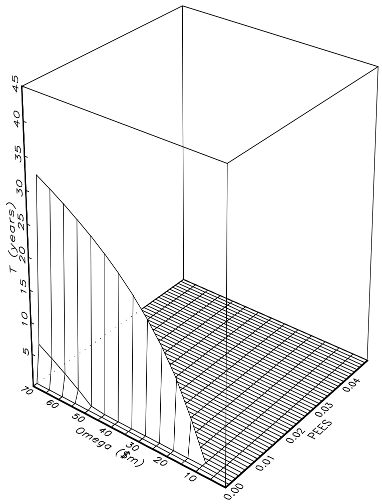

Figure 1a: $\rho = 0.01$

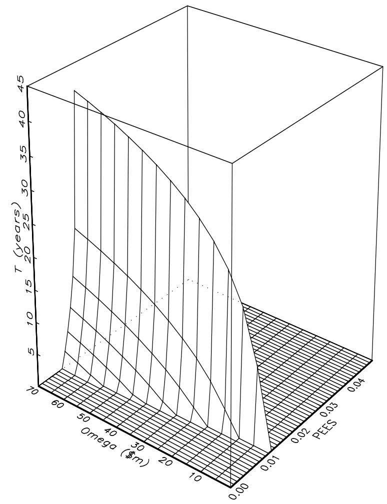

Figure 1b: $\rho = 0.04$

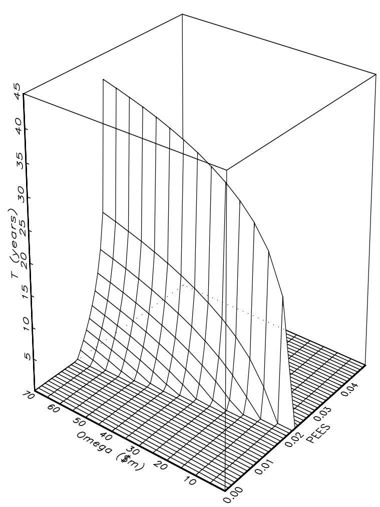

Figure 1c: $\rho = 0.07$

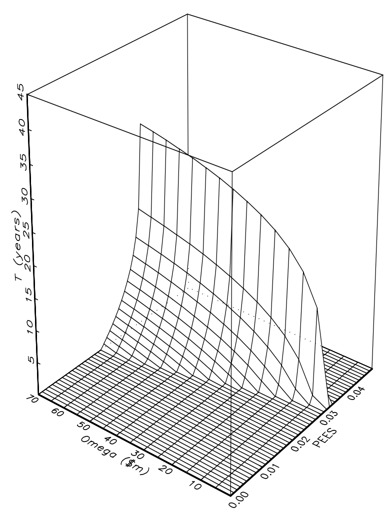

Figure 1d: $\rho = 0.10$

Table 1:
Base case parameter values and results

Parameter		
N	Consumer surplus status quo	585
νN	Increase in consumer surplus in A$m pa	175
P	Producer surplus status quo	135
πP	Decrease in producer surplus in A$m pa	66
$\Omega(0)$	Invasion damage in A$m pa	52
λ	PEES	0.01
ϕ	Defensive expenditure share	0.33
ρ	Real rate of discount	0.04
α	Mean rate of invasion damage reduction	0.15
σ	Exogenous standard deviation of R&D	0.1
Results		
$F(C(0))$	Autarky net present value ($\$bn$)	19.2
$f(C(0))$	Free trade net present value ($\$bn$)	18.9
T	Expected number of years of R&D	5.5

Table 2:
Expected years of R&D for varying demand and supply elasticities

Elasticity of Demand		Elasticity of Supply	
		1^a	1.25
-0.5^a	CS	585	585
	ΔCS	175	175
	PS	135	108
	ΔPS	-66	-63
	$\Omega(0)^b$	52	34
	T	5.5	0.5
-0.75	CS	389	389
	ΔCS	180	180
	PS	135	108
	ΔPS	-66	-63
	$\Omega(0)^b$	52	34
	T	5.0	0.0

[a] Reproduced from Table 1.
[b] Producer surplus losses from an invasion event, $\Omega(0)$, are taken to be 75% of the free-trade producer surplus.
See Table 1 for all other parameter values.

Table 3:
Expected years of R&D for varying PEES, λ, and invasions damage, $\Omega(0)$, with adjusted defensive expenditure share, ϕ.

λ	ϕ	Ω		
		35	52	69
0.005	0.17	0.0	0.0	0.0
0.010	0.33	1.1	5.5	8.7
0.020	0.66	8.0	10.8	12.9
0.030	0.99	9.6	11.7	13.2

See Table 1 for all other parameter values.

Table 4:
Expected years of R&D for varying defensive expenditure share, ϕ, and invasion damage, $\Omega(0)$.

ϕ	$\Omega(0)$		
	35	52	69
0.251	51.6	56.7	60.4
0.33	1.1	5.5	8.7
0.400	0.0	2.5	5.3

See Table 1 for all other parameter values.

Table 5:
Expected years of R&D for varying R&D success, α, and R&D uncertainty, σ.

α	σ		
	0.05	0.1	0.2
0.01	0.0	0.0	11.5
0.05	0.0	2.4	11.3
0.10	1.7	4.5	10.7
0.15	3.7	5.5	10.0
0.20	4.7	6.0	9.4
0.25	5.3	6.2	8.9

See Table 1 for all other parameter values.