A Practical Border Quarantine Measure for Imported Livestock*

Tom Kompas
Australian Centre for Biosecurity and Environmental Economics
Australian National University
Canberra, ACT 0200
tom.kompas@anu.edu.au

Tuong Nhu Che
Australian Bureau of Agricultural and Resource Economics
Canberra, ACT

September 2009

Abstract

Quarantine measures have generally provided an essential protection against the importation of exotic diseases, thus protecting both consumers and producers from major health concerns and pests and diseases that can potentially destroy local agricultural production. However, quarantine measures also impose costs in the form of expenditures on the quarantine program itself and the welfare losses that are associated with such trade restrictions. This paper develops a simple model to determine the optimal level of quarantine activity for imported livestock by minimizing the present-value of the direct costs of the disease, the cost of the quarantine program and any resulting welfare losses. The result defines a practical measure for the optimal number of infected livestock that may potentially enter a region in a given month. The model is then applied to the case of Ovine Johne's Disease and its potential entry to the sheep industry in Western Australia. All key parameter values are subject to random variation and the optimal solution and sensitivity measures are obtained with a genetic algorithm.

*Thanks to John Edwards, Chris Hawkins, Tony Higgs, Roy Casey and Peter Morcombe at Agriculture Western Australia, Nico Klijn and Steve Beare at the Australian Bureau of Agricultural and Resource Economics, R. Quentin Grafton at the Australian National University, participants at the 47th annual Australian Agricultural and Resource Economics Society conference in Fremantle, Western Australia and an anonymous referee for very helpful comments on an earlier version of this paper and valuable assistance with parameter estimates.

1. Introduction

The development of trade between regions and countries is an increasingly important characteristic of modern agriculture, in which the exported value of livestock alone contributes more than $U\$5$ billion a year (Food and Agriculture Organisation of the United Nations (FAO), 2002). Along with a great deal of benefits trade carries with it the risk to import exotic animal diseases. In this regard, the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) of WTO is vital to prevent the danger of introducing exotic diseases, which can seriously threat human health and social-economic welfare. In this regard, quarantine activities have generally provided an essential protection against the importation of exotic animal diseases, thus protecting both consumers and producers from major health concerns and pests and diseases that can potentially destroy local agricultural production.[1] The consequences of a potential entry of devastating diseases such as Foot and Mouth Disease and Sheep Pox (belong the A list of the Office International des Epizooties (OIE)) provide dramatic examples.

However, quarantine programs, by their design usually have much economic effects as other, more traditional, import restrictions generating the loss as a result of reducing the economic welfare from free trade. Thererfore a serious concern is also on the use of the SPS regulations as a measure for trade restrictions, especially with the reduction in tariffs resulting from the Uruguay Round and bilateral trade agreements. A recent debate on a Free Trade Agreement (FTA) between United Sates and Australia is an example. Whilst United States expects this FTA could increase the GDP of $2.1 billion by 2006, and the net benefit over the next two decades could amount to $10.3 billion (US Department of Commerce, 2003) the concern of Australian quarantine is obvious. To US "the biggest problems in trade with Australia was the country's stringent quarantine system" (US Trade Representative, 2003). Particularly, it is argued that "the Australian government maintains an extremely stringent regime for the application of sanitary and phytosanitary (SPS) measures, resulting in restrictions on and prohibitions of many agricultural products" (USTR, 2003). Much more worse, the European Union concerns "Australia has built a quarantine system which is highly efficient at blocking the import of agricultural products into this country" (EU, 2003)([2].

In addition, quarantine programs also impose costs. Decreasing the likelihood of a

[1] Hinchy and Fisher (1991) provide an analysis of the 'public good' aspect of quarantine programs and James and Anderson (1998) discuss the general costs and benefits of quarantine measures, with an application to the case of banana imports to Australia. Bicknell, Wilen and Howitt (1999) provide a comparable study on the control of bovine tuberculosis in New Zealand.

[2] Australia's quarantine system has already been challenged in the past. In 1998 the WTO ruled that the Australian quarantine system for salmon violated WTO rules following a complaint by Canada and the US. In 2002 the Philippines, supported by Thailand, requested their own WTO consultations on the Australian quarantine system for pineapples and other fruit and vegetables.

disease entering the border through imported livestock, for example, requires significant expenditures on items such as serological tests, surveillance and border screening patrol that vary considerably with the severity of the quarantine activity in place. Given all these issues an 'appropriate' quarantine measure evidently maybe usually the most severe measure because is should balance the potential benefit of preventing exotic dieases threaning to agriculture, the trade restriction effects and the cost of implementing the quarantine itself.

This paper develops a practical model to determine an optimal quarantine measure against the risk of importing an exotic disease in livestock.[3] Put simply, the idea is to minimize the sum of the costs of a potential disease incursion[4], the cost of the quarantine program and the trade losses resulted from quarantine restrictions, through a variation in the potential number of infected livestock that enter a region in any given period. Clearly, the larger the expenditure on a quarantine activity the larger are welfare losses and the cost of the quarantine program itself. However, the more severe the quarantine activity the smaller is the risk of a disease incursion and thus the smaller are the direct costs of the disease to the affected industries. In principle, there will be cases where the disease is serious damage that the direct costs of an incursion will require vast expenditures on quarantine services and large welfare losses to guarantee that the risk of a disease entry is virtually zero. On the other hand, for some diseases, reducing the risk of a disease entering to zero may imply that the cost of the quarantine measures and the resulting trade losses more than surpass the (present-value) of the direct cost of the disease to the local economy. The implementation of a quarantine measure should rely on the 'acceptable level of risk' (see Nunn, 1997) or the 'optimal' expected value of the likelihood a disease entry for the case of imported livestock. Finding the correct value of the likelihood a disease entry, and with it the associated expenditure level and optimal quarantine activity, thus requires minimizing all of the (properly discounted) potential and actual costs associated with managing imported livestock[5].

The model is applied by the case of Ovine Johne's Disease (OJD) and its potential entry to Western Australia from imported rams. Over the last decade the disease has been major concern for Australia (Australian National Johne's Disease Program (NJDP), 2002) causing serious economic impact on the sheep industry, which contributes more than $A$$4.5 billion gross value of produciton a year (Australian Bureau of Statistics

[3]The model is practical in the sense that it can be easily calibrated for use in policy-making, provided that required parameter values are available or can be estimated, while being based on the properties of a formal stochastic optimal control framework (Kompas and Che, 2002), without the difficulty of attempting to find explicit optimal solutions to complicated stochastic processes.

[4]including the loss in output and productivity, the costs of disease management and the loss of potential export trade restrictions due to the presence of the disease and in many cases the spill-over impacts outside farm sectors.

[5]An properly calculated optimal quarantine measure may also provide a sensible and analytical justification for quarantine activities as non-tariff barriers to trade.

(ABS, 2002). More recent estimates for NSW and Victoria suggest a cost of increased mortality over a twenty year period may range from $A\$13$ to $A\$30$ million a year, depending on an assumed spread rate of flocks infected (SRRATRC, 2001). Whilst the disease has been damaging the east states fortunately still exotic in Western Australia but risky to be introduced through imported premium rams. However for the sheep industry in Western Australia importing premium rams is vital to maintain and improve the genetic quality of sheep.

Part 2 describes the contents of quarantine activities nalysed in this study for which a key function is a front-line defence to prevent the importation of exotic diseases from imported goods. Quarantine activity described in this study forcuses on checking and preventing the entry of exotic diseases into a country by measures applied in the 'barrier' or border or the border quarantine policy.

Part 3 of the paper sets out the analytical framework of the optimal quarantine measure. Specifically, section 3.1 characterizes the damage function for the risk of importing an exotic disease given the cost per head that results from the entry of an infected animal. The disease, once it enters a region, is assumed to transmit by a Verhulst-Pearl logistic growth function until reaching the point of the maximum infection level. Until this point, the direct cost of the disease is the discounted value of the cost of the accumulated number of infected livestock that enter each month. After the disease becomes sufficiently endemic, the direct cost of the disease, given that the number of infected livestock (or farm properties) is at its maximum infection level. Section 3.2 defines the expenditure function for a quarantine activity. Values are defined for the expected number of infected animals that enter with no quarantine activity in place and the maximum quarantine expenditure that (virtually) guarantees no disease entry. For intermediate cases, lowering the risk of disease (measured by the expected value of infected livestock entering) requires increased expenditures (at an increasing rate) for quarantine services. Section 3.3 approximates the welfare loss that results from quarantine measure as a restricting imports and section 3.4 details the nature of the optimal solution for the quarantine measure.

Part 4 is devoted to the the case of Ovine Johne's Disease (OJD) and its possible entry to the sheep industry in Western Australia (WA). After analysing the characteristics and bacground of the WA sheep industry (section 4.1), including the various possible quarantine measures that are practically available (section 4.2), section 4.3 calibrates parameter values for WA and section 4.4 calculates the value of the potential number (on avearge) of infected rams that may optimally enter WA per month in order to minimize total costs. All key parameter values are subject to random variation and the optimal solution and sensitivity measures are obtained with a genetic algorithm. Part 5 presents the results of algorithm process for an optimal quarantine measure for OJD in Western Australia. Part 6 concludes.

The economics of animal diseases has not got a long history and even 'has not been widely explored' (McInerney, 1996). A number of researches such as Bennett, 1992 and McInerney, 1996 had set out to characterise animal disease as an economic problem and explore an economist's approach to what might otherwise be considered an essentially veterinary problem. However for long term non farm sectors can be adjusted its structure given the expected long term production in famr sector. Therefore it is assumed that in long run the non-farm sectors are rational expectation so the economic impacts of the disease is only before the diease reaching.

2. Quarantine Activities

For agricultures, especially those rely heavily on the production of, and international trade in agricultural products. The relative freedom from major disease could save a huge potential cost caused by disease outbreak and also giving a significant comparative advantage on world markets. In most cases, the outbreak or development of exotic disease may cause significant economic losses and the on-going problems with trade restrictions. In such sense quarantine activities is vital to protect agriculture from an introduction of exotic diseases from fimported livestock. Quarantine by providing an essential screening service is a protective measure in the truest sense of the world: it is design to protect citizens, animals, plants and the environment from the problems that can arise through importing pests and diseases via possible carrier products (James and Anderson, 1998) .

The scope of the quarantine activities can be viewed widely and comprehensively such as by Mumford, 2002 and Nairn *et al*, 1996. By Mumford, 2002 it involves prevention, detection (surveillance) and containment and eradication (disease control strategy). Following Nairn *et al*, 1996 and Tanner, 1997 the contents of quarantine in Australia include: pre border, border and post border quarantine. The term 'border' is used in preference to 'barrier' in recognition of the fact that, given natural migrations and modern methods of transport, in fact no country or state has a 'barrier' around it, only a border. Pre border quarantine provide a means of identifying potential high risks. The border quarantine provide an effective checking and control on the entries that may introduce unwanted diseases. In fact an appropriate preparedness and response strategies of the border quarantine is developed based on the identification of potential high risks thereby the pre-border quarantine is a part for the border quaratine policy. The post border quarantine is considered 'passive' surveillance and preparedness and contingency plan for disease eradication or control (Tanner, 1997). Quarantine activity described in this study forcuses on checking and preventing the entry of exotic diseases into a country by measures applied in the 'barrier' or border or the border quarantine policy. There are the key reasons on the need of economic assessment of the border quarantine policies. Firstly, the border quarantine plays a highest profile role with the heaviest demand of service and because of its highly regulatory nature it tends to attract most public and politics interest (Nairn *et al*, 1996, Tanner, 1997 and AQIS,2003). Secondly, the border quarantine results the risk of possibility of an exotic diease entering into the economy, which directly drive the economic consequence caused by the threat of a diease incursion. Thirdly, the impact of quarantine policy as trade restrictions in fact resulted directly from the border quarantine therefore the border policy is atracted public and politics interest. The concern of using quarantine measure as a trade restriction in fact resulted from the effects of the border quarantine policy.

Practically, although the function of surveillance and eradication maybe considered as a new scope of quarantine (Nairn *et al*, 1996, Tanner, 1997) but until now in Australia the quarantine activities disease surveillance and diease managment are responsed by the separate agecies. The Australian Quarantine and Inspection Service (AQIS) is in charges of overall border quarantine activities. Surveillance is implemented by the Product Integrity, Animal and Plant Health of Australia (PIAPH) for 'early detection'. If an exotic diseases become established its eradication and control become the responsibility of a separate (usually state) agency[6].

3. An Practical Border Quarantine Measure

3.1. The risk of an incursion and the growth of an exotic disease

To structure the problem in a simple way assume a given probability distribution over the event of a disease entering an area and let x be the expected number of infected livestock that enter in any one month. Furthermore, let every probabilistic measure of x correspond to an outcome of a quarantine activity. The more strict the quarantine activity the lower on average is the expected value of x. Next, assume that once (or if) an infected livestock enters an economy or region that it transmits the disease to the current non-infected or free flock in that area at an average net transmission rate g. In practice, it is often the case that biologists with provide a more elaborate model of the disease spread, such as spatial Markov process (e.g., Scanlan, *et al.*, 2001), but even here an implied growth rate g can be estimated on the basis of these results.

Following Schaefer (1957), assume that the growth of the disease growth follows a Verhulst-Pearl logistic function. Thus, at month τ, an initial infected number of imported livestock x grows to an infected number of animlas q_τ following an epidemiological growth model given by

$$q_\tau = \frac{Q_s}{1 + \left(\frac{Q_s}{x} - 1\right) e^{-g\tau}} \tag{3.1}$$

[6] For example the surveillance of Papaya Fruit Fly is implemented by PIAPH, the Fire Ant eradication campaign is responsed by the Ministry of Primary Industries of Queensland (Kompas and Che, 2001).

where Q_s is the maximum number of infected animals or 'maximum infection level' in a region (in a manner comparable to maximum carrying capacity) and depends on the size of the susceptible population and other biological and environmental parameters. The value of an initial incursion x will vary given the quarantine activity in place. Every month the importing economy potentially adds an additional x units of infected livestock from other states or regions so that a new 'vintage' x of infected animals transmits the disease to the remaining free flock or herd according to equation (3.1). Therefore at τ the total number of diseased livestock is now the accumulated number of infected animals caused by adding a new value of x every month over period τ, or[7]

$$Q_\tau = \sum_{t=0}^{\tau} \frac{Q_s}{1 + \left(\frac{Q_s}{x} - 1\right) e^{-gt}} \tag{3.2}$$

Define T_s as the point of time at which the disease reaches the maximum infection level, indicating either that the disease has effectively saturated the livestock population or, depending on the context, that the number of infected farm-properties has reached its maximum level. Equation (3.2) thus only applies to the case of $\tau < T_s$. After T_s there is no further growth in the disease or the number of infected livestock (or farm properties for any particular livestock) remains unchanged at Q_s. At T_s the total number of infected animals given by equation (3.2) equals the maximum infected number of animals or Q_s, so that

$$Q_s = \sum_{t=0}^{T_s} \frac{Q_s}{1 + \left(\frac{Q_s}{x} - 1\right) e^{-gt}} \tag{3.3}$$

and

$$\sum_{t=0}^{T_s} \frac{1}{1 + \left(\frac{Q_s}{x} - 1\right) e^{-gt}} = 1 \tag{3.4}$$

In equation (3.4) T_s is clearly an implicit function of Q_s, g and x. The larger is the initial number of infected animals x (and thus the less severe is the quarantine activity), the larger the growth rate of disease transmission g and the larger the maximum number of livestock infected Q_s, the larger is T_s.

[7] Alternatively, the growth model can be expressed in terms of infected area and density growth in each area, or a combimation of both the numbers of livestock, area and density (Kompas and Che, 2001).

3.2. Potential economic impacts of an exotic disease incursion

The direct economic costs of a disease incursion are first and most easily recognised in the livestock sector, resulting (depending on the severity of the disease) in a loss of output or animal weight and higher mortality rates and disease management costs. The indirect costs of a disease incursion can be widespread and in some cases potentially devestating, affecting proceesing, wholesale and retail sectors and consumer welfare, as well as resulting in substantial if not complete trade restrictions (McInerney, 1996).

Let the potential average cost of the disease per animal in the livestock sector alone be c_t, including production loss, disease managment costs, including containment or eradication, and the cost of potential export trade restrictions due to the presence of a disease. In general, the value of c_t is time dependent and given the growth of the disease defined by equation (3.2) depends on the total number of infected animals Q_τ. It follows that average costs are an increasing function of the initial amont of infected animals that enter a region. Using equations (3.2) and (3.3), the potential total cost C_L of a disease incursion in the livestock sector is thus

$$C_L = \sum_{t=0}^{T_s} \beta_t c_t \frac{Q_s}{1 + \left(\frac{Q_s}{x} - 1\right) e^{-gt}} + \sum_{t=T_s+1}^{T} \beta_t c_t Q_s \tag{3.5}$$

for $\beta_t = 1/(1+r)^{(t/12)}$, the discount factor, defined over monthly periods to T_s where the maimum infection level is reached, and from this period to the end of the planning horizon T. It is easy to see from equation (3.9) that the higher the expected initial incursion x in any given month the the greater the cost caused by the disease over T. By reducing the level of x, say through more rigorous quarantine measures, the potential costs that result from the incursion of an exotic disease will also be reduced.

For convenience, let the indirect costs of a disease incursion be some multiple ψ of C_L. The value of ψ will depend on the specific disease and the nature of the affected commodity, and can extend broadly from food and processing sectors to final retail trade and the toursim industry. The total cost of the disease incursion is thus given by

$$C = (1+\psi) \left(\sum_{t=0}^{T_s} \beta_t c_t \frac{Q_s}{1 + \left(\frac{Q_s}{x} - 1\right) e^{-gt}} \right) + \sum_{t=T_s+1}^{T} \beta_t c_t Q_s \tag{3.6}$$

3.3. Expenditures on a quarantine activity

Assume that the quarantine measure is efficient in the sense that the more severe the quarantine activity (or the larger the quarantine expenditure) the lower the probability of an infected animal entering a region. Precise functional forms between quarantine expenditure and the expected value on x are not available, but the basic relationship between the value of x and the associated expenditure on a quarantine measure is easy to understand. Let E_t be the quarantine expenditure (e.g., physical inspection, serological screening tests, and so on). Given an effectiveness of a quarantine system it is assumed that the more strict the quarantine system (the lower is x) the larger is the required quarantine expenditure, so that that resulting quarantine expenditures fall as the expected value of x rises, or $E_t'(x) < 0$ and $E_t''(x) > 0$. In addition, assume that if $E = 0$ (or there is 'free entry') the maximum number of infected animals that may enter in any given time period is R_m and as $x \to 0$ the associated maximum expenditure on a quarantine measure asymptotes to E_m. Under all of these assumptions, the expenditure function takes the form[8]

$$E_t(x;\eta) = \frac{E_m(R_m - x)}{R_m(\eta x + 1)} \tag{3.7}$$

or a hyperbola with intercepts R_m and E_m.[9] The value η represents a coefficient of quarantine effectiveness, reflecting the marginal benefit of each extra dollar spent on quarantine, determining the precise curvature of $E_t(x)$.Everything else equal, the higher η means the lower the expenditure on quarantine for a given x, or the more convex is the expenditure function. When $\eta = 0$ that curve is linear and downward sloping.[10] The aggregate present value of quarantine expenditures or TE is the discounted value of quarantine expenditures of every month, or

[8]Bennett, 1992 and McInerney, 1996 obtain a similar function when modelling the relationship between the disease control expenditure and infection level (measured by disease losses).

[9]The functional relationship given by equation (3.7) implies that either E_t or x can be used as a choice variable (all other variables are known). An inverse function, for x as a function of E_t, can accordingly be defined as

$$x(E;\eta') = \frac{R_m(E_m - E_t)}{E_m(\eta' E_t + 1)}$$

for $\eta' = \eta\frac{R_m}{E_m}$, which is useful in cases where quarantine expenditure E_t is the choice variable, so that an increase is quarantine expenditures lowers initial entry x. However, since the epidemiological growth model is section 3.1 is defined in terms of x it is easier to work directly in terms of equation (3.7), with x as the control variable. The corresponding optimal value of E_t is then easily computed from the optimal value of x.

[10]In this sense the value of η represents an 'effectiveness coefficient' for the overall quarantine system within a region. For example, in Western Australia, the technology (e.g., screening devices, surveillance, serological tests and the required administration of the service) remains unchanged regardless of the exact quarantine program being used. Variations in x are thus simply the result of expenditure levels or the extent of the quarantine activity in place. However, across regions and technologies it is reasonable to assume that the value of η varies, so that for a given x a higher value of η implies that the marginal cost ($\partial E/\partial x$) of reducing x by one unit is smaller.

$$TE(x;\eta) = \sum_{t=0}^{T_s} \beta_t \frac{E_m(R_m - x)}{R_m(\eta x + 1)} \tag{3.8}$$

over T_s. After T_s (the point in time which corresponds to the maximum infection level) a quarantine service is superfluous, and hence there are no quarantine expenditures.

3.4. Welfare losses from import trade restrictions due to quarantine activities

As mentinoned, quarantine activities can restrict trade, much like tariff and other non-tariff barriers. To approximate welfare losses from restricting imports with a quarantine activity assume, following James and Anderson (1998), linear supply and demand schedules for livestock. At month t define p^0 as the domestic regional price and p^*as the import price for $(p^0 - p^*) > 0$. Let the volume of imports with no quarantine restrictions be M at p^*. With a quarantine (partially restricting imports) the import price rises by the cost of conformance (e.g., serological export clearance and certificate costs etc) to say p^q. Define this conformance cost per livestock as $m = p^q - p^*$. The welfare cost from the loss in trade at t is thus approximated by

$$L_t = \frac{1}{2}(M' + M)(p^q - p^*) \tag{3.9}$$

for

$$M' = M \frac{(p^0 - p^q)}{(p^0 - p^*)} \tag{3.10}$$

or the volume of imports after the quarantine activity is in place. Substituting (3.9) into (3.10) gives

$$L_t = mM - \frac{1}{2} \frac{m^2 M}{(p^0 - p^*)}. \tag{3.11}$$

In actual practice the cost of conformance is typically paid by the exporter and the cost of the quarantine service at the border (or on arrival) is paid by the host region, with additional follow-up tests in subsequent years. The more strict the quarantine activity the higher the cost of prevention and detection of the disease for both the exporter and importer. Consequently, the cost of conformance can be represented as some fraction α of the total quarantine expenditure $E_t(x)$. The (undiscounted) welfare loss from the restriction in trade now becomes

$$L_t = \alpha E_t(x) M - \frac{1}{2} \frac{\alpha^2 E_t(x)^2 M}{(p^0 - p^*)} \tag{3.12}$$

for $E(x)$ given by equation (3.7). The aggregate present value of total welfare losses TL is thus

$$TL = \sum_{t=0}^{T_s} \beta_t \left[\alpha E_t(x) M - \frac{1}{2} \frac{\alpha^2 E_t(x)^2 M}{(p^0 - p^*)} \right] \tag{3.13}$$

for β_t the discount factor.

3.5. An optimal quarantine measure

The problem for the policy maker is now to minimize total costs by minimizing the potential discounted economic cost of the disease's incursion, the expenditure for the quarantine activity and the welfare loss that results from implementing the quarantine restrictions on trade. Unlike the direct cost of the disease, however, discounting the value of any welfare loss and quarantine expenditure is only applicable from the initial period to time T_s. Once the disease reaches its maximum there is no point for a quarantine activity and thus no quarantine expenditures or welfare losses from T_s to T to discount. From equations (3.6), (3.8) and (3.13), the problem now becomes one of minimizing total cost TC, or

$$\begin{aligned} \min_x TC \;=\; & (1+\psi)\left(\sum_{t=0}^{T_s(x)} \beta_t c_t \frac{Q_s}{1 + \left(\frac{Q_s}{x} - 1\right) e^{-gt}} \right) + \sum_{t=T_s+1}^{T} \beta_t c_t Q_s \\ & + \sum_{t=0}^{T_s(x)} \beta_t \frac{E_m(R_m - x)}{R_m(\eta x + 1)} \\ & + \sum_{t=0}^{T_s(x)} \beta_t \left[\alpha E_t(x) M - \frac{1}{2} \frac{\alpha^2 E_t(x)^2 M}{(p^0 - p^*)} \right] \end{aligned} \tag{3.14}$$

through a variation in x. The optimal choice of x will determine the severity of the quarantine activity. The more 'dangerous' (higher values of growth rate g), the more costly a disease, or the less expensive is the quarantine activity and resulting trade losses, the lower the optimal level of x^* and thus the more restrictive should the quarantine system be.

Unfortunately, it is not possible to find an exact optimal x^* from traditional methods, using equation (3.14), or from the relevant first-order condition directly, and especially so since T_s is a variable. An alternative search procedure for x^* is thus needed. In the following section an optimal solution and sensitivity measures are obtained with a genetic algorithm.

4. Quarantine Activities and OJD in Western Australia

4.1. The sheep industry in Western Australia and Ovine Johne's Disease

As the second largest agricultural industry in Western Australia, the sheep industry contributes the gross value of production of roughly A$1 billion a year, including A600 and A400 million for the wool and sheep meat industries respectively (ABS, 2002). Total sheep numbers are well over 26 million with a gross value for live sheep exports of more than A190 million a year (ABS, 2002). The state relies thus heavily on the production of and international trade in agricultural products. Its relative freedom from major pests gives it a significant comparative advantage on world markets. Protecting the domestic sheep industry from threat of an exotic disease the state has been an important objective of the quarantine system, ensuring not only secure overseas trade but also trade with the rest of Australia.

Many sheep producers of both commercial and stud sheep in WA seek to improve the genetic quality of their flocks by importing sheep from other states. Annual importation for this purpose averages more than 5000 premium rams from the eastern states (and other countries) with a value of around A$10 to 15 million. New South Wales and South Australia provide the majority of imported sheep for WA with smaller contributions from Victoria, Tasmania and Queensland (Higgs and Hawkins, 1998). While importing rams is vital for sheep flock development, the threat of introducing OJD from imported premium rams to Western Australia is a serious concern.

OJD is a significant intestinal disease of adult sheep caused by the bacterium *Mycobacterium paratuberculosis.* Infection by this bacterium produces a thickening of the intestinal wall which greatly interferes with the absorption of nutrients and water. The disease is usually transmitted through ingesting faeces from the infected animal (Casey, 1997, Prowse, 2000 and Manning *et al.*, 2001). There is no known treatment for the disease. Sheep infected with OJD typical shed large numbers of the bacterium in their faeces months before clinical signs of the disease appear. This fact, coupled with the lack of an accurate diagnostic test, makes OJD difficult to control. Although not a devastating disease (such as Sheep Pox or Foot and Mouth Disease), OJD causes serious economic losses from export trade bans, shortened life expectancy, lower wool productivity and smaller carcass weight at slaughter. Once signs of the disease appear the health of affected animals progressively deteriorates. Within six months they invariably die.

The impact of OJD is perhaps most significant in stud flocks, with the cessation of ram sales and reduced returns from cull ewes which can no longer be sold as breeding stock. The disease was first diagnosed in a sheep flock of New South Wales in 1980. For many years it appeared to be a localised disease although the number of infected properties was gradually increasing. However according to Australian National Johne's

Disease Program (ANJD) (2002) the disease become now a major concern of the Australian sheep industry. In 2001 about 620 flocks in New South Wales and it was reported infected flocks and about 900 reported suspected flocks. More recent estimates for NSW and Victoria suggest a cost of increased mortality over a twenty year period of \$13 to \$30 million a year, depending on an assumed spread rate of flocks infected (SRRATRC, 2001). Since 1998 the Australian Animal Health Council and the OJD infected states has spent million dollars per year for surveillance and control the disease (Australian National Johne's Disease Program (2002). Although Western Australia is currently a 'declared free zone' for OJD, it is clearly at risk of a disease incursion given trade flows, in particular, between states in Australia.[11]

4.2. Quarantine activities in Western Australia

Following the Quarantine Act 1908 (Commonwealth) and its related legislation, the Quarantine Proclamation and the Quarantine Regulation of Australia, AQIS is responsible for preventing the entry of exotic diseases from overseas and between states in Australia. For example, the AQIS in New South Wales and Victoria implement quarantine measures to prevent Med Fruit Fly and Footrot, which are endemic in Western Australia, from entering these states. Likewise, AQIS in Western Australia applies quarantine measures to prevent incursions of Coding Moth and OJD from New South Wales and Victoria. For OJD the quarantine activities in Western Australia include the requirement of an OJD export clearance certificate for each ran (basically, a herd certificate indicating the OJD-free status of the flock and supporting serological tests), serological screening tests during the process of importation and further blood tests at six month and one year intervals after importation.

The management options faced by Western Australia to prevent OJD from entering the state are relatively straightforward. As implied by equation (3.7), variations in the number of potentially infected sheep that may enter WA depend on the extent of quarantine expenditures on screening, surveillance, serological screening tests, and so on. Table 1 lists four possible quarantine activities and the resulting mean value of the number of infected sheep that are likely to enter WA under each program per year. The estimates of the number of infected sheep under given quarantine measures are based on historical and scientific data (drawn largely from the experience in NSW), a study by Higgs and Hawkins (1998), as modified in APP (2000b), and probabilistic measures based on Beta-distributions (see Vose, 1996) to allow for occasionally large errors (for example) in serological screening tests.[12]

[11] Although no case of OJD has been detected in sheep, a single case of OJD has been confirmed and eradicated in a goat herd approximately 150 km east of Perth (SRRATRC, 2001).

[12] It is important to note that blood tests for OJD may only be up to fifty per cent effective on each trial (APP, 2000). The more severe the quarantine activity the more often blood tests and surveillance

Free entry or no quarantine activity is taken as a benchmark case. Without any attempt to prevent OJD from entering WA, the cost of quarantine services and the welfare loss from trade restrictions are obviously zero. However, the threat of a disease incursion is greatest.[13] The Australian Sheep Johne's Disease Market Assurance Program is a program that aims to identify, protect and promote sheep flocks that are most likely to be free of OJD. It employs serological screening tests and the adoption of property management regimes that prevent the risk of the introduction of the disease. The Movement Restrictions program is simply a more extensive application of the Market Assurance program, with added serological tests and target surveillance after importing rams. Clearly, the more severe the quarantine activity the larger the amount spent on quarantine expenditures and the larger the welfare loss through trade restrictions. Finally, the National OJD Management Program (currently not in place) is designed to approach a near eradication of OJD throughout Australia, at least in principle, through an even more extensive testing for the disease and the isolation and eventual elimination of infected flocks.

4.3. A quarantine measure for Western Australia

The calculation of the optimal value of x for Western Australia, and thus the appropriate level of quarantine activity, requires estimates of all parameters in equation (3.14). All values are drawn from data and reports from Agriculture Western Australia and Agriculture New South Wales. Since all reported values are to a certain degree uncertain a calibrated simulation (within the genetic algorithm) is run with an assumed normal probability distribution over each parameter value. Table 2 presents a summary of key parameters, probability distributions and sources.

The number of sheep is 26 million with the standard deviation is 0.5 million for ABS statistics. Recall that T_s measures the length of time from when OJD first enters a region to the point at which the dieases reaches its maximum infection level. Experience in New Zealand and New South Wales suggests this period of time is roughly 20 years. However, since Western Australia is relatively dry and sheep farms are far less concentrated, the length of time over which the disease spreads is undoubtedly longer and estimated to be approximately 50 years (Casey, 1997, 2000; Edward, 2000; SRRATRC, 2001). Based on this number and comparable estimates for NSW and New Zealand the growth rate of the disease in WA is estimated at 1.4 per cent per month, with an assumed 0.5 percent standard deviation, drawn from a normal distribution or $N(1.4, 0.5)$. This standard deviation implies that the length of time would take for OJD to reach its maximum infection level ranges from 30 to 50 years under 'free entry' policy (based on Casey,

are administered, and hence the larger the quarantine expenditure.

[13] Estimates suggest (see APP 2000b) that OJD, once sufficiently endemic, can cost WA agriculture as much as A\$8 million dollars per year.

2000).

The maximum number of infected sheep that enter WA without any quarantine activity in place, or R_m, is estimated from data on the status of the disease in other regions and the number of consignments to WA with the assumption of STDEV of risk assessment from APP,2000b. Under the current quarantine the volume of imports (M') is 500 rams per month, and the difference between the import price and the domestic price ($p^0 - p^*$) is $A\$1,000$ (calculated from Agriculture Western Australia Statistics, 2000). The conformance cost of ($m = p^0 - p^p$) is A$75/ram (estimated from APP,2000b and SRRATRC, 2001). The volume of imports with no quarantine restrictions M is estimated from (3.13)[14] to be about 550 rams per month. About twenty-five percent of these sheep are drawn from highly infected areas (Higgs and Hawkins, 1998, APP, 2000b) and the probability of the number of infected but unidentified sheep in NSW is estimated to be from five to ten percent (Collins and Collins, 1996; Casey, 2000; Edward 2000 and Agriculture New South Wales, 2000). The current quarantine expenditure is about $A\$40,000$ per month (calculated from APP, 2000c)[15]. and a mean entry of 1.9 infected rams per month (computed from Higgs and Hawkins, 1998 and APP,2000b). The mean value of R_m is thus estimated to be 18.4 per month with a STDEV of 1.8 (following the assumption of APP, 2000b of risk assessment). The maximum quarantine expenditure E_m which reduces the risk of disease entry to virtually zero is $A\$300,000$ per month (estimated from APP, 2000c with the risk evaluation analysed from Higgs and Hawkins, 1998). The value of η in equation (3.12) is estimated to be 3.13 for the quarantine measure on OJD in WA.

As with all diseases, from New Soth Wales experience it appears that some sheep are more susceptible to OJD than others *(*NJDP, 2002). Also, there will be differences in exposure to bacteria within a flock, with some sheep ingesting an 'infective dose' of the bacteria, while others do not (Casey, 1997 and Agriculture New South Wales, 2002). Although young sheep are generally thought to be more susceptible the affects of the disease appear only in adult sheep. The older the sheep the higher weight loss and mortality rate and thus cost of the disease. The proportion of adult sheep (older than 2 years) in WA is around 35 per cent (ABS, 2002) so that the maximum infection level of the disease in WA is assumed to be about 75 per cent of adult sheep or 26 per cent of the total sheep flock, with a 5 per cent standard error.

Based on the experience of the cost of OJD in NSW over time (Collins and Collins, 1996, APP, 2000b and SRRATRC, 2001) it is assumed that at time t the average cost per infected sheep c_t starts at fixed cost per head $\bar{c}$, increases with disease density level, which is measured as a ratio between number of infected sheep Q_t given by equaton

[14] particularly, $M = M' \frac{p^0 - p*}{p^0 - p^p}$.

[15] This cost include all costs related (labour, equipments and other costs for quarantine activities. The cost is estimated from the accounting expenditures for animal diseases by APP, 2000c.

(3.3) to the maximum infection level Q_s, or

$$c_t = \overline{c} + \xi \left(\frac{Q_t(x)}{Q_s} \right). \tag{4.1}$$

Following cost estimates by Collins and Collins (1996), APP (2000b) and SRRATTRC (2001) the maximum cost per infected sheep c_m is estimated to be $A\$14$ per head with standard error of $A\$1.4$ [16] and the fixed cost ($\overline{c}$) is $A\$7$ per head, at 2000 prices . The cost coefficient ξ from equation (4.1) is thus 7. The difference in average price between the domestic market and the imported price from NSW is roughly $A\$1,000$ per sheep [17]. The cost of conformance per sheep, or α, is $A\$75/A\$40,000$ (APP, 2000b).[18] All values are measured in 2000 prices and the value of the interest rate (r) is taken as 0.05. Finally, the potential welfare effects of OJD in affected economic sectors is based on Che (2000). It is estimated that a dollar farm gate value lost in the sheep industry sector caused by OJD cost $A\$0.2$ for abattoirs, $A\$0.4$ for whole and retail sheep sale industry, and $A\$0.1$ for live animal export agents. Therefore the coefficient ψ in equation (3.10) is calculated to be 0.7.

5. Results

The minimization of equation (3.17) through a variation in x is obtained with a genetic algorithm. The genetic algorithm provides a search mechanism for the optimal solution, allowing for uncertainty in parameter values and variability in the search pattern (see Goldberg, 1989). The sampling technique is Latin Hypercube and the crossover and mutation rate is 0.5 and 0.1. A genetic algorithm routine was imported into *MATLAB* to obtain results, with a stopping value at convergence (with a 1 per cent tolerance) and numerous repeated trials to ensure consistent results. The time horizon for the optimalisation is 100 years. The main result is reported in table 3. With a growth rate in the transmission of OJD of 1.4 per cent per month, a maximum infection level is

[16] The value c_m can be given by $c_m = \delta_1 c_c + \delta_2 c_s + c_{tr}$, where δ_1 and δ_2 are the proportional shares between commercial and stud farms and c_c, c_s and c_{tr} is the average cost per head in commercial and stud farms and the cost of export trade restrictions if the disease is detected. According to ABS (2000), APP (2000b) and Collins and Collins (1996), $\delta_1 = 0.9$, $\delta_2 = 0.1$, $c_c = \$104.00$, $c_s = \$3.37$ (including the average cost of death from the disease or \$0.59 and the cost from selling the sheep from slaughter alone or \$2.78) and $c_{tr} = \$0.56$.

[17] measured as the difference between the price of ram alternatively imported from OJD free areas in overseas and the ram price imported from New South Wales (based on the market prices for rams in Western Australia in 2000) with the analysis of APP, 2000b.

[18] The cost of the ELISA test is \$4.5 per test for a 250 sheep sample in a flock of 2500. Under current quarantine activities in WA imported sheep are required to be tested three separate times and must also incur a flock certificate fee indicating disease free status (APP, 2000b). The costs of herd certificate, administration etc are also included.

26 per cent of total sheep and the maximum average cost per infected sheep of $A\$14$, along with standard errors, all other parameter values, summarized in table 2, and including the cost of quarantine and welfare losses, the optimal quarantine measure x^* gives a potential entry of 0.264 infected rams per month (or approximately 3.2 infected rams per year instead of 22.1 under the current quarantine measure). This roughly translates to a quarantine program of a severity that results in one potentially infected ram every 3-4 months. The corresponded optimal quarantine expenditure is $A\$160,000$ per month (about fourth time compared with the current expenditure). The minimum total cost over the period of 100 years is $A\$197$ million (with STDEV is $A\$80$ million) roughly decomposes into $A\$36.5$ million in quarantine costs and $A\$35.5$million in trade losses (discounted from the point of maximum carrying capacity at T_s to the initial time period). The direct (discounted) economic loss form the initial time period to T_s is $A\$47$ million (including $A\$27.6$ million for the sheep industry and $A\$19.3$ for other affected economic sectors) and from T_s to T is $A\$78$ million. Of the currently available quarantine activities (table 1), the Movement Restrictions Program with the quarantine expenditures with added quarantine activities at the expenditures around $A\$160,000$ per month is a good candidate. It certainly dominates 'free entry' and the Market Assurance Program, and although it is not possible to differentiate between the efficacy of the Market Assurance and National OJD Management Program on this basis of this result, a potential incursion of zero does not appear optimal.

Although every care has been taken to obtain the most accurate measure of each parameter value, along with the fact these values were conditioned by a probability distribution and standard errors in the simulation, to allow for uncertainty, it is useful to determine how sensitive the optimal solution is to changes in these parameters. Table 3 summarizes the sensitivity results for changes in the growth rate of OJD transmission, the maximum carrying capacity (or maximum infection rate) and the average cost per infected sheep. Of these, changes in the growth rate and average cost per sheep generate the largest effects. For the growth rate (scenarios 1 to 4), perhaps the most difficult to estimate correctly, scenarios 1 and 2 are for the growth rate is lower than the main model (1.0 per cent and 1.2 per cent per month) increases optimal potential entry from 0.264 to 0.742 and 0.491 per month with corresponded quarantine expenditure decreasing $A\$80,000$ and $A\$115,000$. Scenarios 3 and 4 imposing the higher growth rate of transmission (at 1.6 and 1.8 per cent per month) decreases optimal potential entry from 0.264 to 0.073 and 0.059 requiring the corresponded quarantine expenditure increasing to $A\$240,000$ and $A\$260,000$ per month respectively. As expected throughout, the larger the growth rate of transmission the larger the value of minimized total costs and the smaller the value of $x^*$and the higher quarantine expenditure. Scenarios 5 and 6 alter the maximum infection rate over the population of sheep. An increase, for example, to 0.36 (from 0.26) results in a fall in x^* to 0.063, since the cost of the disease in now spread over a larger proportion of sheep. A fall in the maximum infection rate to

0.16 results in an increase in potential entry to 0.635. Minimum total costs is lower to $A\$169$ million over 100 years given that the time it takes the disease to reach maximum carrying capacity is now much smaller but the cost of the disease is less devastating since it affecting a smaller proportion of sheep. Finally, an increase in the maxium cost per infected sheep to \$18 per head (scenario 8) results in a fall in x^* to 0.131, causing the quarantine expenditure increases to $A\$210,000$ per month; a decrease to \$10 per head (scenario 7) increases x^* to 0.635 so lowering the required quarantine expenditure to $A\$94,000$ per month, with a comparable fall in minimum total costs.[19]

6. Concluding Remarks

The economics for determining an appropriate quarantine system is complex, requiring the complete analysis of all contents related: the potential economic threat of exotic incursion; the expenditures required for functioning effectively quarantine measures and the trade restriction effects resulted from quarantine policy. Economic analysis of each contents itself complicated. In terms of estimation the economic threat of an diseases "there is no established conceptual framework for analysing disease as an economic phenomenon, and despite its undoubted significance in a substantial sector of agriculture we have not explored its characteristic as an economic issue (McInerney, 1996). In terms of estimation of the effectiveness of a quarantine measure indicated by the relationship between quarantine expenditure and the outcome is challenger. In addition, evaluation of trade restriction effects resulted from quarantine is also complicated. The risk and uncertainties associated make quarantine analysis somewhat more complicated than standards economic policy analysis. (MacLaren, 1997). However the need for economic assessment on quarantine issue is undoubtedly extreme important given the objective of pursuing trade liberalisation committed by WTO members. An appropriate quarantine measure should be balanced between the function of disease prevention and its economic effects of trade restriction and required expenditures.

This study provides a simple approach to determine an optimal border quarantine measure for imported livestock with the expectation to encourage economists to pursue further work in this area. It is not necessarily the case that the best quarantine activity requires a severity or expenditure level that guarantees that the risk of a disease incursion is virtually zero. The direct cost of the disease must be weighed against the amount of quarantine expenditures necessary to reach a target level for the likelihood of a disease entry and the costs incurred from the resulting trade restrictions that must remain in place. Minimizing all costs determines an optimal quarantine activity. The more costly the disease is to the local industry, the larger the maximum carrying or infection rate of

[19] Given the observed variations in costs in NSW and New Zealand, the value of the standard error for costs per head was left unchanged at 10 per cent of its mean value in each case.

the disease, the more cost effective is a quarantine activity or the lower the discount rate on future costs and expenditures as a result of the disease, the lower the optimal value of a likely disease entry and the more severe should the optimal quarantine activity be. In the case of Western Australia, the estimated result indicated that the optimal quarantine measure is not the most severe one, which is able to reduce the risk of OJD entering to zero. The optimal quarantine program for OJD results 'an acceptable level of risk' for the possibility of missing one infected sheep in every 3-4 months. However, sensitivity results indicate that correct estimates of the growth rate of disease transmission and the costs of the disease per head are critical in the determination of optimal potential entry and the corresponding quarantine activity.

REFERENCES

Agriculture New South Wales, 1999, “Ovine Johne’s disease in New South Wales,” *Surveillance Report*, Sydney

Agriculture New South Wales, 1998-2003, “Ovine Johne’s disease,” *Surveillance Report*, Sydney.

Agriculture New South Wales, 2002, *Frequently asked questions about Johne’s Disease*, Sydney.

Agriculture Protection Program (APP), 1998, *An economic evaluation of preventive measures for Ovine Johne’s disease in Western Australia*, Agriculture Western Australia, Perth.

Agriculture Protection Program (APP), 2000a, *Annual Action Plan,* Agriculture Western Australia, Perth

Agriculture Protection Program (APP), 2000b, *The threat to Western Australia from Ovine Johne’s disease, vols. 1 and 2*, working report prepared by N. Che, T. Higgs and C. Hawkins, Agriculture Western Australia, Perth.

Agriculture Protection Program (APP), 2000c, *The annual account book for the Agriculture Protection Program,* Agriculture Western Australia, Perth

Agriculture Western Australia, 1999-2002, *Statistics*, Perth.

Australian Bureau of Agricultural and Resource Economics (ABARE), 1997, “Ovine Johne’s disease: evaluation of control and eradication strategies,” *Report to the Australian Animal Health Council*, Canberra.

Australian Bureau of Statistics (ABS), 1998-2002, *Statistics,* Canberra.

Australian National Johne’s Disease Program (NJDP), 2002. “ Ovine Johne’s Disease (OJD) Websites. Circular No AI 2002/08.

Australian Quarantine and Inspection Service (AQIS), 2003. “The Nairn report Documents”. Canberra, Australia.

Bennett.R.M. 1992., “The use of ‘economic’ quantitative modelling techniques in livestock health and disease-control decision making: a review”. Preventive Veterinary Medicine, 13 (1992) 63-76.

Bicknell, K. B., Wilen, J. E. and Howitt, R. E., 1999, “Public policy and private incentives for livestock disease control,” *Australian Journal of Agricultural and Resource Economics*, 43, 501–521.

Casey, R., 1997, “Johne’s disease in cattle,” *Farmnote,* 23/97, Agriculture Western Australia, Perth.

Casey, R., 2000, OJD, internal correspondence, Agriculture Western Australia.

Che, N, 2000., “Cost Sharing of Agricultural pest protection in Western Australia”. Working Paper, Vol 1 and 2. Agriculture Western Australia.

Collins, B. A. and Collins, D. J., 1996, *Evaluation of Ovine Johne’s disease control and eradication strategy*, Agriculture New South Wales, Sydney.

Edward, J., 2000, OJD, internal correspondence, Agriculture Western Australia.

EU, 2003. "European Union to challenge Australia's protectionist food import regime at WTO". WTO Dispute Settlement: What's new?. Brussels, 31 March 2003, Website: http://europa.eu.int/comm/trade/whatwedo/index_en.htm.

Food and Agriculture Organisation of the United Nations (FAO), 2002, "Trade Commerce" Yearbook, Vol.54, 2002.

Goldberg, D., 1989, *Genetic algorithms in search, optimization and machine learning*, Addison-Wesley, Reading, MA.

Higgs, T. and Hawkins, C., 1998, "Sheep Johne's disease: analysis of the risk to Western Australia from importing sheep from New South Wales," *Australian Veterinary Journal*, 76, 546-550.

Hinchy, M. D. and Fisher, B. S., 1991, *A Cost-Benefit Analysis of Quarantine*, ABARE technical paper, Australian Bureau of Agricultural and Resource Economics, Canberra.

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.

Kompas, T. and Che, T. N., 2001, *An economic assessment of the potential costs of red imported fire ants in Australia*, ABARE, Canberra.

Kompas, T. and Che, T. N., 2002, "A stochastic optimal control model for quarantine activities," working paper, Asia Pacific School of Economics and Management, Australian National University, Canberra.

MacLaren,D. 1997., "Uncertainty aversion and technical barriers to trade: an Australian example", in Orden, D and Roberts, D. (eds), Understanding Technical Barriers to Agricultural Trade, University of Minnesota's Department of Applied Economics for the International Agricultural Trade Research Consortium, St Paul. (1997):255-71.

MATLAB, MathWorks, Inc., Natick, MA.

Manning, E.J.B and Collins, M.T., 2001. "Mycobacterium avium subsp. paratuberculosis: pathogen, pathogenesis and diagnosis". Rev. sci. tech. Off. int. Epiz., 2001, 20 (1), 133-150.

McInerney.J. 1996., "Old economics for new problems-livestock disease: presidential address". Journal of Agricultural Economics. Vol 47, No.3 (September 1996): 295-315.

Mumford.J.D. 2002., "Economic issues related to quarantine in international trade". European Review of Agricultural Economics Vol 29(3) (2002):329-48.

Nairn, M.E., Allen, P.G., Inglis, A.R. and Tanner,C. 1996., "Australian quarantine: a shared responsibility". Canberra: Department of Agriculture, Forestry and Fishery of Australia (1996).

Nunn.M., 1997. "Quarantine Risk Analysis". The Australian Journal of Agricultural and Resource Economics. 41:4 (1997): 559-78.

Power. L.P and Harris.S.A., ???. "A cost-benefit evaluation of alternative control policies for foot-and-mouth disease in Great Britain.

Prowse, S., 2000, *Ovine Johne's Disease: A scientific review of the current knowledge of Ovine Johne's Disease in Victoria and elsewhere, its impact in Victoria and an assessment of potential strategy for its eradication and control*, CSIRO, Canberra.

Scanlan, J. C., Mohandrass, S. and Vanderwoude, C., 2001, *Modelling the rate of spread of red imported fire ant in Australia*, Department of Primary Industries, Brisbane.

Schaefer, M.B., 1957. "Some consideration of population dynamics and economics in relation to the management of commercial marine fisheries". *J. Fish. Res B. Can.*14:669-81.

Senate Rural and Regional Affairs and Transport References Committee (SRRA-TRC), 2001, *The Incidence of Ovine Johne's Disease in the Australian Sheep Flock, Second Report*, Parliament of the Commonwealth of Australia. Canberra.

Tanner. C. 1997., "Principles of Australian Quarantine". The Australian Journal of Agricultural and Resource Economics. 41:4 (1997): 541-58.

United States Department of Commerce (USDC)., 2003. Office of Trade and International Analysis. Web http://www.commerce.gov.

United States Trade Representative, 2003.,"The 2002 National Trade Estimate Report on Foreign Trade Barriers". Web http://www.ustr.gov.

Vose, D., 1996, *Quantitative Risk Analysis: A Guide to Monte Carlo Simulation Modelling*, London: John Wiley & Sons.

Table 1: Quarantine options and the risk of OJD entering

Possible quarantine measures	Risk of infected rams entering *(no/month)*
• Free entry or no quarantine activity	18.5
• Australian Sheep Johne's Disease Market Assurance Program	0.5
• Movement Restrictions Program	Less than 0.5 (depends on level of restriction)
• National OJD Management Program	Close to 0
•	

Source: *Agriculture Protection Program (APP) 2000b.*

Table 2: Summary of key parameters, probability distributions and sources

	Mean value and standard error	Related parameter	Sources
1. Total production loss			
• Number of sheep in the state *(number)*	N(26 000 000, 500 000)		ABS (2002)
• Maximum infection level *(% of total sheep)*	N(26, 5)	calculating Q_s	Estimated from ABS (2002) and SRRATRC (2001)
• Growth rate of OJD transmission *(%/month)*	N(1.4, 0.5)	g	Estimated from Casey (2000)
• Maximum average costs of OJD *($/head)*	N(14, 1.4)	c	Estimated from Colins and Colins (1996) and APP(2000b)
• Discount rate *(%/year)*	5		
2. Quarantine expenditures			
• Max quarantine expenditures *($/month)*	$300 000	E_m	Estimated from APP(2000c)
• Risk of infected rams entering under 'Free Entry' *(no/month)*	N(18.5, 1.85)	R_m	Estimated from Higgs and Hawkins (1998)
• Current quarantine expenditures *($/month)*	$40 000	calculating η, α	Calculated from APP (2000c)
• Current risk of infected rams entering *(no/month)*	N(1.84, 0.18)	calculating η	APP (2000b)
3. Welfare losses from trade restrictions			
• Volume of rams imported *(no/month)*	550	M	Estimated from WA Statistics, 2000 and APP, 2000b.
• Difference of domestic price and imported price *($/ram)*	$1 000	$(p^0\text{-}p^*)$	WA Statistics, 2000 for premium ram prices
• Conformance cost for ram exported *($/ram)*	$75/ram		Computed from SRRATRC (2001)

Table 3: Optimal solution and sensitivities

	Sensitivity parameters			Optimal (genetic algorithm) solution		
	Growth rate of OJD transmission	Maximum infection level	Max cost per infected sheep	x^*	Quarantine expenditures	Minimum sum costs
	(%/month)	*(%)*	*($/head)*	*(no/month)*	*($/month)*	*($)*
Main result	N(1.4, 0.5)	N(26,5)	N(14, 1.4)	0.264	160 000	197 000 000 *(80 000 000)*
Sensitivity of the growth rate of OJD transmission, (g) *(%/month)*						
Scenario 1	**N(1.0, 0.5)**	N(26,5)	N(14, 1.4)	0.742	80 000	139 000 000 *(80 600 000)*
Scenario 2	**N(1.2, 0.5)**	N(26,5)	N(14, 1.4)	0.491	115 000	177 000 000 *(84 200 000)*
Scenario 3	**N(1.6, 0.5)**	N(26,5)	N(14, 1.4)	0.073	240 000	259 000 000 *(73 840 000)*
Scenario 4	**N(1.8, 0.5)**	N(26,5)	N(14, 1.4)	0.059	260 000	280 000 000 *(74 2000 000)*
Sensitivity of maximum infection level (Q_S) *(number)*						
Scenario 5	N(1.4, 0.5)	**N(16,5)**	N(14, 1.4)	0.713	86 000	161 000 000 *(63 000 000)*
Scenario 6	N(1.4, 0.5)	**N(36,5)**	N(14, 1.4)	0.063	250 000	225 000 000 *(80 400 000)*
Sensitivity of the maximum cost per infected sheep (c_m) *($/head)*						
Scenario 7	N(1.4, 0.5)	N(26,5)	**N(10, 1.4)**	0.635	94 000	169 000 000 *(69 000 000)*
Scenario 8	N(1.4, 0.5)	N(26,5)	**N(18, 1.4)**	0.131	210 000	230 000 000 *(91 000 000)*

Note: *A bold number indicates a change in the value of the parameter (or sensitivity) compared to the main result.*