Area-Wide Management of Fruit-Flies: What Are the Costs and the Benefits?

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Abstract

Increasing volumes and speed of agricultural trade and the opening of new markets for agricultural products create greater challenges to systems established to protect countries from invasive organisms that can be harmful to human and animal health, crops and natural environments. In reaction to the threat of exotic pests and diseases, the World Trade Organization recognises the right of country members to protect themselves from the risks posed by exotic pests and diseases through the application of Sanitary and Phytosanitary (SPS) measures. One possible response from exporting countries facing SPS trade barriers is to obtain pest-free area (PFA) certification. While large benefits can potentially be achieved from greater access to world markets through the establishment and maintenance of a PFA, certification can be expensive. This paper aims to identify a theoretical framework on which to base the cost benefit analysis and the costs and benefits to be measured, from which a methodology for measuring costs and benefits may be developed. The literature relevant to analysing PFAs reveals that cost benefit analysis of the establishment of PFAs incorporate complex links between the economic aspects of this type of pest management and the biological characteristics of the pest or disease targeted and its environment.

Keywords: Eradication, Surveillance, Queensland Fruit Fly, Area-Wide Management of Pests, pest-free area, invasive species, biosecurity

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1. Introduction

The development of world trade and increase in the intercontinental movement of people and goods has raised concern about threats from invasive organisms that may affect human and animal health, agriculture and natural environments (Abdalla *et al.,* 2000; Cook and Fraser, 2008; Horan *et al.,* 2002; Klassen, 2005; Lichtenberg and Lynch, 2006; Mumford, 2002; Olson and Roy, 2002; Sharov and Liebhold, 1998). In relation to agriculture, invasive species can be the cause of significant costs in production, including increases in pest management expenditures, yield reduction, reductions in consumers' and producers' welfare and loss of export and domestic markets. Investment in research and development (R&D) on biosecurity has, as a consequence, become increasingly important.

The allocation of funding between R&D projects addressing biosecurity issues should be based on expected welfare gains to consumers and producers. Cost benefit analysis (CBA) is a standard economic tool to assess priorities for new biosecurity R&D projects and guide investment decisions. The aim of this literature review is to identify a theoretical framework on which to base the cost benefit analysis, to identify the costs and benefits to be measured and to propose a methodology for measuring costs and benefits. One type of pest management is analysed: the establishment and maintenance of fruit fly free areas through surveillance and control. A methodologically sound CBA is an essential starting point to measure gains from research and development into improved methods of surveillance and exclusion.

The remainder of this review is organised as follows: Section 1 introduces the theoretical framework that constitutes the basis of the cost benefit analysis and reviews important factors that link the development of pest management strategies to the characteristics of the pest and the environment studied, Section 2 examines in detail the costs and benefits to be measured per type of agent (producers, consumers and government), and Section 3 provides methods for estimating key parameters of CBAs for a pest free area.

2. The analysis of pest-free areas: a review of the literature

In reaction to the threat of exotic pests and diseases, the Agreement on the Application of Sanitary and Phytosanitary (SPS) Measures of the World Trade Organization (WTO, 1995) recognises the right of WTO members to protect themselves from the risks posed by exotic pests and diseases. A country may impose bans, quarantine measures or other trade restrictions on products (from a trading partner) that bear potential risks to human, animal or plant life or health (Cook and Fraser, 2008).

One possible response from exporting countries facing these types of SPS trade barriers is to obtain pest-free area (PFA) certification (Klassen, 2005; Lichtenberg and Lynch, 2006). However, this can be expensive, as the establishment and maintenance of a PFA requires the implementation of surveillance systems, exclusion measures and a plan for rapid response in the case of an outbreak (for instance Plant Health Australia's system of response; PHA, 2009).

There is an extensive literature relevant to analysing PFAs, but some of this literature addresses national rather than regional biosecurity schemes. To develop a methodologically sound CBA for a regional PFA requires modification of the national scale approaches already extant in the literature. According to Fischhoff (1977), an accurate CBA assumes that: (1) all significant consequences can be enumerated in advance; (2) meaningful probability, cost and benefit judgments can be produced; (3) the often disparate costs and benefits can somehow be compared to one another; (4) people really know how they value different consequences today and how they will value them in the future; and (5) what people want is to maximize the difference between expected benefits and costs. Thus, the objective is to analyse the cost and benefits of the establishment of a PFA over a period of time.

2.1 Prevention versus control

Prevention and control are the two basic ways of reducing the costs of an invasive species (Olson and Roy, 2005). The regulatory authority or policy maker has to make a choice between different activities aimed at avoiding or mitigating damages from a pest. The choice of establishing and maintaining a PFA results in considerable resources being allocated to prevention activities and strategies for early detection. The only control strategy implemented in case of an outbreak is eradication. In this literature review we compare the choice of PFA certification with its most probable alternative (i.e. pre- and post-harvest control of crops and fruit). Since prevention and control have different costs and deal with the problem of invasive species in different ways, the fundamental question is the right balance between prevention and control measures.

Some studies have examined the role of both prevention and control strategies. Shogren (2000) formulated the problem of managing invasive species as a choice between mitigation (e.g. quarantine, trade and transport regulations to reduce the risk of introduction, and control efforts to reduce the pest population if it has been introduced) and adaptation (changes in production and consumption decisions to reduce the damage caused by the pest). His bioeconomic model does not distinguish prevention and control measures as separate economic problems and, consequently, it cannot be easily approached from a PFA perspective.

Olson and Roy (2005) analyse the optimal levels of prevention and control that minimise expected social costs (from prevention, control and invasion damages) and how these optimal levels vary with the initial invasion size, the invasion growth rate and probability distribution of pest introductions. They obtain different combinations of prevention and control levels depending on the expected marginal damages, the marginal costs of control and the marginal costs of prevention. The authors however, do not compare the changes in social welfare between the different prevention and control levels.

Kim *et al.* (2006) consider the optimal allocation of resources between preventive (exclusionary) measures and control activities. They distinguish in their analysis the notion of discovery as opposed to the arrival or establishment of the pest, noting that there is a time gap between the arrival of the pest, its discovery and its establishment. The regulatory authority or policy maker might then implement control measures upon discovery of the pest (i.e. prior to its establishment but not necessarily soon after of its arrival). Their model examines the trade-offs between pre-discovery preventive activities, post-discovery preventive activities, and post-discovery control activities. Their analysis reveals that it is economically efficient to allocate more resources to prevention measures before an invasive species is discovered as long as the marginal net benefits (avoided damages) from expenditures on pre-invasion preventive activities exceed the net benefits of expenditures in prevention and control after discovery. However, the authors treat discovery as a function of the arrival time and do not consider possible policies that could change the speed of discovery such as surveillance and monitoring activities, which are important investments for the maintenance of PFAs.

Lichtenberg and Lynch (2006) examine the invasive species management problem directly from a PFA perspective. They consider the welfare gains from PFA certification. They analyse and compare two different situations for an exporting country or region: first, the pest is present in the region but the region remains a net exporter; and second, the region chooses to certify itself as a PFA. They assumed the presence of the pest risks a complete cessation of exports, leading to a short-run increase in the supply of produce on the local market. This reflects the case where costs of quarantine or of post-harvest treatment become prohibitive, or there is an export ban. The authors first consider the optimal choice of control measures when the pest is present and then the choice of PFA. Subsequently, they analyse the costs and benefits of PFA certification (see appendix A).

The welfare gains are highly concentrated on producers. When an exporting country or region certifies itself as a PFA then producers may gain from reduced pest damage (increased marketable yield), reduced pest control (e.g. insecticide cover spraying) and reduced quarantine and/or post-harvest treatment. If this PFA certification is recognised by importers then market access can be improved (producers can henceforth export their produce to new markets where a higher price is received). Reduced use of chemicals for pest control and post-harvest treatments may improve the quality of the fruit, which can then be sold at a higher price. However, local consumers' welfare may be reduced as a result of higher prices when a considerable part of the product is exported.

A minimum level of surveillance and monitoring has to be undertaken within the region and at its borders to achieve PFA certification and maintain pest-free status. Maintaining pest-free status also requires immediate eradication in case of an outbreak. After the establishment of a PFA, some surveillance and monitoring costs are variable functions of the frequency and intensity of monitoring. However, once the system has been demonstrated to be effective these costs may become fixed. Hence, fixed costs of surveillance, monitoring and eradication protocols under area freedom certification are assumed in Lichtenberg and Lynch's model.

Lichtenberg and Lynch's analysis provides a basic framework for a deterministic evaluation of welfare gains from PFA certification. However, further elements could be included in their study. In particular, those associated with the characteristics of the pest and spatial factors.

2.2 The characteristics of the pest and spatial factors

With PFA certification, the expected costs of eradication partly depend on the probability of new incursions. Lichtenberg and Lynch (2006) assume this probability to be constant. Yet the probability of incursions might change over time for some invasive species. In the case of Queensland Fruit Fly (Qfly) in Australia, there has been an increase in the incidence of outbreaks in areas such as the Murrumbidgee Irrigation Area, Sunraysia (both located within the Fruit Fly Exclusion Zone) and Adelaide since 1987 (Sutherst *et al.*, 2000). Climate change may permanently shift the distribution of the fly through time, possibly increasing the probability of incursion in more temperate areas.

Moreover, as the Qfly population spreads and finds more hosts, the density of the fly population beyond the borders of the Fruit Fly Exclusion Zone (FFEZ) can naturally increase over time. Consequently, the probability of Qfly being spread through new and numerous transit vectors may increase (for instance, due to an expansion in the traffic of fruit). Therefore, there may be a trend of increasing numbers of incursions independent of climate change.

The pest population size and its spread are important components of their impact upon crops. In the Lichtenberg and Lynch (2006) model, the pest population size changes over time according to its net natural growth (including immigration) after control measures are put in place. However, the initial size of introductions and the rate of spread of infestations are not necessarily known with certainty. Generally, there is little empirical evidence to accurately assess the probability of establishment of a pest, its distribution and impact in a new environment (Myers *et al.*, 1998). Moreover, the Lichtenberg and Lynch (2006) analysis does not include spatial factors determining invasions and their control, such as the area occupied by the pest, the impact of the pest per area unit, the dispersal patterns of the invader and heterogeneity of the landscape.

Bioeconomic analyses of invasive species management policies have only incorporated recently the spread geometry and rate of spread of the pest in their models. Sharov and Liebhold (1998) consider some spatial factors of invasions and their control in their study. They analysed the costs and benefits of modifying the rate of spread of invasive species. They consider the dispersal patterns of the pest by including spread predictions that assume random diffusion in a homogenous environment (reaction-diffusion model, with a radial rate of spread that is constant in every direction; see appendix C). Although the study does not approach the problem from a PFA perspective, it emphasises the importance to a CBA of certain factors that may significantly affect results. The authors demonstrate that when a pest is present, stopping its spread is not an economically viable strategy unless there are natural barriers (see also Sharov, 2004). The optimal pest management strategy (eradication of the pest, slowing the spread of the pest or doing nothing) depends on the size of the infested area (compared to the potential species range), the damage caused by the pest per unit area and the discount rate chosen to calculate the present value of net benefits. The authors acknowledge however, that for theoretical purposes the assumptions of reaction-diffusion models are more convenient, but the rate of spread of a pest from its introduction point can change according to the direction of spread and the area that can potentially become infested.

Carrasco *et al.* (2009) also adopt a reaction-diffusion model of pest spread. The authors identify the optimal control policy depending on the size of the invasion at discovery, the rate of spread of the pest and the capacity of the regulatory authority to reduce this rate of spread. They analyse the switching point between different management policies depending on the stage of the invasion (arrival, establishment and spread). They demonstrate that eradication is optimal for small initial sizes of invasion when the pest is detected or for larger sizes of initial invasion if the regulatory authority has a high capacity of reducing the rate of spread of the pest.

However, reaction-diffusion models do not capture long distance dispersal events (when invasive species expand their area of infestation via establishment of isolated colonies). Jump-diffusion models amend reaction-diffusion by including long distance jumps as a second method of dispersal alongside localised diffusion (Shigesada *et al.*, 1995). In the case of fruit flies, a jump can be triggered by travellers carrying infested fruit away from the pest population front creating isolated colonies (or satellite colonies). If not controlled, these colonies grow, coalesce, and contribute to population spread (Sharov, 2004). Consequently, accelerating rates of dispersal can be observed.

Working on the economics of surveillance, Kompas and Che (2009) assume that both the spatial growth of an infested area and growth in population density follow logistic functions, rather than a Malthusian constant rate of growth. In the case of surveillance, this implies that the area infested can initially grow almost exponentially, then growth slows as saturation begins and when the species reaches its potential range, growth stops; so with all else equal, surveillance expenditure has diminishing marginal benefits.

2.3 Pest-free areas and surveillance activities

The benefits of managing the population spread are also determined by how early the pest is detected. The time until detection may be reduced by investing more heavily in a surveillance programme, with early detection likely critical to successful eradication. Kompas and Che (2009) analyse the problem of determining the optimal plant surveillance measure for an exotic pest or disease.

An optimal level of surveillance effort is one that minimises the costs associated with a potential pest or disease invasion at three levels: the damage and revenue losses caused by the pest or disease before and after it has been detected, the costs of pest or disease management once it has been detected and the cost of the surveillance programme itself (see appendix B). Kompas and Che (2009) apply their model to the case of surveillance of Papaya fruit fly (Pfly) in Australia. In general, the earlier the pest is detected, the lower will be the damage incurred and the cost of pest management. There is a trade-off between earlier detection and cost.

2.4 CBAs of pest-free areas and research and development investment

The above models will have to be adapted before providing a theoretical framework for CBA that is useful in policy-making and prioritising investment in R&D. Research on biosecurity is an investment (in the production of knowledge) that competes with other activities for scarce resources. Like for any investment, a choice has to be made between alternative investments (Alston *et al.*, 1995), so the results of CBAs may provide a guide for biosecurity R&D projects to be prioritised.

Research projects provide knowledge that either complements existing technologies or substitutes them. The regulatory authority then faces the problem of choosing an investment on biosecurity research that optimises the technology in use or an investment that develops a new one. The dynamics of technological competitions, however, can be quite complex. The system usually tends to reinforce the use of an already dominant (extensively used) but inferior technology, locking the market into one technology, and ignoring other competing technologies (with a relatively small amount of development) that could well be superior if developed (Cowan and Gunby, 1996). Policy directions should therefore concentrate resources in a way that overcomes this inertia.

3. Welfare impact

Pest-free area certification represents a welfare increase when the economic gains from exports, reduced pest control and reduced pest damage offset the cost of surveillance, monitoring and eradication protocols necessary to maintain area freedom certification. A cost benefit analysis is based on a comparison of a country or a region over a planning horizon with and without PFA certification. For a full CBA, the measure of welfare is the sum change in consumers’ and producers’ welfare for the affected population over the life of the PFA, relative to the costs of establishing and maintaining the PFA. Instead of a full CBA, some studies only account for producer surplus and implicitly assume that consumer surplus is unchanged (for instance PricewaterhouseCoopers, 2001). The welfare impact on different types of agents (producers, consumers and government) are considered in turn.

3.1 Producer welfare

With the establishment of the PFA, producer surplus (profit plus fixed costs) may be subject to any of the following effects: First, a *price effect* as average producer prices rise due to a larger proportion of produce selling to high price export markets. Second, an *input use effect* resulting from a reduction in the application of pesticide. Third, a *crop damage effect* with reductions in crop losses due to the absence of pests. Fourth, a *post-harvest cost effect* where the PFA mitigates the need for expensive post-harvest treatments such as chilling prior to the supply of produce to export and domestic markets. Fifth, a *quality effect* where fruit exported without post-harvest treatment tends to be of a higher quality and thereby receiving a price premium on both domestic and export markets. Sixth, a *compliance effect* relating to costs associated with complying with the surveillance, monitoring and eradication (in case of an outbreak) requirements for PFA certification. Other effects can be identified, such as benefits to those involved in the stages of production beyond the farm gate, and the improved attractiveness of the PFA for agricultural investments, but quantifying reliable values for these benefits is likely to be difficult.

Producer welfare should be assessed both in the short run and long run. For instance, the establishment of a PFA may lead to investment and establishment of new production capacity leading to a new equilibrium in the industry. In contrast, the demise of a PFA may see a gradual reduction in production until the industry reaches a new equilibrium.

3.1.1 Price effect

Export markets demanding low pesticide and/or low pest commodities are growing (Hendrichs *et al.*, 2005; Mumford, 2005). As a response to this, countries or regions seek PFA certification and implement area-wide integrated pest management programmes to increase trade opportunities (Devorshak, 2007). This is the case for the FFEZ (Jessup *et al.*, 2007). With area freedom certification potentially providing access to high price export market, then CBAs of pest-free area certification need to include the benefits of new market opportunities or improved retention of existing markets.

The costs of restricted market access have to be evaluated conservatively in order to avoid overestimating the total welfare benefits of PFAs (Beare *et al.*, 2005). For instance, the assumption that the removal of area freedom certification permanently closes the access to a particular market may lead to overestimation. In some cases, producers might be able to continue exporting to the same markets after disinfesting the fruit. Mango exports from north Queensland during the Pfly outbreak can be cited as an example of this. Mango exports to Japan were stopped soon after Pfly was detected and rapid restoration of these exports was a priority. An acceptable vapour heat treatment was developed and the lucrative Japanese market re-opened with only one season lost to local growers (Cantrell *et al.*, 2002). In some other cases, the estimates of lost market access can also increase if the commodities produced outside the infected area are also (assumed to be) banned. Beare *et al.* (2005) cited as an example the possible overestimation of market losses during the citrus canker incursion in Queensland.

Moreover, to estimate the gains from exports the variability in response of importing countries to either pest presence or pest outbreaks in the exporting country, and the prices received from different markets (international and domestic) for produce, have to be compared. When the pest is present and, as a result, a ban is imposed by one or more importers then alternative markets not imposing these prohibitive bans may replace the traditional one. Consequently, production hitherto exported to those countries might be diverted to other international markets (that do not impose a ban but require quarantine or post-harvest treatment when the pest is known to be present) as well as the domestic market. Hence, high-priced markets may be lost but the commodity may be sold to alternative markets where a lower price is received (Beare *et al.*, 2005; Waage *et al.*, 2004).

In contrast, some revenue losses could be neglected. The Productivity Commission (2002) highlighted that revenue losses may continue even after an animal disease has been eradicated, due to the time taken to rebuild international markets. This is also the case for horticultural products: even if the pest is no longer present, a number of years of proven pest-free status may be necessary before access to some markets is again approved (Enkerlin, 2005; Hinchy and Fisher, 1991).

3.1.2 Input use effect

Another important benefit of pest-free status is the avoided cost of pest control. Without PFA certification, producers would have to implement control measures (e.g. insecticide cover spray) to diminish yield losses caused by the pest. However, depending on the case studied, the estimation of avoided control costs may be fairly complex. In the case of a programme that eradicates or reduces a pest, the previous costs of control (prior to the implementation of the programme) are relatively well known. Mau *et al.* (2007) showed the benefits to single farmers of reduced insecticide cover spraying after participating in the Hawaii Area-wide Fruit Fly Pest Management programme. But for non-invaded areas the potential costs of control if the pest becomes established can only be estimated from the expected value of inputs that would be necessary to control the pest (e.g. pesticides, the costs of labour and equipment). This cost would depend on the potential distribution, abundance, and spreading rates of the invaders (Stohlgren and Schnase, 2006).

PricewaterhouseCoopers (2001) estimated the likely annual costs of fruit fly control in the Fruit Fly Exclusion Zone (FFEZ) if PFA certification was abandoned. They obtained information on the control costs per hectare for some horticultural products in Queensland and multiplied it by the estimated areas under production of the same products in the FFEZ. Although the authors adjusted the costs for a lower intensity of infestation in the FFEZ compared to the infestation in Queensland, they did not actually calculate this infestation intensity and did not take into account the potential distribution of the pest and its rate of spread. There is always some question about the validity of supposing what the impact of a pest would be in a particular area from experience in another region because conditions can vary greatly (Hinchy and Fisher, 1991). So the economic evaluation of pest control requires an understanding of the biological features of the pest and accurate taxonomic, geographic, and temporal data concerning the pest in the region studied (Stohlgren and Schnase, 2006).

3.1.3 Crop damage effect

Some of the benefits of PFA certification correspond to the reduction or elimination of the estimated production losses. Without certification, farmers would take action to reduce damage caused by the pest. Hence, production losses would be overestimated if instead no pest management was assumed (Joffe, 1998). For this reason, when evaluating the costs and benefits of pest-free area certification, studies that try to identify the potential loss to agriculture in the absence of pest control and compare this potential loss with the actual or prospective costs of control are not relevant to this literature review (e.g. Wright, 1986; AECgroup, 2002). The potential yield losses that a pest can cause are important since the optimal control policy for a pest can change significantly depending on the damage costs per unit of invaded area (Carrasco *et al.*, 2009; Kompas and Che, 2009; Sharov, 2004; Sharov and Liebhold, 1998).

In order to calculate the potential production losses of a pest over time, a number of biological parameters must be considered (Kompas and Che, 2009). Scientific analysis may provide this information, as well as the estimated production losses under different control strategies. However, agricultural production may be stochastic· Producers may apply a certain level of inputs in order to produce a planned level of outputs, but the actual output can be different from the planned output because of factors that are not under the control of producers, such as weather, natural disasters and diseases (Hinchy and Fisher, 1991). Additionally, as it has been mentioned before, the empirical evidence may not provide an accurate assessment of the probability of establishment of a pest, its rate of spread in time and space, and its behaviour in a new environment.

Some other important elements have to be considered when estimating the crop damage effect. The evaluation of producer losses due to an exotic pest becoming established is generally based on cuts in farm yield (usually calculated through the value of crops multiplied by the estimated potential physical loss)[1] and do not take into account the ongoing effects on producer revenues[2] (Myers *et al.,* 1998). This may lead to an overestimation of the benefits. Also when uncertainty exists regarding the probabilities of biological invasions, the public and decision makers might consider the potential losses more seriously than if better information on the risks was available[3] (Hoagland and

[1] Pimentel *et al.* (2000) estimated in the value of crop losses in the USA due to introduced pests. The authors multiplied the value of total potential US crop production by the percentage of crops that introduced pests destroy. Mau *et al.* (2007) presented the estimated benefits to single farmers from applying the Hawaii Area-wide Fruit Fly Pest Management programme (the programme's objective was to suppress populations of three types of fruit flies). These benefits include the yield increase, improved quality (price increase), improved labour productivity and reduced control costs.

[2] A pest can reduce farm yield, but depending how these losses are distributed between producers, the actual costs to producers might be smaller than the value of yield loss. For instance, if the pest is widespread, in agricultural systems a loss in output can increase revenues to producers (the price of the commodity is adjusted by the law of supply and demand, according to the price elasticity).

[3] Given the uncertainty attached to both the probabilities of biological invasions and the productivity of preventive biosecurity measures, another set of questions involves the decision maker's choice between prevention and control as a function of human preferences for risk (see Finnoff *et al.*, 2007).

Jin, 2006). In such cases, the expected benefits of biosecurity measures, and the reduction of the risk of pest invasions, tend to be overestimated (Horan *et al.*, 2002; Perrings, 2001).

3.1.4 Post-harvest cost effect

Reduced quarantine and/or post-harvest treatments of products grown in a PFA are also a significant advantage mainly because post-harvest disinfestations treatments are relatively expensive processes (Lindner and McLeod, 2009). These benefits apply to domestic as well as export markets. Chemical treatments (mainly methyl bromide or ethylene dibromide fumigations and dips) and cold storage are used for many fruits and fruit fly species (Hallman and Quinlan, 1996; Lindner and McLeod, 2009).

Estimates of costs of post-harvest treatment per tonne for particular products can be found in some studies. In the case of the FFEZ, cold-disinfestations of citrus and pome fruits have been estimated at $50/tonne and chemical treatment of stone fruit and other fruits at $100/tonne (TriState, 2003). In order to estimate these costs, previous CBAs of different post-harvest disinfestation methods have obtained information on the price applied by companies involved in each type of treatment and the characteristics of the fruit (the type of treatment applicable to the fruit and the amount necessary to disinfest it).[4]

Legal restrictions on the use of chemicals for post-harvest treatments may change the costs and benefits of PFAs and R&D projects. Since the mid 1980's, several countries have progressively banned fumigations with ethylene dibromide due to safety concerns and growing public resistance to chemical pest control (Lindner and McLeod, 2009). This has also been the case for methyl bromide. Although the latter can still be used for quarantine and pre-shipment purposes, its progressive phase out for all other purposes and concerns about its negative impacts on the environment and human health may reduce its availability in the future. Under such circumstances, exporting countries will need to find alternative technologies to secure market access; for instance, integrated pest management systems such as PFAs. Research on alternatives might not have an immediate value but could generate potential benefits if they rapidly provide the industry with an alternative when it will be needed.

[4] Mahlous (2002) estimated the cost of cold storage of dates per tonne per month to compare them with irradiation costs.

3.1.5 Quality effect

The benefits of reduced post-harvest treatments and avoided pest control are not limited to how much these activities would cost: the absence of chemical residues from abatement of pesticides in control and post-harvest treatments may also add to the benefits of PFA certification. Chemical residues and cold storage treatments may reduce the quality of the commodities treated and therefore affect marketability (Sutherst *et al.*, 2000; ABARE, 2009). Fruit of higher quality can also attract price premiums if consumers prefer non-treated fruit and are willing to pay more for it.

3.1.6 Compliance effect

There are also costs associated with the maintenance of PFA for producers. These include compliance costs for surveillance and monitoring in maintaining the PFA, and costs borne by producers during eradication of fruit fly outbreaks. In the absence of a PFA, these costs would be replaced by general control costs. For instance, in the FFEZ when an outbreak is declared, bait spraying is required in the outbreak zone (200 metre radius from the incursion point) and a larger outbreak area (1.5km radius from the incursion point). There are also quarantine costs for producers and packers during the eradication campaign: all fruit fly hosts within 15km from the incursion point are classified as being in a suspension area and has to be disinfested before being sent to fruit fly free areas (PricewaterhouseCoopers, 2001).

3.2 Consumer effects

For a full CBA both consumer and producer's welfare are accounted for. However, some CBAs only take into consideration changes in producers' welfare, or do not provide a thorough analysis of consumers' surplus. It could be argued that when the investment is paid for by producers alone and the establishment and maintenance of a PFA is the result of a commercial decision for producers acting cooperatively, only their welfare would need to be accounted for. However, the success of area-wide integrated pest management programmes largely depends on effective management and public support, which necessarily involves public financing, public accountability, legislation, enforcement, community participation and substantial infrastructure and organisation (Dyck *et al.*, 2005). The problem is then estimating the net social benefits of this pest management strategy, including both consumer and producer's welfare.

Measuring the effects of PFA certification or other policy changes on the welfare of consumers may appear more difficult than that of measuring the impact on producers (Hinchy and Fisher, 1991). The later are assumed to maximise profits, so the change in profits can be used to measure the welfare impact of a policy change. But consumers' welfare is determined by the quantity of goods that they can consume in accordance with their preferences, their income and the prices of the goods. Consumer surplus increases as higher quantities of a product are obtained at a lower price.

On the one hand, the establishment of a PFA will initially reduce domestic consumer surplus as larger quantities of product are diverted to export markets and prices rise. As a result of the absence of the pest and the subsequent reduction in production losses, there is an increase in the overall supply of produce, but larger quantities are exported. Consequently, domestic supply decreases and prices augment in the domestic market. On the other however, consumers may benefit from knowing that a product is free of a particular chemical, therefore there might be a willingness to pay for reduced pesticide contamination in produce.

Clearly, every modification in the pest management strategy will have an impact in both consumer's and producer's welfare. In any case, consumer surplus is likely to be higher when all production is consumed locally. Even in the event of an outbreak (under PFA certification) if post-harvest treatments are excessively costly or an export ban is imposed, the consequent flooding of produce onto the local market may raise consumer surplus in the short term.

3.3 Government expenses

In the literature dealing with invasive species, preventing the entry of a pest in an area is generally regarded as the most profitable strategy when calculating costs of quarantine services (Finnoff *et al.,* 2007). It is usually considered cheaper to protect the PFA (region or country) from the introduction and establishment of a pest and prevent the pest problem than to deal with it through control or eradication (Enkerlin, 2005; Hendrichs *et al*., 2005). However, PFA certification can be expensive, as this requires implementing certain activities to maintain area freedom. These can include border control, surveillance, eradication and maintenance of quarantine areas when an outbreak occurs, research and development, communication/education costs and management costs.

3.3.1 Border control

For the majority of fruit flies, and in particular in the case of Qfly, the main mode of entry into a fruit fly free area is by movement of infested fruit (Clift and Meats, 2001). Border control activities are therefore essential for the maintenance of PFAs and reducing the likelihood of outbreaks. By preventing the entry of the pest, eradication costs are avoided. PricewaterhouseCoopers (2001) obtained information on funding provided by the Commonwealth and State governments and industry to cover costs associated with roadblocks in the FFEZ (road signs, monitoring of the movement of vehicles, accrediting staff and control of the movement of host fruit). In addition to minimising the probability of pest arrival, the maintenance of a PFA also depends on early detection.

3.3.2 Surveillance and monitoring

The objective of surveillance is to minimise the period between the arrival of a pest and its discovery. Early discovery of the pest may diminish the risk of an outbreak, for instance, if the flies are detected and destroyed before they can breed. Effective post border monitoring and surveillance may reduce the time of detection of established outbreaks and the costs associated with the presence of the fly; such as yield losses, control costs and eradication, and loss of market access (Lindner and McLeod, 2009).

The presence and absence of fruit flies is monitored by the national trapping grid in Australia. In the case of the FFEZ, regulatory authorities use a sophisticated grid system of fruit fly traps, bar codes and bar code readers, and an internet-based recording and reporting system to monitor the pest presence (Jessup *et al.*, 2007). Approximately 3000 Qfly and 3000 Mediterranean fruit fly (Medfly) traps are deployed within the FFEZ on a 400 metre grid in towns and a kilometre grid in fruit production districts (TriState, 2003). PricewaterhouseCoopers (2001) estimated the costs of surveillance in the FFEZ using Commonwealth and State government data on operational costs that included activities such as maintenance of the fruit fly trapping grid and fruit fly trap monitoring. In the case of Pfly, Kompas and Che (2009) obtained direct expenditure on lures to estimate the costs of the surveillance system for Pfly in Australia, including their installation, monitoring, diagnosis and embodied travelling time. A percentage was added to account for indirect costs (such as publicity, awareness campaigns, and laboratories). However, indirect costs of administration or other management were not included.

3.3.3 Eradication

In case of an incursion within a PFA, pest populations are eradicated as soon as possible after detection to restore a pest free status. The costs of eradication may be a function of the size of the invading population and the area invaded. According to Myers *et al.* (1998), cost benefit analyses of eradication comprise biases that tend to overestimate benefits and underestimate costs. Eradication costs may be underestimated because they often include direct effects only, such as immediate expenditure for personnel, materials, and equipment, but other costs that are more difficult to evaluate are often ignored. The later can include the pre-treatment preparation[5] and the costs of reducing the pest population before eradication takes place[6]; communication, public relations and consultation spent by the agencies proposing the eradication programme; escalating costs for locating and killing the last individuals[7]; expenditure in higher surveillance to avoid potential reintroduction[8]; additional efforts to prove the absence of the pest; and side effects of pesticide treatments to human health and the environment (e.g. non-target death of native species, chemical accumulations in waterways). In order to estimate eradication costs in the FFEZ, PricewaterhouseCoopers (2001) obtained information on the costs of bait spray applications, the operation of a fruit fly production facility in New South Wales, the sterile fruit fly maintenance and release activities and other operational costs associated with eradication.

3.3.4 Research and development

The boundaries of the costs of R&D concerning a particular programme may be difficult to fix. The costs of research and development directly related to a PFA can be limited to the costs assumed by the regulatory authority or to the costs of projects that unequivocally benefit the PFA establishment and maintenance. For instance, PricewaterhouseCoopers (2001) estimated the costs of research and development directly related to the FFEZ by considering only two research projects: one designed to gain a deeper understanding of the movement of Qfly infested fruit into the FFEZ and another in relation to sterile insect technology. However, research conducted by other agencies can also generate substantial benefits to the PFA and, consequently, the costs of research and development may easily be underestimated.

Substantial benefits may be generated by fruit fly R&D.[9] Research that develops better surveillance systems may reduce the risk of losses that would result from a fruit fly incursion through earlier detection. Improved surveillance systems, if properly implemented, might increase the benefits generated by the establishment and maintenance of PFAs (e.g. add to the benefits of the FFEZ).

[5] These can include all demonstrations and trials to prove the effectiveness of techniques and to build technical capacity and public confidence before a particular technique is used for eradication.

[6] For instance, in order to use Sterile Insect Technique (SIT) for eradication, the pest population has to be reduced to a low-enough density level so that the SIT control is effective. In the case of Medfly this can cost approximately US$6000 per km^2 (Mumford, 2005).

[7] The marginal costs of eradication increase with falling pest population density (Hoagland and Jin, 2006), but this is usually not taken into account when estimating the costs of eradication. Moreover, marginal costs of killing an insect also rise with spread. Thus the costs of locating and killing the last individuals depend upon the pest population size and its spatial spread. Kotani *et al.* (2009) indicated that the cost structure of an eradication programme depends on the methods or technology used.

[8] Stricter quarantines and other exclusion tactics may have to be implemented to decrease the probability of reintroduction and to prove pest-free status (Mumford, 2005).

[9] Quantifiable benefits from fruit fly research projects can be either potential or realised benefits. For an examination of why prospective benefits might not always be achieved see Lindner and McLeod (2009).

Research that demonstrates non-host status of produce could enable access to new markets for horticultural exports. Better methods for the control and management of fruit flies might reduce some of the crop losses caused by the pest, lower the costs of control activities and/or attract new agricultural investments that enable the development of new industries (Lindner and McLeod, 2009). Alternative methods of control that reduce or substitute pesticide use could result in less negative side effects to human health and the environment. Improved and cost-reduced post-harvest treatment processes can generate new market access benefits. However, some research outcomes, such as lower costs of control activities and improved post-harvest treatments, could reduce the gains from the maintenance of PFAs.

3.3.5 Education/communication costs

Expenditure in education/communication is also important for the maintenance of pest-free status, as lack of awareness within the community can compromise the PFA by increasing the frequency of incursions and the time taken to detect pest outbreaks. These costs can include information provided to packing sheds and growers and education to the community and travellers in the surrounding area.

3.3.6 Management costs

Management costs generally include strategic planning, staff management, technical support and management of all legal and policy aspects of a PFA. They can also incorporate accreditation and inspection of packing sheds, and audit of compliance agreements. However, some costs associated with the absence of the pest are sometimes ignored. These can include the costs of publicity and marketing of the improved pest free quality produce from the PFA, and additional management and infrastructure necessary to deal with the possible increased pressure on land use resulting from the absence of the pest (Mumford, 2005).

4. Methods for estimating costs and benefits related to a PFA

4.1 Probability of pest outbreak

The potential production costs (crop damage effect) depend on the probability of pest outbreak. The benefits of border control can be estimated as the gains obtained from delaying the time to the next pest outbreak (Beare *et al.*, 2005) or keeping outbreaks as far as possible from cropabundant zones. The threat of pest outbreak is determined by the risk of the pest arrival and how likely it is for the pest to become established[10] (see appendix E). A pest incursion is more likely to occur when border activities are not effective and a high number of potential carriers of the pest can enter the PFA. The amount of infested fruit carried by each of them also affects the probability of pest introduction (Horan *et al.*, 2002). However, reliable data on the number of pest carriers entering a PFA and the amount of infested fruit that they carry might not be available. As a consequence, different methods have been used to calculate the probability of outbreak; in particular, by looking at the number of past incursions.[11] As it has been mentioned before, however, this probability might not remain constant over time for some pests (due to climate or other changes to the distribution of the pest).

Once the pest has been introduced, a number of factors determine how likely it is for the pest to spread and become established. Knowledge about this is essential to evaluate the invasion pressure (Hendrichs *et al.*, 2005). The spread or dispersal ability and the probability of establishment of a pest depend on a number of variables such as host density, host numbers, and season (Hinchy and Fisher, 1991). Some other factors that should be considered when looking at the spreading and establishment potential of a pest include the environmental characteristics that may predispose a habitat to invasion, potential for adaptation of the pest, reproductive strategy of the pest, method of pest survival, movement of commodities and potential natural enemies of the pest (Nairn *et al.*, 1996; Stohlgren and Schnase, 2006).

If the pest is introduced into a PFA and an outbreak is declared, the pest populations are soon eradicated to restore pest-free status and maintain certification. Therefore, the probability of pest outbreak not only has an effect on the potential production costs but also on the potential costs of eradication. Moreover, when an outbreak is declared, it is important to investigate how successful eradication activities may be.

4.2 Probability of eradication

The expected costs of eradication are determined by the probability of pest outbreak and how likely it is for the eradication campaign to be successful. Myers *et al.* (1998) and Kompas and Che (2009) identified some factors that may affect the success or failure of eradication programmes. The

[10] According to Stohlgren and Schnase (2006), studies that focus on particular species in selected regions might get more accurate probabilities because the characteristics of the species' life history are important factors to estimate potential invasions.

[11] Kompas and Che (2009) estimated the probability of a Pfly incursion in Australia by looking at the number of Pfly incursions since 1990. They obtained a probability of one every five years and assumed that this probability is characterised by a normal distribution with a standard deviation of 10%, or N(0.2, 0.02).

timing of the discovery of a pest in a PFA and how long it takes for the regulatory authority to initiate an eradication programme to restore area freedom are important factors. Eradication programmes have more chances of being achieved when monitoring techniques for low densities are efficient and inexpensive. Eradication also has more chances of being rapid and cost-effective when the pest is detected early. The way in which the eradication campaign is carried out can significantly change the outcome; an aggressive eradication programme supported by the public may result in a successful eradication. Public conviction that a pest is of potential economic importance, and support from effective education programmes, are key elements also contributing to the success of eradication campaigns.

Some other factors, linked to the biological characteristics of the pest or disease targeted, make a pest more or less susceptible to eradication. Organisms that migrate by short-distance dispersal[12], have low reproductive rates, few generations per year, do not have genetic variability and do not develop resistance or behavioural change to control pressures are more likely to be successfully eradicated (Myers *et al.*, 1998; Shigesada *et al.*, 1995). The host and the habitat requirements of the pest also need to be considered; with greater probability of eradication when the potential species range and its likelihood of adapting to the new location are low.[13] Powerful suppression methods (such as sterile male, insecticide baits, and potent insecticides) also influence the success of eradications. Other pest characteristics that might have an effect on the probability of eradication includes, among others: the survival of the pest; its capacity to move independently of infested hosts; the range of hosts it can attack; and, the attractiveness of lures in the case of fruit flies.

4.3 Behavioural elements

The probability of an outbreak within a PFA decreases when biosecurity measures increase in efficiency and make introductions less likely. Invasion pathways and the frequency of pest introductions into a vulnerable area depend on patterns of trade and travel (Perrings *et al.*, 2002). So the invasion probability increases with the number of potential carriers of the pest (e.g. travellers carrying Qfly infested fruit into a PFA). When the number of potential carriers becomes very large then invasion becomes virtually certain (Horan *et al.*, 2002). Some authors explain this by emphasising the fact that prevention of invasive species in agriculture depends on the least effective contributor. For example, in the case of border control, if one roadblock is not effective and fails to

[12] Pest migration by short-distance dispersal expands the infested area from its periphery, while long-distance dispersal generates new satellite colonies that can be far from the pest population front (Shigesada *et al.*, 1995).
[13] For instance, some characteristics of the screwworm might contribute to its successful control. One of them is its association with mammals. Major populations of screwworms are likely to be associated with herds of domesticated mammals, so its distribution is easier to monitor for the release of sterile males. Also, the fact that screwworm flies can be trapped and are easily produced and sterilised in the laboratory contributes to its eradication (Myers *et al.*, 1998).

keep the pest out of the PFA, the fact that all others may be effective is irrelevant. The risk to all depends on the capacity of the weakest contributor (Perrings, 2001). The prevention of pest invasions has therefore been described by some authors as a public good problem of the "weakest link" type: a public good because of its non-rival benefits and non-excludable beneficiaries (Hinchy and Fisher, 1991; Burnett, 2006), and a "weakest link" because the level of prevention is determined by the weakest contributor (Horan *et al.*, 2002; Perrings, 2001; Perrings *et al.*, 2002; Shogren, 2000). This is also true for monitoring and controlling pests, whether the control involves eradication, suppression, containment or any other type of control (Perrings, 2001; Perrings *et al.*, 2002).

Some authors argue, however, that the prevention of invasive species should be modelled as a "weaker link", instead of a "weakest link" public good (Burnett, 2006). If the level of prevention is considered to be determined by the weakest contributor, this would imply that zero prevention by one contributor causes the overall level of prevention to be zero effective. Generally, this should not be the case. So, for a weaker link public good, lower investments by some contributors reduce the returns of those that invest more, but those that invest more may benefit from higher protection than the poorer contributors. However, the incentive structure that results from the weaker link public good problem causes contributors to inadequately invest in invasive species prevention (individual contributors might invest less expecting that others will provide sufficient levels of prevention; see appendix D).

5. Conclusion

Investment in R&D on biosecurity has become increasingly important as a result of growing concern about threats from invasive organisms. The evaluation of past research investments on biosecurity, the analysis of alternatives and prioritising research investment are all determined by economic and productivity issues.

There is an extensive literature analysing the (economic) problems caused by invasive species. Parts of the literature focus on the benefits of living without a particular pest or disease (e.g. AECgroup, 2002; Mumford *et al.*, 2000; Waage *et al.*, 2004; Wright, 1986). Other approaches concentrate on the optimal trade policy to address the invasive species issue (Cook and Fraser, 2008; Costello and McAusland, 2003; James and Anderson, 1998) or optimal preventive measures (Horan *et al*., 2002; Mumford, 2002).

Knowledge on the bioeconomics of pests and diseases management has significantly increased in recent years. After an invasive species has been introduced into a new environment, some studies concentrate on assessing the optimal trade-off between preventive (exclusionary) measures and control efforts (Finnoff *et al.*, 2007; Jensen, 2002; Kim *et al.*, 2006; Leung *et al.*, 2002; Olson and Roy, 2005) or determining the biological and economic parameters that induce a country to control an invasive species (Saphores and Shogren, 2005). Some others have focused on determining if eradication is the optimal pest management strategy (Burnett *et al.*, 2007; Eiswerth and Johnson, 2002; Fraser *et al.*, 2006; Kotani, 2009; Myers *et al.*, 1998; Olson and Roy, 2002).

Many of the bioeconomic modelling approaches have concentrated on pest population dynamics (Andow *et al.*, 1990; Shigesada, 1995), but few have included the dispersal patterns of the invasive species (Cacho *et al.*, 2008; Carrasco *et al.*, 2009; Sharov and Liebhold, 1998; Sharov, 2004).

The literature relevant to analysing PFAs reveals that cost benefit analysis of the establishment of PFAs incorporate complex links between the economic aspects of this type of pest management and the biological characteristics of the pest or disease targeted and its environment. Cost and benefit estimates can lead to different outcomes depending on how these links are examined. There is a risk of overestimation of benefits and underestimation of costs that may inefficiently direct biosecurity R&D investments.

The welfare gains of establishing and maintaining a PFA are highly concentrated on producers/growers, whereas its implementation depends on government intervention. In terms of economic efficiency, the main justification for public-sector investment in this type of pest management is that there is a "market failure" in the private production and funding of key activities necessary to the maintenance of PFAs. The prevention, monitoring and control of invasive species are therefore a public good problem. This is also the case for research on biosecurity and has implications for investments priorities. Because public resources are limited, to solve the problem of a market failure the regulatory authority should concentrate a higher proportion of the resources available on types of research that the private sector has relatively little incentive to support, but have a high social payoff.

Further research on the subject could incorporate a number of elements that have been either ignored or simplified in previous work. First, the variability in response (of importing countries) to either pest presence or pest outbreaks (in the exporting country) may be studied, allowing for strategic behaviour on the part of the importers in terms of quarantine or PFA requirements. Second, the spatial dimension of invasions and their control could be analysed under different assumptions than those put forward in reaction-diffusion models (random diffusion in a homogenous environment); for instance, by including functions that take into account the distribution of host fruit and other characteristics of the invaded environment. Finally, the invasive species issue raises the problem of private actions where individuals do not consider the consequences for social welfare.

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Appendix A

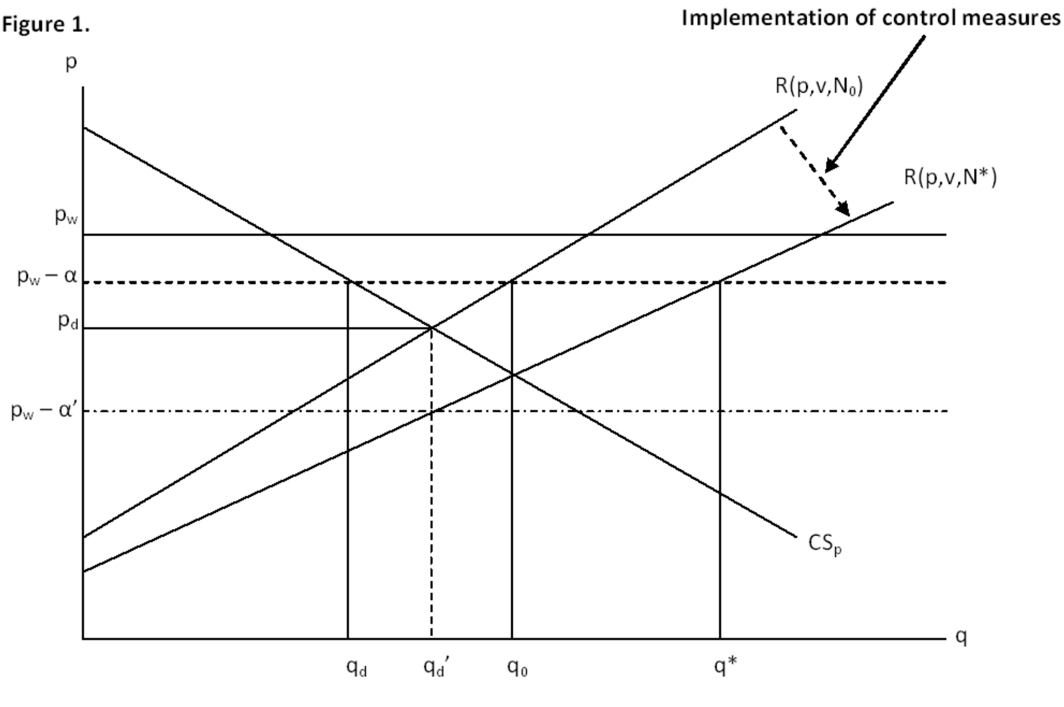
Optimal certification of pest-free status

Lichtenberg and Lynch (2006) analyse the case of an exporting country or region with and without PFA certification.

Without PFA certification, when a pest is present, the region (country) decision maker may choose different levels of control level w at a unit cost of c_w for different periods in order to maximise consumer and producer's surplus in the long term. Consumer surplus $CS(p)$ is a function of p, the price of the product. Production is characterized by a restricted profit function, $R(p,v,N) = \max_s \{pf(s,N) - \sum v_j s_j\}$, where $s_1,..., s_J$ are inputs, $v_1,..., v_J$ are input prices, N is the pest population size and $f(s,N)$ is the production function.

Let p_w be the world market price and α the unit cost of the quarantines and/or treatments required for exports when the pest is known to be present. The country remains a net exporter when the level of α allows for $p_w - \alpha > p_d$; in this case, exports would equal $q_0 - q_d$. If the quarantine or treatment requirements are prohibitively costly α' such that $p_w - \alpha' < p_d$, the country or region ceases to be a net exporter and consumes q_d', as illustrated in Figure 1.

Figure 1.



N_0 corresponds to the initial pest population. The net natural growth of the pest population is an upside-down U-shaped function $G(N)$. The use of control measures w reduces the pest population by an amount $k(w)$ (so $N' := dN/dt = G(N) - k(w)$), and consequently increases the supply of the product (the supply curve moves to $R(p,v,N^*)$). In the long term, infestation levels are reduced to an equilibrium level N^* that maximises consumer and producer's surplus

$$\int_0^\infty \{CS(p_w - \alpha) + R(p_w - \alpha, v, N) - c_w w\} e^{-\rho t} dt$$

subject to $N' = G(N) - k(w)$. ρ corresponds to the discount rate.

With PFA certification, the exporting region is not required to quarantine or treat the product for exports and avoids these costs (α). Therefore, the region receives the full world market price p_w. But the maintenance of area freedom requires implementing a minimum level of surveillance and monitoring activities. Let M be the costs of monitoring. In case of an incursion, the pest is eradicated soon after detection to restore area freedom at a cost $F(c_w)$. Let μ be the probability of a new incursion, so that the expected costs of maintaining pest-free status equal $M + \mu F(c_w)$. Then the total welfare is

$$CS(p_w) + R(p_w, v, 0) - M - \mu F(c_w)$$

Certification is worthwhile if the region's long-run equilibrium welfare with certification exceeds its long-run equilibrium welfare without certification

$$[CS(p_w) + R(p_w, v, 0) - M - \mu F(c_w)] \quad > \quad [CS(p_w - \alpha) + R(p_w - \alpha, v, N^*) - c_w w^*]$$

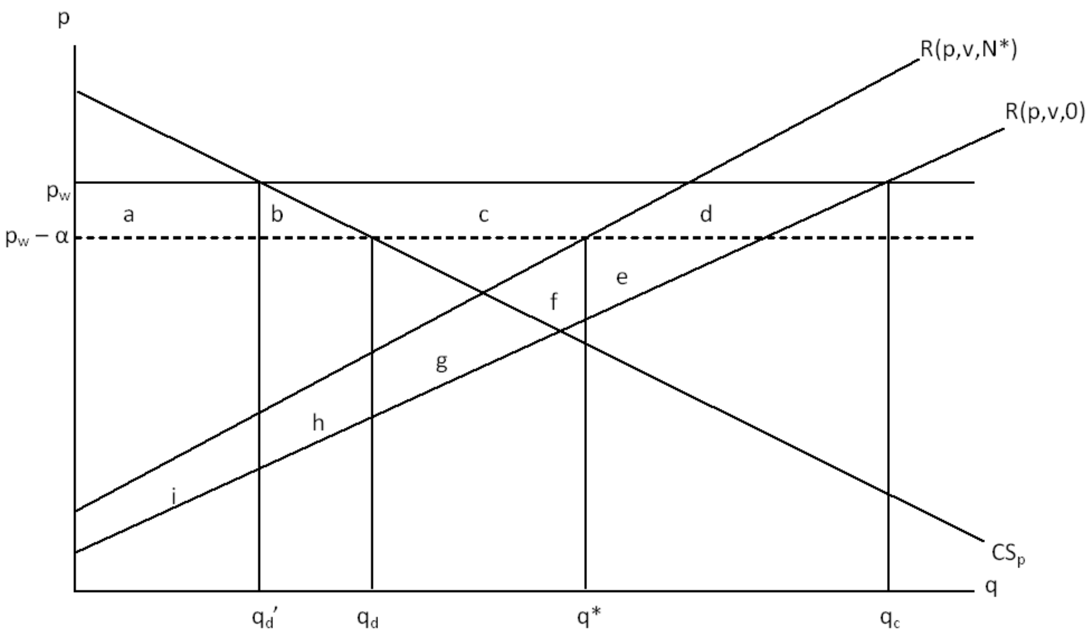
This can be rewritten:

$$[R(p_w, v, 0) - R(p_w - \alpha, v, N^*)] \quad > \quad [CS(p_w - \alpha) - CS(p_w)] + [M + \mu F(c_w) - c_w w^*]$$

The term on the right side of the inequality is the increase in producer surplus (profit) that results from increased average producer prices (*price* and *quality effects*), reduced level of crop loss due to the absence of pests (*crop damage effect*), and removal of expensive post-harvest treatment (*post-harvest cost effect*). The first term on the left side of the inequality is the reduction of the region's consumer welfare due to increased prices. The second term is the difference between the costs of maintaining pest-free status and the pest control costs when the pest is present without PFA certification (which allow for the *compliance effect* and the *input use effect* to be measured).

Producers gain the area a + b + c + d + e + f + g + h + i of increased revenue (Figure 2), but consumers lose the area a + b. So the net benefit of PFA certification is c + d + e + f + g + h + i.

Figure 2.



Appendix B

Optimal surveillance

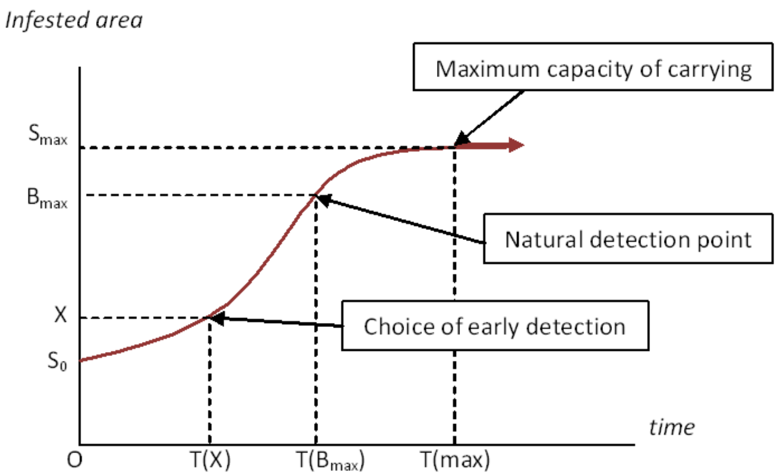
Kompas and Che (2009) analyse the problem of determining the optimal plant surveillance measure against an exotic pest or disease. Optimal surveillance is one that minimises the total present value of (1) the potential production costs (crop damage) before and after the pest is detected, (2) the potential costs of pest management, and (3) the costs of the surveillance programme itself.

The potential production costs depend on the probability of pest outbreak σ, the production loss per unit area c_p (which is a function of the density of the pest $D(t)$), and the size of the infested area $S(t)$. At time t the infested area is

$$S(t) = \frac{S_{max}}{1 + \left(\frac{S_{max}}{S_0} - 1\right) e^{-gt}}$$

where S_{max} is the maximum carrying capacity of the pest, S_0 is the initial infested area and g is the net area growth rate. Figure 3 illustrates the growth of the infested area (following a logistic function, first growing at an increasing rate, then, as saturation begins, the growth slows, and when the maximum carrying capacity is attained, growth stops). Without surveillance, the pest will be detected at some point by the public; this natural detection point is B_{max}. The objective of surveillance is early detection, so that the pest is detected at time $T(X)$ when the infested area is X, before $T(B_{max})$, when the infested area is B_{max}.

Figure 3.



The value of $T(X)$ can be written as

$$T(X) = \frac{\left(\ln\frac{S_{max}}{S_0} - 1\right) / \left(\ln\frac{S_{max}}{X} - 1\right)}{g}$$

Similarly, at time t the pest density is

$$D(t) = \frac{D_{max}}{1 + \left(\frac{D_{max}}{D_0} - 1\right) e^{-ht}}$$

where D_{max} is the maximum capacity of pest density, D_0 is the initial density and h is the net density growth rate.

The production cost caused by the pest is given as

$$CP_p(t) = \sigma \ c_p(t) \ S(t)$$

The production loss per unit area is a function of the density of the pest so that

$$c_p(t) = c_p(0) \ D(t)$$

where $c_p(0)$ is the initial cost unit per an unit area at the initial density $D(0)$. The potential production cost per year can then be written as

$$CP_p(t) = \sigma \ c_p(0) \left[\frac{D_{max}}{1 + \left(\frac{D_{max}}{D_0} - 1\right) e^{-ht}}\right]\left[\frac{S_{max}}{1 + \left(\frac{S_{max}}{S_0} - 1\right) e^{-gt}}\right]$$

Under a given surveillance programme, there are production losses before the pest is detected (from $T(0)$ to $T(X)$) and after it has been detected until it is completely eradicated (from $T(X) + 1$ until T_E). So the aggregated present value of production loss since the arrival of a pest until it is eradicated is

$$PVCP_p = \sum_{t=0}^{T_E} e^{-rt} \ \sigma \ c_p(0) \left[\frac{D_{max}}{1 + \left(\frac{D_{max}}{D_0} - 1\right) e^{-ht}}\right]\left[\frac{S_{max}}{1 + \left(\frac{S_{max}}{S_0} - 1\right) e^{-gt}}\right]$$

for r the discount rate. During the period of pest management (after the pest has been detected, the outbreak declared, and until the pest is eradicated) the present value of ongoing production losses are given as

$$PV \ CP_E = \sum_{t=1}^{T_M} e^{-r(T(X)+t)} \ \phi \ X \ AR$$

where T_M is the time required to manage the pest, ϕ is a management coefficient (denoting the buffer area included in eradication) and AR is the average loss in production revenue per unit area (due to lost revenue from domestic sales and trade bans). Thus the total potential production losses are given by

$$TCP = \sum_{t=0}^{T_E} e^{-rt} \ \sigma \ c_p(0) \left[\frac{D_{max}}{1 + \left(\frac{D_{max}}{D_0} - 1\right) e^{-ht}}\right]\left[\frac{S_{max}}{1 + \left(\frac{S_{max}}{S_0} - 1\right) e^{-gt}}\right]$$

$$+ \sum_{t=1}^{T_M} e^{-r(T(X)+t)} \ \phi \ X \ AR$$

The potential costs of pest management depend on the probability of pest outbreak, the size of the area infested when the pest is detected and the management cost per unit area $c_M(t)$ (which is a function of the pest density $D(t)$). At $T(X)$ the potential pest management cost is

$$C_M(X) = \sigma\ c_M(t)\ X$$

The cost per unit area is a function of the density of the pest so

$$c_M(t) = c_M(0)\left[\frac{D_{max}}{1+\left(\frac{D_{max}}{D_0}-1\right)e^{-ht}}\right]$$

where $c_M(0)$ is the initial cost unit per unit of area at the initial density $D(0)$. By substitution, the pest management cost for an infested area X is given as

$$C_M(X) = \sigma\ \ c_M(0)\left[\frac{D_{max}}{1+\left(\frac{D_{max}}{D_0}-1\right)e^{-ht}}\right]X$$

At $T(X)$ the present value of the total costs of pest management is

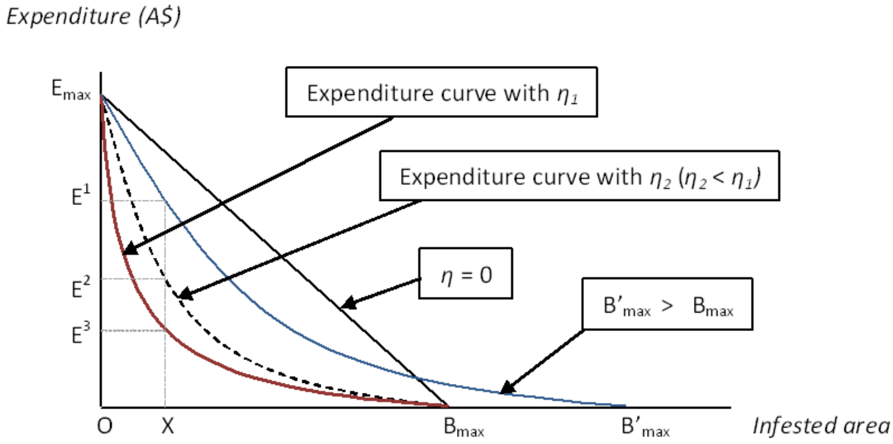
$$TC_M(X) = e^{-rT(X)}\ \ \sigma\ \ c_M(0)\left[\frac{D_{max}}{1+\left(\frac{D_{max}}{D_0}-1\right)e^{-ht}}\right]X$$

The costs of the surveillance programme depend on how early is the pest detection objective $T(X)$ (so that a corresponding area X is infested when it is detected) and the efficiency of surveillance activities. Thus the more effective is the surveillance programme, then the lower the expenditure on surveillance for a given area X. Assuming that the marginal benefit of surveillance expenditure decreases continuously, and η is the coefficient of surveillance effectiveness, the shape of the surveillance expenditure function $E(X,\eta)$ is a hyperbola that gets closer to the vertical and horizontal axes as surveillance efficiency increases. The expenditure function is given by

$$E(X,\eta) = \frac{E_{max}(B_{max}-X)}{B_{max}(\eta X+1)}$$

where $E(X,\eta)$ is the surveillance expenditure corresponding to X and η, E_{max} is the maximum surveillance expenditure for the earliest detection, B_{max} is the size infested area at the latest detection, X is the infested area under a given surveillance programme. Figure 4 illustrates the surveillance expenditure function.

Figure 4.



The aggregate present value of surveillance costs until the pest is detected at $T(X)$ is

$$TE(X,\eta) = \sum_{t=1}^{T(X)} e^{-rt} \frac{E_{max}(B_{max} - X)}{B_{max}(\eta X + 1)}$$

Optimal surveillance minimises the surveillance costs, the potential production costs and the potential management costs:

$$\min_{stX} TC = \sum_{t=1}^{T(X)} e^{-rt} \frac{E_{max}(B_{max} - X)}{B_{max}(\eta X + 1)}$$ **Surveillance costs**

Potential production costs

$$+\sum_{t=0}^{T_E} e^{-rt} \ \sigma \ c_p(0) \left[\frac{D_{max}}{1 + \left(\frac{D_{max}}{D_0} - 1\right) e^{-ht}}\right]\left[\frac{S_{max}}{1 + \left(\frac{S_{max}}{S_0} - 1\right) e^{-gt}}\right] + \sum_{t=1}^{T_M} e^{-r(T(X)+t)} \ \phi \ X \ AR$$

$$+ e^{-rT(X)} \ \sigma \ c_M(0) \left[\frac{D_{max}}{1 + \left(\frac{D_{max}}{D_0} - 1\right) e^{-ht}}\right] X$$ **Potential management costs**

Appendix C

Spread model of invasive species

Few bioeconomic models of invasive species dynamics take into account the geometry of the invasion (Carrasco *et al*., 2009). Some of those that have considered the dispersal patterns of the invader incorporate spread predictions of reaction-diffusion models into the management of invasions. Reaction-diffusion models assume random diffusion in a homogeneous environment. They are partial differential equations where the main parameters are ε, the rate of population growth, and ψ, the diffusivity of the population. Carrasco *et al*. (2009) includes an example of this type of models, the Skellman model:

$$\frac{\partial D}{\partial t} = \psi \left(\frac{\partial^2 D}{\partial x^2} + \frac{\partial^2 D}{\partial y^2} \right) + \varepsilon D$$

where $\partial D / \partial t$ represents the change in population density D at time t and spatial coordinates (x,y) that is caused by random diffusion (first term of the right hand side of the equation) and local population growth (εD). The solution of the reaction-diffusion model is:

$$m = \sqrt{4\varepsilon\psi}$$

which predicts the spread of the invasive species to follow a continuous expansion at an asymptotically constant radial velocity represented by m.

Appendix D

The weaker link model

Burnett (2006) modelled the prevention of invasive species as a "weaker link" public good. Previous literature identified five distinct public good technologies: (1) the ordinary summation model given by

$$A = \sum_i a_i$$

where a_i denotes the contribution of individual *i* to the public good, and *A* is the total provision of the public good; (2) the best shot model,

$$A = \max_i a_i$$

in this case, the total quantity available to each individual equals the largest individual contribution; (3) the weakest link model,

$$A = \min_i a_i$$

in this case, the total quantity available to each individual equals the smallest individual contribution; (4) the weights model,

$$A = \sum_i \beta_i a_i$$

where $\beta_i = 1$ for the smallest a_i, and $0 < \beta_j < 1$ for the larger a_j's, in this case, full weight is put on the minimum contribution and fractioned weights on any larger contributions; and (5) the geometric mean model,

$$A = \left(\prod_{i=1}^{n} a_i\right)^{1/n}$$

which highlights the fact that weaker links are important because the smaller contributor has the highest marginal effect on the supply of the public good (since $\partial A/\partial a_i = A/na_i$).

Burnett (2006) defines the aggregation technology for the prevention public good as the geometric mean over all contributions and assumes symmetry in benefits from the public good and asymmetric costs of provision. The total amount of public good provided in a two-region case is given by

$$A(a_1, a_2) = \sqrt{a_1 a_2}$$

The utility from investing in the prevention of invasive species corresponds to the net benefit from the provision of this public good. Individual utility can be then defined as

$$U^i(a_i, a_j) = A - c_i a_i^2$$

which represents the difference between the gains from avoided damages and the costs *c* of executing and operating the prevention measure. Each region decides how much to contribute to the public good. Strategies should be greater than zero (to avoid the weakest link case) so that $0 < a_i(c_i) < \infty$ and all contributions generate a quadratic contribution cost, with $0 < c_i \leq 1$.

For efficient prevention (Pareto optimal contribution levels), the regulatory authority maximizes the utility of one region while holding the other constant by simultaneous choice of a_i and a_j

$$\max_{a_i, a_j} \left(a_i, a_j\right)^{1/2} - c_i a_i^2 \text{ such that } U^j \geq \bar{U}^j$$

under symmetric costs:

$$a_i = \frac{1+\lambda}{4 c_i \lambda^{1/4}} \quad , \qquad a_j = \frac{1+\lambda}{4 c_j \lambda^{3/4}}$$

or asymmetric costs:

$$a_i = \frac{1+\lambda}{(4c_i)^{3/4}(4\lambda c_j)^{1/4}} \quad , \qquad a = \frac{1+\lambda}{(4c_i)^{1/4}(4\lambda c_j)^{3/4}}$$

where λ is the Lagrange multiplier (i.e. the weight that the regulatory authority places on region *i*'s utility). However, equilibrium prevention levels might differ from the efficiency level.

Under complete information, regions can calculate their preferred contribution quantity based on their own cost and the other regions' cost. Region *i*'s problem is then given by

$$\max_{a_i} \left(a_i a_j\right)^{1/2} - c_i a_i^2$$

The Nash Equilibrium for the complete information case is

$$a_i(c_i)^* = \frac{1}{(4c_i)^{3/4}\left(4c_j\right)^{1/4}}$$

Under incomplete information, the other regions' prevention costs are not known. Burnett (2006) assumes that costs of prevention are either high (c_H) or low (c_L) with probability θ and $1 - \theta$ respectively. The appropriate solution is the Bayesian Nash Equilibrium. Region *i*'s optimal strategy will give the highest possible expected utility given region *j*'s optimal strategy. Both regions' optimal contributions will be cost-contingent.

For $c_i \in \{c_L, c_H\}$, region *i*'s problem is

$$\max_{a_i(c_i)} \sqrt{a_i(c_i)\left[\theta a_j(c_H) + (1-\theta) a_j(c_L)\right]} - c_i a_i(c_i)^2$$

The symmetric Bayesian Nash Equilibrium is

$$a^*(c_H) = \frac{1}{4\sqrt{\theta c_H^2 + (1-\theta) c_H^{4/3} c_L^{2/3}}}$$

$$a^*(c_L) = \frac{1}{4\sqrt{\theta c_L^{4/3} c_H^{2/3} + (1-\theta)c_L^2}}$$

The equilibrium level of provision under complete and under incomplete information will be below the efficient level, since the Lagrange multiplier λ is greater than zero. Prevention will not be optimal as individual regions observe the possible costs of prevention and respond according to their own optimal contribution level, ignoring the effect of their decision on the other's utility.

The utility-maximising contribution levels (under complete and incomplete information) are convex in costs, which implies that the contributions that maximise the utility of the other region's expected cost is less than the contributions that maximise the utility of known costs multiplied by their probabilities. That is, for all *i* = L, H,

$$\theta a_i^{COMPLETE}(c_i; c_H) + (1-\theta) a_i^{COMPLETE}(c_i; c_L) \;\; \geq \;\; a_i^{INCOMPLETE}(c_i)$$

Substitution gives the comparison of the two expected contribution levels as:

$$\frac{\theta}{(4c_i)^{3/4}(4c_H)^{1/4}} + \frac{1-\theta}{(4c_i)^{3/4}(4c_L)^{1/4}} \;\; \geq \;\; \frac{1}{4\sqrt{\theta c_H^2 + (1-\theta)c_H^{4/3} c_L^{2/3}}}$$

and

$$\frac{\theta}{(4c_i)^{3/4}(4c_H)^{1/4}} + \frac{1-\theta}{(4c_i)^{3/4}(4c_L)^{1/4}} \;\; \geq \;\; \frac{1}{4\sqrt{\theta c_L^{4/3} c_H^{2/3} + (1-\theta)c_L^2}}$$

Contributions made under incomplete information will always be less than those made under complete information.

Appendix E

The probability of incursion

Horan *et al.* (2002) describe a species invasion as a Bernoulli event: an invasion either occurs or it does not occur. There is a potential "pathway" for species invasions that consist of a route and a carrier. The choices of the ith carrier are denoted by the input vector u_i. Biosecurity control costs are $C_i(u_i)$. The biomass of species z ($z = 1, \ldots, Z$) introduced to a particular area by the potential carrier i is denoted by H_{iz}. This cannot be controlled with certainty by a potential carrier, so introductions are random but the probability of a particular level of biomass is determined by the input choices and characteristics (b_i) of the carrier. The probability that H_{iz} is introduced is $\Pr_{iz}(H_{iz}|u_i,b_i)$.

An introduced species may or may not invade the area (establish and spread) and cause damage (Horan, 2002, assumes that damages only occur from a successful invasion). The probability of an invasion depends on the scale of the introduction and the characteristics of the area where the invasive species is introduced (ω). The probability that an introduction results in an invasion is $\Pr_z(\text{survival}|H_{iz},\omega)$ and is increasing in H_{iz}. Consequently, the probability that introductions of species z by the potential carrier i lead to an invasion is $\Pr(u_i, b_i, \omega) = \sum_{H_{iz}} \Pr_z(\text{survival}|H_{iz}, \omega)\Pr_{iz}(H_{iz}|u, b_i)$. So invasions take place via a particular carrier and the probability of an invasion via one carrier is independent of introductions by other carriers[14].

The probability of an invasion of species z via any one of n potential carriers of the species is:

$$P_z(u_1, \ldots, u_n) = P_z(V_z \geq 1)$$

$$= 1 - P_z(V_z = 0)$$

$$= 1 - \prod_{i=1}^{n} \left(1 - \Pr(u_i, b_i, \omega)\right)$$

where V_z is the number of times that species z invades a given area. If biosecurity measures are effective and make introductions less likely, the probability P_z decreases. The probability P_z increases with the number of potential carriers. As $n \to \infty$, invasion becomes virtually certain (i.e. $P_z \to 1$).

[14] However, this may be a simplification for species that depend on a large number of introductions to become established. It is a realistic assumption only for species that can establish viable populations from only small initial introductions, and are suited to the new habitat.