A Review of Literature on the Economics of Invasive Species[*]

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Executive Summary

There is increased demand within the regulatory processes of the United States Department of Agriculture (USDA) for a higher level of analysis that integrates pest risks with economic considerations. This paper reviews the literature of methodological developments and empirical analyses over the past decade that potentially enhance such studies. Policy-oriented economic benefit-cost analysis that integrates risk assessment and related mitigation and control costs has to incorporate three components into an inter-disciplinary framework. The first component is based purely on risk science, such as probabilities of pest risk of infestations or transmission, or procedures for control of pest outbreaks. The second component inherently involves a mixture of pest risk science and economic considerations, such as an assessment of the effectiveness of specific mitigation or pest control measures and their likely economic cost. The third component is based purely on economics in that it involves the construction of the economic model in which the specific and net effects of alternative policy decisions are evaluated, taking information from the first two components into account.

The risk of invasive species introductions is usually analyzed within the context of two influencing forces: economic activities that create risk and economic activities that reduce risk. A major concern in the economics of invasive species is to find the optimal balance or mix of these forces and to search for the right policy instruments that can maximize welfare of producers and consumers, net of the cost of implementing these policy measures.

One of the major pathways of invasive species entry is through foreign trade. Three policy instruments have been most widely analyzed for preventing trade-based introductions of invasive species: import bans, import tariffs, and risk mitigating strategies. While a total ban can control entry of invasive species, it can result in significant costs to consumers because of higher prices and limited availability and diversity of commodities in the market. Import tariffs can also reduce invasive species introduction but they are not the most desirable policy to address pest risks in principle, nor are they a policy instrument likely to be available to regulatory agencies. The optimal tariff can be prohibitive (equivalent to a ban) especially if there is high risk of invasion and high productivity loss of pest outbreaks. In other cases, because of its better economic implications the literature strongly recommends the use of mitigating measures to reduce invasive species risks. This includes use of a systems approach that involves a set of compliance and monitoring measures with mutually reinforcing risk-reduction effects that may be implemented in the countries exporting potentially tainted commodities as well as in the importing country.

A key point of focus for this review has been the model developed by Peterson and Orden (2008) that incorporates pest risks and the costs associated with mitigation measures and the occurrence of invasive species outbreaks into the economic assessment of alternative trade-related regulatory policies. Several insights from the review might enhance the future development and uses of this modeling framework. Attention is directed in recent survey papers to additional policy instruments, such as use of criminal/civil liability, that might be incorporated in the set of policies evaluated. A scoping monograph for United Kingdom (UK) regulatory agencies highlights systematic stochastic assessment of the risks and costs associated with invasive pests over time, evaluated in a multi-period, static framework. Several other papers reviewed demonstrate the emergence of an increasingly sophisticated literature in terms of inclusion of mitigations strategies and assessments of their effects. The studies reviewed that focus on control or eradication of established pests point toward the need for dynamic treatment of trade and the resulting effects from invasive species.

In any specific case in which regulation is being considered or re-evaluated, there can be gaps in knowledge in any one, or more than one, of the three components of an analytic model. The empirical results in the literature are sensitive to the level of risk and uncertainty of invasive species, unknown or uncertain efficacy and costs of potential intervention measures, and uncertainty about economic behavior of producers and consumers. The economic models developed can provide rich policy insights provided there is sufficient information available related to each of these necessary dimensions. That is, the critical aspect in the design of policy that can optimally accommodate the dual concerns of minimizing the possibility of entry of invasive species and of minimum trade distortions is uncertainty. Some consider uncertainty about invasive species risks as an exogenous variable. But uncertainty is an endogenous variable. Policy makers can allocate resources to learning more about invasive species and therefore improve knowledge about them. This can be done through data gathering, surveys, observation from trials and experiments, and other research. Likewise, investments in attaining knowledge of key economic parameters and the development of realistic economic models will contribute to better regulatory decision making.

1. Introduction

The phenomenon of invasive species[1] is not new. It can be traced back to the arrival of agriculture and pests about 10,000 years ago (Gren, 2008). Invasive species are harmful because they compete for resources and therefore displace native species in the host region. Williamson (1996) has noted that although the probability of establishment and spread of invasive species is very low, once established and spread progressed, the economic damage of invasive species can be very high. Furthermore, some scientists have found strong indications that harmful invasive species are often one of the main pressures on threatened or endangered species and there are other hard to quantify adverse environmental effects (Olson, 2006).

The damaging effects of invasive species have long been recognized. In the United States invasive species policies go back to the 1900 Lacey Act (Olson, 2006). In 1993, the Congressional Office of Technology Assessment (OTA) provided estimates of the economic impact of invasive species. In the period from 1906 to 1991, the documented losses from 79 harmful exotic species amounted to $97 billion, which translated to $1.1 billion per year over this period (OTA, 1993). These were mostly losses due to control costs and damage to marketable goods. Recent estimates of Pimentel et al. (2005) showed that the economic damages and the associated control costs from more than 50,000 existing pest and invasive species in the U. S. amounted to $120 billion per year – broken down to $34.5 billion for plant invasives; $25.7 billion for microbes; and $59.8 billion for animals. Pimentel et al. (2005) considered these as conservative estimates because they did not include monetary values of extinction of native species, losses in biodiversity, ecosystem services and aesthetics. The total cost would be significantly higher than the $120 billion per year if these factors were taken into account.

There are also cost estimates of the potential damage from specific invasive species in several other countries that are available in the literature. But these studies include fewer species compared to the paper of Pimentel et al. (2005) for the United States. In these country studies, not all invasive species nor their impacts were included. Also, different methods were used in each of these individual studies, thus the estimates may not be comparable. We cite these estimates in this survey (Table 1) because they provide useful information of the possible range

[1] May refer to alien species, alien invasive species, non-indigenous species, etc.

of potential damages of invasive species, but Olson (2006) has noted that these numbers are not very reliable statistical estimates. These estimates are nation-wide annual values.

Table 1: Annual Economic Impact of Terrestrial Invasive Species on a National Scale

	Type of Invasive		
Country	Plant	Animal	Microbial
Australia ($AU)	4 billion [a]	491.5 million (9 species) [b] 703.9 million (10 species; includes environmental cost) [c]	
Canada ($CAN)	3821 million (leafy spurge and knapweed) [d]	101.3 million (3 species) [d] 14-16 million (emerald ash borer) [e]	1.5 million (Dutch elm disease) [d] 73.34 million (potato wart fungus) [e] 1 million (BSE) [e]
Germany (€)	103 million (8 species) [f]	60.2 million (6 species) [f]	5 million (Dutch elm disease) [f]
New Zealand ($NZ)	100 million [g]	270 million (vertebrates) [h] 2 billion (invertebrates) [i]	
United States ($US)	34.5 billion [j]	59.8 billion [j]	25.7 billion [j]

Source: Quoted from Olson (2006)

a. Sinden et al (2004)
b. Bomford and Hart (2002)
c. Mcleod (2004)
d. Colautti wt al. (2006)
e. One-time event, Colautti et al. (2006)
f. Reinhardt et al. (2003)
g. Williams and Timmis (2002)
h. Clout (2002)
i. Barlow and Goldson (2002)
j. Pimentel et al. (2005), more than 50,000 species of plant, animal and microbes

There are several pathways (vectors) through which invasive species can be introduced. Introduction of invasive species can be through production of crops, transport of goods, tourism activities and movement of people. Of these pathways, the major one is through foreign trade of goods and services. This is especially true during the recent period of rapid growth in world trade volume which has grown (until the recent recession) by six percent per year since the mid-1990s – twice as fast as the growth of global output.

In the literature, the risk of introduction of invasive species is usually analyzed within the context of two influencing forces: economic activities that create risk and economic activities that reduce risk. Increased trade flows of goods and services among countries can increase the risk of invasive species introduction. However, activities such as prevention and monitoring of pests and diseases or control through containment and eradication measures can reduce invasive species introductions or their damage. A major concern in the economics of invasive species is to find the optimal balance or mix of these activities that create risk of invasive species and activities that prevent, reduce or control the occurrence of invasive species.

The literature on the economics of invasive species is vast. Recent journal-article length review papers of Olson (2006); Gren (2008); and Costello, Lawley, and McAusland (2008) provide comprehensive surveys of several issues related to activities that increase risk of introduction of invasive species as well as policy instruments for prevention and control. Waage et al. (2005) provide a book-length review of invasive species issues facing Great Britain's regulatory agencies. Under the Program of Research on the Economics of Invasive Species Management (PREISM) of the Economic Research Service (ERS) of the USDA which started in 2003, a number of research studies have been conducted to analyze the economic basis of policies regarding invasive species (USDA, ERS, 2009). These studies looked at how to detect, monitor, eradicate, and control invasive species and how to restore the damage they have caused in the U.S. Invasive species include exotic pests of crops, forest, range land (such as insects, weeds, and disease-causing pathogens), foreign livestock, poultry, and zoonotic diseases (transmittable between animals and humans).

Clearly, the scope of research on invasive species is wide. There are specific case studies that focus on estimating the potential economic damage of invasive species. There are studies that focus on analyzing policy instruments for prevention whose aim is to avoid or minimize damages and/or control costs of invasive species. There are also studies that focus on how to control and contain the spread of invasion as well as total eradication of pests.

Within this framework, the first purpose of this paper is to briefly summarize key points from the four related review papers cited above and to discuss some of the recent work in the literature that has not been touched upon or has only been briefly discussed in these four papers. Similar to these other surveys, this review will discuss papers on prevention and control. The initial emphasis is on policies of prevention that minimize the potential damage of invasive species resulting from the flow of goods across national borders; later in the review, the emphasis turns to control studies for established pests. As Waage *et al*. observe (p. 13): there is no *a priori* reason to assume that "prevention is better than cure." Rather, alternative strategies for managing risk of invasive species and combinations of these strategies have to be compared in specific cases.

A second purpose of this paper is to identify from the review of literature the directions in which studies of risk management and the economic impact of invasive species by the USDA Animal and Plant Health Inspection Service (APHIS) can be strengthened to inform regulatory decision making. Specifically, in the project for which this paper has been prepared one template APHIS is investigating for integrating risk assessment and risk-related costs into economic analysis of regulatory decisions rests on the model developed by Peterson and Orden (2008) to assess regulatory decisions related to avocado imports from Mexico and also applied by Orden et al. (2007) to possible imports of fresh apples from China. These papers are described in some detail in the review. Once the review is completed, we identify several areas in which models such as these can be further developed along lines pursued in the other studies examined.

The paper is organized as follows. The next section provides a synopsis of the four recent survey papers. The third section reviews several papers that analyze the link between trade and invasive species. The fourth section discusses a framework of analysis that can be used as a guide in understanding the optimal balance of factors that affect invasive species introduction or spread. The fifth section reviews several papers that analyze trade and mitigation measures that minimize entry of invasive species. The sixth section reviews several illustrative case studies that analyze the effects of several measures that control the spread of invasive species. The seventh section discusses two additional methodological issues that can arise in specifying empirical studies. The last section gives a few insights for research and policy and discusses the avenues for further model development. The various papers included in the review are tabulated in Appendix A as a quick guide to the scope of the review and basis for comparison of the included papers by subject focus.

2. Synopsis of Four Recent Review Papers

The four recent reviews cited above have somewhat different scope and take somewhat different approaches to organizing the summaries they present. There is also substantial overlap in the issues they address and their broad conclusions. Olson (2006) provides the summary of studies assigning values to the economic impact of terrestrial invasive species replicated in Table 1. He then reviews a set of empirical studies that present dynamic programming models for optimal control of pest spread and damages. Subsequent sections address the economics of invasive species prevention, including citations to and summaries of a number of studies related to border measures that limit trade, pest-risk reduction measures imposed as preconditions for imports, and inspection and pest detection strategies to reduce invasive species introductions. Additional economic case studies (estimates of damage costs and costs/benefits of specified prevention and control policies) are surveyed for the separate pest categories of invasive plants, animals, and plant and animal diseases.

Gren (2008) also provides a survey of substantial scope. She provides illustration (replicated below in section 4) of a general framework for choosing an optimal policy for pest management. She notes that optimal policies are comprised of target setting and interventions in three areas: prevention of introductions; control of establishment and spread; and limiting of damages once pests become established (which she terms "adaption"). Gren (2008) notes that prevention strategies have the advantage of precluding costs of control and damages from establishment of invasive species, but control and adaption measures have the advantage of being targeted toward more sure events. Optimal interventions often incorporate elements of each strategy and Gren (2008) discusses expected utility as well as alternative policy decision rules under uncertainty. She then turns to the advantage and disadvantages of different policy instruments ranging among command and control regulations, economic (price-based) incentives, market trading of rights to risk creation, and public dissemination of information about pest risks. Acknowledging that economists often assert that economic incentives are most efficient, Gren (2008) points out that there may be a bias toward market-based instruments because conclusions are drawn mainly with respect to cost-efficiency and not based on other criteria such as certainty in achieving objectives, equity considerations, or transaction costs.

Within her discussion, Gren (2008) points out that many studies have focused on efficient design of differential tariffs based on pest risk, as discussed further below. Like Olsen (2006), she highlights several studies that consider alternative instruments such as inspections in conjunction with or substitutes for tariffs (e.g. McAusland and Costelle, 2004). This is a theme we also examine, because pest risk management agencies of national governments usually lack tariff-setting authority and in addition the multilateral rules of the World Trade Organization (WTO) preclude differential tariffs among member countries as an instrument for addressing pest risks. Finally, Gren (2008) considers non-trade policies, including compensation payments for control measures and policies directed toward damage reduction through liability rules. She concludes the latter are challenging to implement because of the difficulty of linking pest damages to specific responsible actors. Throughout her review, Gren cites relevant empirical studies that address the conceptual points she articulates.

The review by Costello, Lawley and McAusland (2008) has a tighter focus than the first two. They maintain that trade is an important vector for invasive species and focus primarily on preventive measures, rather than control (what they term "reactive") measures. They articulate a taxonomy of four characteristics of invasive species (observability, separability, traceability and predictability) and discuss how these characteristics affect the relative efficacy of different types of policy instruments (price-based, quantitative import restrictions, product versus process standards, and criminal and civil liability). Many of their findings match those by Gren (2008). Costello, Lawley and McAusland (2008) point out that governments can invest in reducing uncertainty and that trade policy and risk assessment need to be considered "in tandem".

Waage et al. (2005) is a scoping document for the UK's Department of Environment, Food and Rural Affairs (DEFRA). This review examines the long-term levels of past invasive species establishment and damages in the UK. The historical assessment is complemented by a future-oriented "horizon scanning" qualitative exercise that assesses emerging market (e.g. expansion of trade with Asia, changes in EU farm policy) and social (e.g. taxpayer attitudes toward the environment) forces that may affect the concerns about invasive species, the likelihood of these pressures, and the magnitude of their effects in coming decades. Waage et al. (2005) formulate a multi-year, stochastic, static economic framework using the @Risk computer software to assess the net costs from invasive species taking into account uncertainty about establishment and spread of the pests, control costs and yield losses. Their analysis is designed to make operational the evaluation of the magnitude, timing and uncertainty of the impacts of pest invasions. They provide preliminary applications of the model to six specific pests (Colorado beetle, wild boar, potato ring rot, Newcastle disease, Gyrodactylus salaries, and creeping thistle).

While their empirical analyses are acknowledged by the authors to be somewhat stylized, the six cases demonstrate the types of empirical results the model generates, illustrate the range of expected relative impacts of these pests, and highlight some of the data constraints faced in evaluating invasive pest risks and effects. Waage et al. (2005) use anticipated future changes in UK beef trade and domestic production from their horizon-scanning exercise to assess the expected impacts of foot-and-mouth disease (FMD). They also use the model conceptually to assess the optimal levels of expenditures directed toward prevention versus containment or eradication of invasive species. The net benefits from these alternative interventions are illustrated with a hypothetical example, and Waage et al. (2005) draw conclusions to guide DEFRA's strategic planning from their inter-related historical, scoping and model-based assessments.

3. Link between Trade and Establishment of Invasive Species

The literature shows a strong positive link between trade and establishment of invasive species. There are several papers that have established empirically the trade-species correlation. For purposes of this review, discussion of two papers will be sufficient to emphasize this link. One paper presents evidence from a cross-country study and another paper shows evidence in the U.S. case. Waage et al. (2005), while recognizing the importance of unintentional contamination of imported agricultural products, also emphasizes the risks associated with deliberate importation of plant and animal species.

The volume of world trade has achieved unprecedented growth because of globalization. At the same time, historical trends show an exponential increase in the establishment of alien species. Using data on established alien plant species in 29 countries in different continents, Dalmazzone (2000) tested the hypothesis whether economic activities can explain the rate of alien species introductions. In the study, invasive species introduction was indicated by the ratio of established alien species to indigenous species. Economic activities were represented by various indicators which included: Gross Domestic Product; flows of trade and composition of trade; volume of tourism; economic growth rates; land used for agriculture and livestock; forest land with wood cover; import duties; population density; and geographic characteristics of the countries. A cross-country regression analysis was conducted in which the dependent variable was invasive species introductions while the independent variables were the various economic indicators. Two of the important conclusions drawn from the paper are: (a) there was a strong statistical correlation between economic variables and the country's vulnerability to invasive species introductions; and (b) trade flow variables such as merchandise imports were positively correlated with invasive species introduction while import duties were negatively correlated, although the correlation with import flows was not as highly statistically significant as with import duties.

Levine and D'Antonio (2003) constructed species-import curves using historical data for the U.S. on trade and establishment of invasive species. They fitted individual curves to three types of invasives (mollusks, plant pathogen, and insects) using cumulative number of exotic species and cumulative trade volume since 1920 in three different functional forms: log-log; log-linear; and Michaelis-Menten[2]. The fitted curves were evaluated using R^2. The computed R^2 of the fitted equations ranged from 0.74 for plant pathogens in log-log form to 0.99 for mollusks in Michaelis-Menten functional form. Using these fitted curves and the projected trade import volume of the U.S. they estimated the number of invasive species that will be established between 2000 and 2020. Their conservative (lowest) estimates predicted 115 new insect species and 5 new plant pathogens. Levine and D'Antonio (2003) claimed that even if only 10 percent of these invasives become harmful, they could add substantially to the overall financial burden of invasive species control and prevention.

Because of the strong link between trade and invasive species introductions, and because of the considerable amount of potential damage in the economy, environment, and ecology in the event of entry, establishment and spread in the host country of invasive species, there are public policy debates on whether international trade regulation can be a primary measure in reducing the potential risk and scale of invasive species and in controlling domestic damages. The WTO has recognized the seriousness of the potential damage of invasive species to the host region, and therefore has established the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) and the Agreement on Technical Barriers to Trade (TBT Agreement). The SPS measure protects "animal or plant life or health within the territory of the Member from risks arising from entry, establishment or spread of pests, disease, disease-carrying organisms or disease-causing organisms" (WTO, 1994, Annex A: Definitions). Cleaning,

[2] The form is $S = (S_{max} \cdot I) \div (B + I)$, where S is cumulative number of species, I cumulative volume of trade, S_{max} and B are constants, estimated using maximum likelihood estimators.

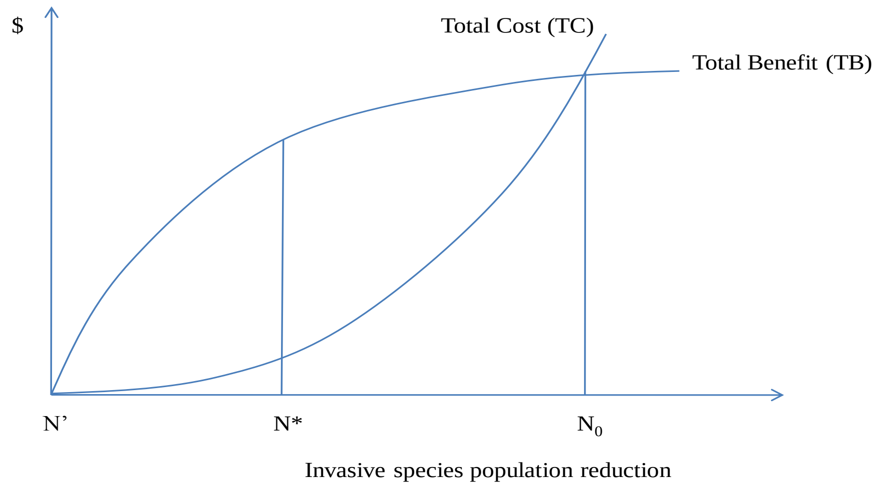
quarantines, inspections, tariffs, bans, and other interventions are controls that may fit among the SPS measures (Wilson and Antón, 2006). Although these measures can reduce the risk of invasive species introductions, they create the potential danger that SPS measures become disguised economic protection since it is generally difficult to determine whether a particular trade barrier reflects health concern or not. A careful review of this interface between health-protection and trade-expansion objectives, and an assessment of the performance of the WTO in disciplining SPS measures, are provided by Josling, Roberts and Orden (2004). Trade barriers increase prices and limit the availability of goods in the market which have negative effects on consumer welfare. Thus, the analysis in the literature addresses these concerns by taking into account overall welfare of the country in question, which generally comprises welfare of producers as well as of consumers. In addition, the literature also includes in the analysis the cost incurred to prevent and control or eradicate invasive species introductions.

4. Framework of Analysis

In the economics of invasive species, the critical question is: How does one manage optimally the activities that create risk of invasive species and the activities that reduce this risk? Totally banning trade flows, for example, would reduce entry, establishment and spread of harmful species, but this would also lead to significant losses in consumer welfare from higher prices and less availability of goods in the market. Moreover, is total eradication of an invasive species population the best policy measure if establishment and spread occur? These critical invasive species management issues were raised in the survey paper of Gren (2008, p.1) through the following questions: (a) “how does one set targets for species damage mitigation?”; and (b) “what are the policy instruments needed to achieve the targets?”

In analyzing these questions, Gren (2008) employed a simple analytical economic framework that is representative of the analysis in many studies. The guiding principle in invasive species management is to maximize the total net benefit from the measures used against the damages of species invasion, where net benefit is the difference between total benefit and total cost of implementing invasive species policy measures. Figure 1 shows the total benefit (TB) curve and the total cost (TC) curve. The horizontal axis is the reduction of invasive species population, while the vertical axis is in dollars. The TB curve illustrates a common feature of declining benefits of further reduction in invasive species population, which implies that increases in benefits from additional reduction of a certain invasive species population diminishes as the reduction level increases. The TC shows an increasing cost curve. This means that cost increases as the reduction of invasive species population intensifies.

Figure 1: Efficient Reduction in Invasive Species Population



Source: Gren (2008)

Along the horizontal axis, point N’ is zero, which means there is no reduction in species population nor benefits achieved. The curves TB and TC intersect at point N_0. Total cost exceeds total benefits at points beyond point N_0. This implies that in this region, measures to reduce invasive species population should not be implemented because the cost is greater than the benefit that is generated. However, benefits exceed cost at points between N’ and N_0. Within this region, measures to reduce invasive species population should be pursued because benefits that are generated are higher than the corresponding cost of implementation. But within this region there is only one point on the horizontal axis where one gets the most benefit out of the cost of implementing measures to reduce invasive species population. This point is at N*. This is where the difference between TB and TC is the largest. In a similar fashion, Josling, Roberts and Orden (2004) had earlier described regulatory overprotection as a situation in which relaxing a regulation would increase the traditional gains from trade relative to risk-related costs to producers or consumers in the importing country (move toward the optimum policy that maximizes the net gain), while underprotection arises in cases where strengthening of regulations would increase this net gain (again moving toward the optimal policy).

In the literature, there are numerous empirical studies that estimate costs and benefits of one or more particular measures. But these studies often do not take into account whether these measures are at point N* or not. That is, these estimates may well correspond to any point between N' and N_0. Although these studies provide useful information for policy, they do not provide indication whether the measures are optimal in the sense that they generate the largest net benefit. The key idea in most theoretical economic studies on invasive species management is to find policies and measures that correspond to point N* where the net benefit is maximized. That is, the identification of the most efficient level of policy intervention is the important concern. We will use this framework to discuss some of the empirical studies on the economics of invasive species.

5. Some Studies on Invasive Species Crossing Borders

In section 3 we presented empirical evidence which indicates that movement of goods and services across national borders through foreign trade is one major pathway of invasive species entry. This raises two policy concerns: (a) how to minimize the possibility of entry of invasive species through the borders; and (b) how to minimize trade distortions so as to facilitate trade in goods and services across countries. As noted above, these concerns can be contradictory and can seemingly lead to a policy dilemma: while a policy that reduces the flow of foreign trade will help minimize the possibility of invasive species introduction, it will also result in social economic cost through higher prices and lower availability of commodities in the market for the consumers. In the literature on trade and invasive species, the primary challenge therefore is how to design a policy that would accommodate the dual concerns of minimum possibility of entry of invasive species and of minimum trade distortions. The design of such policy can be viewed within the framework in section 4 where the optimal policy generates the largest net benefit. This section will discuss a few studies on invasive species management in international trade.

Tariffs and Risk Mitigation Strategies: The Case of Foot-and-Mouth Disease

The paper of Paarlberg and Lee (1998) analyzed import restrictions in the presence of health risk from FMD. The FMD virus is highly contagious. In recent cases, this disease affected the heath of cattle, swine, and other cloven-hoofed animals. The economic damage of FMD can be substantial because it could affect the production of milk, meat and other livestock products. It also affects indirectly the feeds market. While the paper used the case of FMD as an illustration, the analytical framework can also be applied to study policies concerning plant diseases and pests that originate from other countries. The model developed in the paper is a partial equilibrium model. Thus, the outcome in the FMD-affected market, which is the beef sector in this study, does not affect the rest of the economy.

In the analysis, there are three types of countries: the importing country (country 1); the exporting country with uncontaminated beef (country 2); and the exporting country with FMD-infested beef (country 3). The analysis is focused on the importing country. The model includes a domestic demand function and supply function for beef for the importer. The demand function has the usual characteristic which is decreasing in price. The supply function has two arguments: the price and the number of outbreaks of FMD. Supply is positively related to the price and negatively affected by the number of FDM outbreaks. The number of FMD outbreak is related to the level of imports of beef.

The importing country can import beef from country 2 and country 3. Imports of beef into country 1 from countries 2 and 3 are determined by the excess supply in both exporting countries (i.e., exporting countries' supply net of their domestic demand). An increase in the domestic price of beef in the exporting countries will reduce domestic demand and raise domestic supply in those countries, which in term will lead to higher excess supply which is eventually exported to country 1. Thus, exports are nonnegative functions of the domestic price of beef in both exporting countries.

The importing country imposes discriminatory specific tariffs (t_2 for country 2 and t_3 for country 3).[3] Thus, the price of beef in the importing country is the domestic prices in the exporting countries plus tariff, i.e. $P_1 = P_2 + t_2$ for country 2 and $P_1 = P_3 + t_3$ for country 3, where P_1 is the domestic price in country1, P_2 the domestic price in country 2, and P_3 the domestic price in country 3. To close the model, imports in country 1 are the residual of domestic demand and domestic supply in country 1 (i.e., if demand in the country cannot be adequately supplied by its domestic suppliers, imports will flow in). The level of imports in country 1 is constrained to equal the sum of exports from countries 2 and 3.

In Figure 1 presented above the optimal policy is where total net benefit is maximized. The analysis of total net benefit concerns only country 1 in the paper of Paarlberg and Lee (1998). Total net benefit is composed of three items: consumer surplus, producer surplus, and government tariff revenue. The policy maker in country 1 chooses the level of tariffs on imports from each country so that the total net benefit of country 1 is maximized. This optimization process yields a set of mathematical first order conditions (FOCs).

Without going through the derivation of the FOCs, the optimal policy yields the following results: (a) the country that is exporting uncontaminated beef (country 2) will face a tariff rate that is determined by its export supply elasticity; and (b) the country that is exporting FMD-infected beef (country 3) will face a tariff that is determined by two factors – the excess supply elasticity and the loss in beef output in the importing country due to an outbreak. The tariff rate that is imposed on beef from country 3 will increase if the number of outbreak of FMD in country 1 increases. Therefore, if FMD risk is incorporated in the analysis, the discriminatory tariff will change the import mix (sources of imports) and will favor the country that exports the uncontaminated commodity. If the tariff rate on imports of uncontaminated beef remains the same, the change in the import mix will force down the domestic price of beef in the country that is exporting the infected beef.

[3] For their analytic paper, Paarlberg and Lee (1998) ignore concerns about use of discriminatory tariffs which is precluded among WTO member countries.

Paarlberg and Lee (1998) calibrated their model using data in U.S. beef market. They assumed two levels of risks (high and low) and under three different assumptions on beef output loses per outbreak. Their results are presented in Table 2.

Table 2: Additional Optimal Tariffs on the Infected Exporter Due to FMD Risk (%)

	Percentage of U.S. Loss per Outbreak		
Level of risk	1.4	9.0	15.5
Low /a/	0.76	4.70	8.09
High /b/	86.78	540.47	929.42

Source: Paarlberg and Lee (1998)
/a/ One outbreak expected for every 24,700 thousand tons of imported beef
/b/ One outbreak expected for every 215 thousand tons of imported beef

The results show that the additional tariff due to FMD risk is sensitive to the assumed percentage loss in output in the U.S. and the assumed level of risk from imports. If the level of risk is high, the additional tariff becomes prohibitive. For example, if the level of percentage output loss is also high (15.5 percent), the additional tariff that may be imposed on imports of beef from the contaminated supplier is 930 percent. Since these tariffs are prohibitive, the optimal policy is equivalent to an import ban from the infected country, which is a policy tool that is often used in FMD regulations. But if the level of risk is low, a complete ban does not to correspond to the lower levels of optimal tariffs computed by Paarlberg and Lee (1998).

Wilson and Antón (2006) extended the model of Paarlberg and Lee (1998). The key extension is to include mitigation strategies, but additional issues of strategic trade policy are also added. In the case of reducing FMD risks, mitigating measures such as vaccinations and culling of animals may be applied. These mitigating measures reduce the number of FMD outbreaks in the importing country. The mitigating measures can be applied either in the importing country or in the exporting country with the contaminated commodity. There are costs incurred in mitigation. The cost of mitigation increases with the level of mitigation measures applied. It is zero if there are no imports. If the mitigation measures are applied in both the importing country and the exporting country (with contaminated commodity), the total cost is the horizontal sum of the individual mitigating costs.

Additional strategic trade behavior was introduced in Wilson and Antón (2006).If country 1, the importing country, imposes tariffs, other importing countries (a new fourth group of countries in the model) may react as well by modifying their tariffs or import volumes from the exporting countries (country 2 and 3). This strategic behavior is reflected in the following equation: $\varepsilon^*_{i1} = (1+\lambda_i)\cdot\varepsilon_{i1}$ where ε_{i1} is the excess supply elasticity from country i (exporting country) to country 1 (importing country), The λ_i is a parameter that captures the strategic behavior of other importers. If λ_i is equal to zero, it implies that other importing countries will not react to the tariff rates imposed by country 1. If λ_i is less than zero, it implies that other importing countries will follow country 1 in imposing tariffs on imports from country i. This will reduce the net supply response (supply elasticity) of exports from the exporting country i to the importing country 1. Therefore, ε^*_{i1} will be lower than ε_{i1}.

Except for the mitigation strategies and the additional strategic behavior and, the model of Wilson and Antón (2006) is the same as the model of Paarlberg and Lee (1998). The optimal tariffs are derived from the first order conditions of maximization of total net welfare, where total net welfare is the sum of consumer surplus, producer surplus, tariff revenue less total mitigation cost.

The optimal tariff facing the exporter of uncontaminated commodity (country 2) is the same as in Paarlberg and Lee (1998) where it is determined by the excess supply elasticity, but with the difference that the excess supply incorporates the strategic behavior parameter, i.e., $\varepsilon^*_{21} = (1+\lambda_2)\cdot\varepsilon_{21}$. The optimal tariff facing the exporter with infected commodity (country 3) has four components: (a) the excess supply that incorporates the parameter of strategy behavior, i.e., $\varepsilon^*_{31} = (1+\lambda_3)\cdot\varepsilon_{31}$; (b) the additional tariff that would account for the loss in output in importing country due to the outbreak; (c) the additional cost due to mitigation measures applied in the importing country; and (d) the additional cost due to the mitigation measures applied in the exporting country with infected commodity. In addition, the FOCs also yield the marginal cost of mitigation in the importing country and in the exporting country with contaminated commodity.

Wilson and Antón (2006) also calibrated their model using data on the beef market in the U.S. They developed and analyzed different scenarios using various combinations of values of parameters on risk, mitigation cost, and strategic behavior. We shall not go over their entire discussion of results here, but summarize only a few basic insights. Using only tariffs to protect the importing country from outbreak of FMD will result in prohibitive tariff levels similar to Paarlberg and Lee (1998). However, even if the risk of an outbreak is high, the tariff rate that will be applied will be minimal (3.9 percent) as long as an appropriate mitigation strategy can be implemented. This is a significant policy insight compared to Paarlberg and Lee (1998).

One of the major conclusions of the paper by Wilson and Antón (2006) is that if mitigation strategies that do not involve prohibitive cost to implement exist, then their use can be welfare-improving. The mitigation cost can be shared by the importing country and the exporting country based on their relative efficiency in carrying out the mitigation strategy. The use of mitigation strategies first, and then an additional small tariff later if necessary is optimal in terms of maximizing domestic welfare. The optimal results are sensitive to parameters that indicate the level of risk and the cost of implementing mitigation measures. The model is able to provide rich policy insights provided there is sufficient information available on these parameters.

In a theoretical paper McAusland and Costello (2004) analyzed two policy instruments that can be applied to contain the unintentional introduction of trade-related invasive species: tariffs and port inspections. They have generated several results with important policy implications. An optimal tariff may be set at the Pigouvian level: "…equal to the sum of expected damages from contaminated units not detected during inspections plus the costs of inspections…" (p. 975). This tariff level tends to increase with higher volume of infected traded goods. Another important result indicates that it may be optimal to increase the intensity of port inspection in order to reduce tariff levels. With lower tariffs, there may be lower domestic prices and therefore lower loss in consumer surplus. They also showed that if there are several trading partners, the importing country can set an optimal policy that is based on the differences in the infection rates between countries. However, this may lead to discriminatory policy among countries which may be difficult to apply within the WTO framework (Gren, 2008).

These three papers can be viewed within the framework in Figure 1. The paper of Paarlberg and Lee (1998) used tariff as the policy instrument and then searched for the optimal tariff under certain conditions that maximized total net benefit. The paper of Wilson and Antón (2006) used a similar framework of analysis except that it incorporated mitigating strategies as another policy instrument and also added strategic trade behavior by another importing country. The paper of McAusland and Costello (2004) showed the optimal combination of tariff and port inspection to contain trade-related invasive species.

Tariffs as Control Measures in a Wider Context

We pursue further the issue of a tariff as a trade policy in controlling invasive species introduction because this approach is widely used in the economics literature, despite its impracticality for regulatory agencies in most cases. A tariff as a control measure works through the demand for imports. Holding all factors affecting import demand the same except the tariff, higher tariff leads to lower imports. Lower import volume reduces the risk of invasive species. However, a tariff is a tax that can have economy-wide effects. It also interacts with other existing domestic policies.

Two interesting papers that look at tariffs as a prevention measure but viewed in a wider perspective provide additional insights about the effects of these policies. One paper applied a theoretical general equilibrium framework to analyze the effects of a tariff as a control policy to address invasive species (Costello and McAusland, 2003). The general equilibrium framework with competitive industries takes into account the economy-wide effects of the tariff. Higher tariffs on agricultural primary products lead to lower imports of these products. This encourages domestic production and leads to agricultural expansion in the protected country. This agricultural expansion increases the area of disturbed land available for propagation of invasive species. Thus, Costello and McAusland (2003) concluded that higher tariff that increases domestic production may lead to higher overall damages from invasive species.

The second paper analyzed the interaction of tariffs with other concurrent distortions such as subsidies (Acquaye et al., 2005). In particular, they claimed that estimates of the damage of invasive species on a particular commodity which do not take into account existing commodity policies may not yield the relevant cost of the damage. As an illustration, they analyzed the case of citrus canker. Citrus canker is a bacterial disease affecting most citrus, including oranges, lemons, limes and grapefruit. It causes significant damages to U.S. citrus-producing regions such as California and Florida. But there are commodity policies that support growers. The major government policy support to citrus growers is through specific tariffs on imports of frozen orange juice concentrates. Imports from Brazil, for example, have a tariff of 29.72 cents per gallon. Federal crop insurance is also another support policy for citrus growers. According to Acquaye et al. (2005), in 2002 the total insurance premium for Florida orange juice was $26 million, but there was a subsidy of $19.5 million which translated to 5.15 cents per gallon.

Acquaye et al. (2005) constructed a simple market model for citrus and analyzed the effects of a 10 percent decline in supply due to citrus canker damage. The domestic demand for orange juice is assumed to be a linear function of price with a price elasticity of -1.0. The domestic supply is also a linear function with a positive price elasticity of 1.0. Import supply to the U.S. is also linear with an elasticity of 5.0. Using this model, Acquaye et al. (2005) analyzed four different possibilities: (a) both tariff and subsidy are included; (b) tariff, but not subsidy, is included; (c) subsidy, but not tariff, is included; and (d) neither tariff nor subsidy is included. The results of their calculations are presented in Table 3.

Table 3: Effects of a 10% Citrus Canker-Induced Parallel Supply Shift

Variable	Initial Value	Tariff and Subsidy (a)	Tariff (b)	Subsidy (c)	Neither (d)
Prices	($/gallon)		*Percentage changes*		
U.S. producers	1.276	3.10	3.18	3.36	3.45
U.S consumers	1.224	3.23	3.18	3.50	3.45
World	0.927	4.26	4.21	3.50	3.45
U.S. annual quantities	(million gallons)				
Production	1240	-6.90	-6.82	-6.64	-6.55
Consumption	1426	-3.23	-3.18	-3.50	-3.45
Imports	186	21.30	21.03	17.48	17.24
Changes in			*Million dollars per year*		
Producer surplus		-105.5	-99.9	-101.6	-96.2
Consumer surplus		-55.4	-54.7	-60.0	-59.2
Taxpayer surplus		16.2	11.6	4.2	0.0
National surplus		-144.7	-143.0	-157.4	-155.4
World surplus		-136.6	-135.0	-148.7	-146.8

Source: Acquaye (2005)

Across the various scenarios, production and consumption decline while imports increase under a 10 percent decline in production as a result of canker citrus effects. Prices increase in the U.S. and in the world.

If there are applied tariffs and subsidies (column (a)), and if one does not take these policies into account (column (d)), then one cannot get an accurate estimates of welfare. There will be an underestimation of producer loss by 10 million ($105.5 million minus $96.2 million). Consumer loss will be overestimated by about $4 million ($55.4 million minus $59.2 million). Taxpayer benefit will be underestimated by $16 million. The net result will be an overestimation of national and global costs by about $10 million. While this illustration omits many of the dynamic aspects of the sectors, it shows the importance of carefully taking into account existing commodity policies and their interactions in estimating the cost of damage from invasive species.

Pest Mitigation Strategies: The Case of U.S. Imports of Avocados from Mexico

The paper of Peterson and Orden (2008) presents an interesting case study of mitigation strategy in the U.S. on imports of Mexican Haas avocados. Phytosanitary measures restricted entry of Mexican avocados from 1914 to 1997 because of concerns about avocado-specific pests and fruit flies in Mexico. Avocados from Mexico were permitted entry into Alaska only in 1993. In 1997, Mexican avocados were allowed entry into nineteen Northeastern States and the District of Columbia during limited months from November through February. In 2001, another twelve states were added to the list where Mexican avocados were allowed entry. Also, the importation period was expanded to October 15 through April 15. In 2004, all geographic and seasonal import restrictions on Mexican avocados were removed in 47 states (excluding California, Florida, and Hawaii). Lastly, in 2007 these restrictions were removed in all states.

The model used in Peterson and Orden (2008) is partial equilibrium. There are three supply regions in the model: U.S., Mexico and Chile. The model assumes avocados from Mexico have some risk (probability) of being infected with pests (fruit flies, stem weevils, seed weevils, and seed moth). However, avocados from Chile are assumed not to be infected. In the model, there are four demand regions in the U.S.: States approved for imports prior to 2004; Southeast region; Southwest region plus remainder of the Pacific; and Southern California. Compliance measures are used to reduce pest risk from imports of avocados from Mexico but tariffs are not used as a policy measure for this purpose.

In the demand side of the model, consumers in the four regions in the U.S. have two nested layers in their preference (utility) functions: one involving avocados and the rest of the consumer items, and another among avocado from the three suppliers. The demand functions for avocados in these four U.S. regions are derived as the first order conditions of utility maximization. The derived demand functions are functions of the consumer price of avocados, where the consumer price is determined by the producer price, the fixed wholesale margins, and the compliance cost for Mexican suppliers. Compliance cost included several factors such as: costs of pest control measures in approved orchards, per pound cost of packing plant investment; per pound fixed and variable costs of fees paid to the Mexican phytosanitary agency and the U.S. Animal and Plant Health Inspection Service (APHIS) by the packers; and other inspection costs.

The supply functions of avocados from the three suppliers are derived as the first order conditions of revenue maximization. The derived supply functions are functions of the supply price of avocados, where the supply price is determined by the producer price less grower cost of compliance in the exporting country and less the expected cost of control in the United States. In addition, the supply function of the U.S. is affected by the risk of invasive species entry from Mexico and invasive species spread. That is, if pests from Mexican avocados are able to enter and spread in the U.S., the outbreak will negatively affect avocado production in California. Pest outbreak is determined by a number of pest probabilities which include: probability that pest infects fruits; probability that pest is not detected during packing; probability that pest survives shipment; probability that pest is not detected at the port of entry; and the probability that pest is able to become established.

One can observe that the model incorporates various probabilities of entry and invasion, as well as mitigating measures both in the U.S. and in Mexico. These mitigating measures through the various compliance procedures (reflected in the various compliance cost items) comprise the system approach to risk management which is intended to reduce the pest-risk externality associated with trade of a commodity.

The model is closed with total demand equal to total supply. Total welfare is composed of consumer surplus and producer surplus, but less the cost of compliance/mitigation. Peterson and Orden (2008) calibrated this model to data in the U.S. avocado market and analyzed various scenarios to assess the effects if Mexican avocados are allowed in all 50 states. Three of the scenarios analyzed included: (a) the removal of geographical and seasonal restrictions of

Mexican avocado in the United States while maintaining the other compliance measures of the systems approach; (b) the removal of geographical and seasonal restrictions along with eliminating fruit fly monitoring and related quarantine requirements in Mexico; and (c) the removal of all compliance measures. The paper also assumed various levels of consumption substitution elasticities as well as supply elasticities. The first scenario corresponds to the 2004 decision to remove all geographic and seasonal restrictions on the importation of fresh avocados from Mexico. A model similar to the one in Peterson and Orden (2008), but with pest risk assumed to be zero with the other compliance measures kept in place, was used to provide the economic analysis for that regulatory decision.

In analyzing the welfare implications of avocado pest outbreak in the U.S, the frequency of outbreak and the cost of compliance are important. Peterson and Orden (2008) had estimates of pest outbreak frequencies in each of the three scenarios geographically and seasonally for each of the four invasive species (Table 4).

Table 4: Frequency of Pest Outbreaks

		Risk Probability Levels					
		Scenario a [1]		Scenario b		Scenario c	
Frequency of Outbreak		Average	High	Average	High	Average	High
Fruit Flies							
Season 1:	Region B	1.0E-06	1.0E-05	2.3E-04	2.0E-03	3.6E-03	3.0E-02
	Region C	5.0E-06	4.8E-05	1.2E-03	9.8E-03	1.8E-02	1.5E-01
	Region D	3.0E-06	2.5E-05	5.9E-04	5.0E-03	9.3E-03	7.8E-02
Season 2:	Region B	1.0E-06	7.0E-06	1.8E-04	1.5E-03	2.7E-03	2.3E-02
	Region C	4.0E-06	4.1E-05	9.8E-04	8.3E-03	1.5E-02	1.3E-01
	Region D	3.0E-06	2.5E-05	6.0E-04	5.1E-03	9.4E-03	7.9E-02
Stem Weevil	Season 1	5.9E-03	4.9E-02	6.0E-03	5.0E-02	9.3E-01	7.8E+00
	Season 2	6.0E-03	5.0E-02	6.1E-03	5.1E-02	9.4E-01	7.9E+00
Seed Weevil	Season 1	2.3E-05	2.2E-04	2.4E-05	2.2E-04	7.6E-03	6.9E-02
	Season 2	2.3E-05	2.2E-04	2.4E-05	2.2E-04	7.6E-03	7.0E-02
Seed Moth	Season 1	1.0E-06	7.0E-06	1.0E-06	7.0E-06	2.2E-03	2.2E-02
	Season 2	1.0E-06	7.0E-06	1.0E-06	7.0E-06	2.2E-03	2.2E-02

Source: Peterson and Orden (2008)

1. Scenario (a) is unlimited seasonal and geographical access with existing compliance measure; Sceanrio (b) is unlimited access without fruit fly compliance measures; Scenario (c) is unlimited access without all compliance measures.

For fruit flies, the frequency of outbreak is small (1.0E-06) under the average risk probabilities of scenario (a), but increases under the high risk probabilities (1.0E-05). Among the avocado-specific pests due to imports from Mexico, stem weevil has the highest frequency of outbreak.

The results of the simulations of Peterson and Orden (2008) are presented in Table 5. Eliminating compliance measures against fruit flies increases the probability of fruit fly outbreak under scenario (b). The probability of fruit fly outbreak increases further under scenario (c) in which all systems approach to pest control is removed. However, even in the worst scenario, the expected cost of mitigating fruit fly outbreaks remains minimal.

If the systems approach to pest control is completely eliminated under scenario (c), the frequency of outbreak of avocado-specific pests increases significantly. In this scenario, under the average risk probabilities the estimated cost of control measures in California is $0.013 per pound, but increases to $0.106 per pound under the high risk probabilities.

Table 5: Simulated Outcomes for the Three Policy Scenarios

			Scenario a [1]		Scenario b		Scenario c	
		Base Values	Average Risk	High Risk	Average Risk	High Risk	Average Risk	High Risk
Producer prices					Dollars per Pound			
Season 1:	California	0.87	0.67	0.67	0.66	0.66	0.66	0.70
	Chile	0.58	0.45	0.45	0.45	0.45	0.45	0.45
	Mexico	0.54	0.49	0.49	0.49	0.49	0.46	0.46
Season 2:	California	1.10	0.87	0.87	0.87	0.87	0.87	0.90
	Chile	0.60	0.54	0.54	0.54	0.54	0.53	0.54
	Mexico	0.54	0.57	0.57	0.57	0.57	0.54	0.55
Wholesale price (*weighted annual average*)								
California		1.62	1.40	1.40	1.40	1.40	1.40	1.43
Chile		1.27	1.17	1.17	1.17	1.17	1.16	1.17
Mexico		1.08	1.06	1.06	1.05	1.05	1.01	1.01
Quantities supplied (*annual*)					Million Pounds			
Total		581	764	764	769	769	787	775
California		346	342	342	342	342	340	324
Chile		177	162	162	161	161	161	161
Mexico		58	260	260	265	265	287	289
Mexican compliacne cost					Million Dollars *(dollars per pound)*			
Growers		4.73	8.29	8.29	7.10	7.10	0.00	0.00
		(0.081)	*(0.032)*	*(0.032)*	*(0.027)*	*(0.027)*		
Shippers		1.54	4.79	4.79	3.54	3.54	0.00	0.00
		(0.026)	*(0.018)*	*(0.018)*	*(0.013)*	*(0.013)*		
California cost of control		0.00	0.03	0.23	0.03	0.24	4.27	34.28
			(7.9E-5)	*(6.7E-4)*	*(8.2E-5)*	*(7.0E-4)*	*(0.013)*	*(0.106)*
Welfare effects								
Producer surplus								
California			-76	-76	-77	-77	-82	-102
Chile			-17	-17	-17	-17	-18	-17
Mexico			5	5	5	5	6	6
U.S. equivalent variation			154	154	157	157	168	156
Other fruit fly costs			8.00E-06	7.80E-05	0.002	0.016	0.029	0.244
Net U.S. welfare change			77.5	77.2	80.2	79.9	86.8	54.1

Source: Peterson and Orden (2008)

1. Scenario (a) is unlimited seasonal and geographical access with existing compliance measure; Sceanrio (b) is unlimited access without fruit fly compliance measures; Scenario (c) is unlimited access without all compliance measures.

In both seasons, avocado prices in California decline relative to the base when Mexican avocados are allowed entry to the full U.S. market. This leads to higher Mexican avocado exports to the U.S. and lower supply from California and Chile producers. There is an increase in the total compliance cost for Mexican growers and shippers relative to the base, but lower cost per pound as export volume increases. Under scenario (c) where all systems approach is removed, Mexican producers incur no compliance costs.

Because of lower production in California and Chile, all scenarios result in negative change in producer surplus in these regions, but higher surplus for Mexican producers because of increasing exports to the U.S. market. There is higher consumer surplus in the U.S. because of lower prices. All scenarios will result in net welfare gain for the U.S. Thus, when pest risks and related mitigation and compliance costs are incorporated in the analysis, the simulation results of Peterson and Orden (2008) support the 2004 decision to allow imports Mexican Haas avocados entry into the United States under a systems approach without geographical and seasonal restrictions. Peterson and Orden (2008) show that their results are robust with respect to a range of compliance costs around their initial estimates and with respect to various estimates of U.S. supply and demand elasticities. The highest net welfare gain is under scenario (c), but the paper does not support the idea of eliminating the systems approach "because our knowledge of the magnitudes of the pest-risk probabilities is not sufficient to rule out a smaller U.S. welfare gain compared to when some or all of the systems approach compliance measures are retained."

Pest Mitigation Strategies: The Case of Fresh Apples from China

Orden et al. (2007) analyzed the technical barriers in North America (United States and Canada) that affect imports of fresh apples from China. China is the world's largest producer of apples, capturing 40 percent of total world production in 2005. The United States comes in a far second with only a 6 percent share of world apple production.

The paper analyzed the economic efficiency and welfare effects of increasing market access in North America of Chinese fresh apples through the removal of phytosanitary measures. Fresh apples from China are still banned from entering the U.S market. However, in December 2002, Canada allowed entry of apples from approved and selected orchards and packers in China. Chinese apples in Canada have relatively higher prices than other apples due to their high quality. In Canada, these specialty apples find their way to markets mostly in Asian communities.

The analysis used in the paper was based on an economic model that was generally similar to the model specification in Peterson and Orden (2008). A key difference is that in the case of apples from China in Orden et al. (2007) there was no information available on the probability of pest outbreaks in the U.S. due to the importation. However, similar to Peterson and Orden (2008), where Mexican avocados exported to the U.S. were higher priced than those sold in the domestic Mexican market, apples exported to North America from China were relatively high priced compared to Chinese apples sold in to its domestic and most other export markets due in part to SPS and other production requirements to meet standards for North America.

In the model, there are three net apple exporters: China; U.S., and a set of countries in the Southern Hemisphere which includes Argentina, Chile and New Zealand. Net import regions are: Non-U.S. North America (Canada and Mexico); European Union-15; Association of Southeast Asian Nations (ASEAN); and rest of the world.

The model was used to analyze a few scenarios. If there are assumed to be no pest risks associated with the importation of Chinese apples into the U.S. market, Chinese apples are assumed to capture about 3 percent of the U.S. apple consumption without the import ban, which is similar to the situation in Canada. Chinese apples would have a higher price than U.S. apples. However, because of the increased variety of apples in the U.S. market, there is a small net welfare gain in the United States. There is also a small net producer gain in China.

Since there is no available information about the probabilities of pest outbreak from Chinese apples in the U.S., the risk analysis in the paper computed the maximum probability of pest outbreak that would result in zero change in total net U.S. welfare under assumptions of estimated “low” versus “high” damage costs. The result for the low-cost scenario was a pest outbreak probability of 2.5E-8 per kilogram of imports. Therefore, the U.S. would gain from Chinese apple importation if the probability of pest outbreak is lower than this level. In the high-cost scenario analyzed in the paper, the maximum probability of pest outbreak that leaves U.S. welfare unchanged declines by an order of magnitude to 3E-9 per kilogram of imports. The probability of pest outbreak can be reduced if the level of SPS compliance activities in China is increased (noting that higher level of compliance leads to higher production costs). These results illustrate that a systems approach to mitigating and controlling invasive species can result in welfare gain, while a total import ban can lead to welfare losses. The loss is due to higher consumer price and lesser variety of goods available to the consumers.

Other Case Studies of Non-Tariff Measures to Prevent Invasive Pests

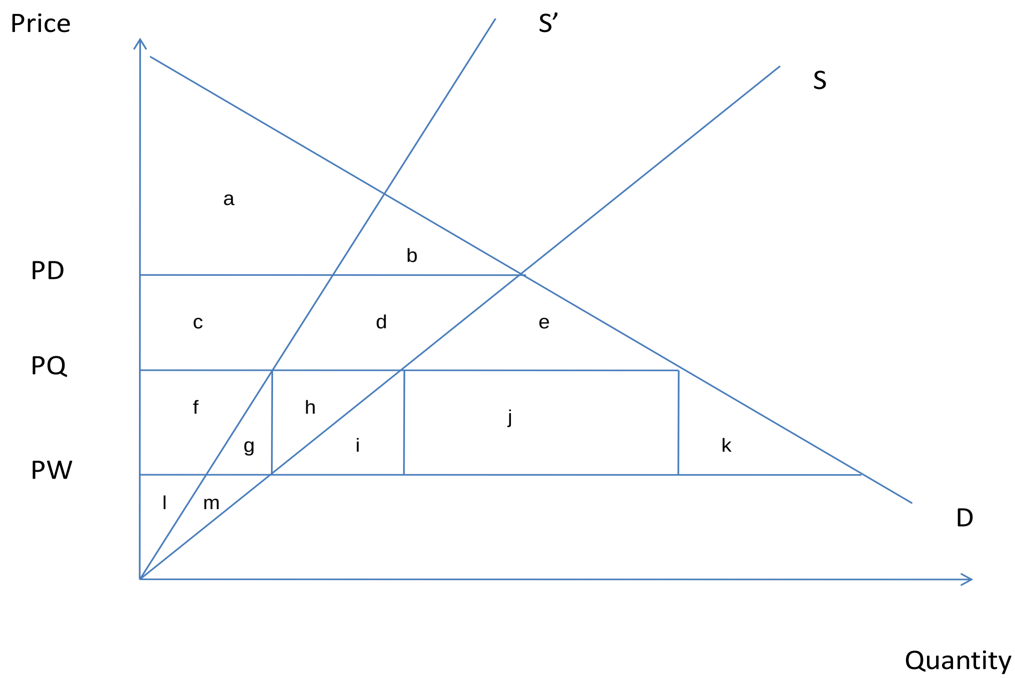
The potential damage of invasive species is a world-wide concern. Several studies have been conducted to analyze the effects in the host countries outside of the U.S. The paper of James and Anderson (1998) analyzed Australia's import bans and several other control measures such as quarantine on many agricultural products within the context of the WTO rules for SPS measures. As an illustration, they used banana. Australia's banana industry is relatively free of diseases that seriously affect a number of banana-producing countries. Invasives such as Moko disease, Papaya Fruit Fly, Spiralling Whitefly and Black Sigatoka can cause serious damage to bananas. They are difficult and expensive to control and can also affect other crops. Another virus, Bract mosaic, though relatively easily to contain may cause high production losses.

James and Anderson (1998) analyzed banana markets in Australia in the 1990s and found that the mean price was higher by more than two times compared to the price in the U.S. and New Zealand where imports are unrestricted. Furthermore, they observed that as a result of higher banana prices, the per capita consumption in Australia was lower compared to New Zealand and Sweden. Thus, this study presented evidence of the trade-off which we emphasized earlier in the paper between tight import controls so as to minimize invasive species introductions and consumer welfare loss due to higher prices and limited availability of goods in the market.

Calvin and Krissoff (1998) analyzed the technical barriers (TB) to U.S. exports of fresh apples to Japan. Both Japan and the U.S. are apple-producing countries. Prior to 1994, Japan imposed an import ban on U.S. apples. Japan was concerned with the spread of fire blight, codling moth and apple maggot. Fire blight is a bacterial disease that affects apple trees. Fruit affected by fire blight will be deformed and not meet commercial quality standards. Fire Blight is indigenous in the eastern U.S. and is now widespread in the U.S. Japan claimed that its apple production is free of fire blight and used this argument to justify their strict regulation regarding the disease. In 1994, Japan lifted the import ban, but implemented several precautionary measures against fire blight. Some of these measures included: dipping the apple in chlorine and inspection both in the U.S. and Japan. These costly phytosanitary requirements together with high tariffs and limited demand for red and golden delicious apples in Japan led to declining U.S. exports to Japan after the market was first opened.

The papers of James and Anderson (1998) and Calvin and Krissoff (1998) applied a similar analytical framework in analyzing trade, restrictions, and welfare. These papers employed a simple comparative-static partial equilibrium analysis shown in Figure 2. This approach allowed them to examine the benefits and costs of various import measures and to link these measures to prices and welfare. In more complex form, this is also the basis for the analysis in Orden et al. (2007) and Peterson and Orden (2008).

Figure 2: Trade and Welfare Effects of Invasive Species



Consider the supply curve S in Figure 2 where there are no effects from invasive species. PD is the domestic price that corresponds to zero imports. In this case, the consumer surplus is indicated by the areas a + b, while the producer surplus is c + d + f + g + h + l + m.

PW is the world price. If there are no trade restrictions, the domestic price will equal the world price. The inflow of imports at PW will augment consumer surplus to equal the sum of the areas from a to k. But producer surplus will shrink to l + m.

If imports are allowed but are regulated with quarantine measures, the domestic price will be PQ. The domestic price at this level can be interpreted as PQ = (1+q) where q is the cost per unit of implementing the quarantine measures, or it could also be interpreted as a tariff rate on imports. If q is prohibitively high, then the domestic price can go up to PD where imports are zero.

At PQ as shown in Figure 2 q is not prohibitive and trade occurs. The consumer surplus will be the sum of areas from a to e. Area j will represent the cost of quarantine. Producer surplus will be the sum of areas f + g + h + l + m. There is a deadweight loss which is represented by area i and k, while area e measures the net gain in national welfare from allowing trade as opposed to banning trade.

The supply curves shifts to S' if invasive species affect production. The cost of quarantine will increase, to the sum of areas h + i + j. Consumers will still enjoy the same surplus represented by the sum of areas a to e. The producer surplus will shrink to the sum of the areas f + l. Thus, invasive species will reduce the producer surplus by the area represented by the sum of g + h + m. This is the disease effect. In determining whether trade is beneficial compared to a ban on trade in this case, the issue is whether this disease effect is less than or greater than area e in the consumer surplus. This is an empirical question because the result will depend upon the slope of the demand and supply curves. If area e is greater than the disease effect, then allowing trade with quarantine measure will lead to higher overall welfare.

In the James and Anderson (1998) application of this framework to Australian bananas, the paper concluded that "the removal of that import ban may well cause a major contraction of banana growing in Australia, simply because of the high economic protection provided by the current ban. Despite that, the economic welfare gains to consumers are shown to almost certainly outweigh the losses to local banana producers." In the Calvin and Krissoff (1998) application to apples for Japan, the technical barriers (TBs) included in the analysis were the phytosanitary requirements on the imported apple into the Japanese market. Using a tariff-equivalent of an import ban, they estimated that for the welfare gain from trade to be completely eliminated would require an average yield loss from invasive species of 30 percent or more. But more important was their strong conclusion: "Our results show that, on average, TBs in Japan are even more important than tariffs in deterring trade. Moreover, the primary role of Japanese TBs for apples appears to be to protect economic rents of domestic producers from foreign competition and not to maximize social welfare."

In a recent paper, Calvin, Krissoff and Foster (2007) analyzed the impact of the 2005 Japanese decision to revise the phytosanitary protocol for fire blight for U.S. apple imports, but to retain the standards that prevent codling moth. Their analysis indicates that the economic cost of the phytosanitary requirements is about 15 cents per pound. This is much higher than the estimated accounting cost of 5 cents per pound. If the fire blight protocol is removed, the phytosanitary cost is reduced by 8 cents per pound. The market price is estimated to decline by 9 cents per pound, which leads to an estimated increase in the annual Japanese Fuji apple imports of 28 thousand metric tons or $31 million of imports. If codling moth protocol is removed, it results in an estimated increase of 73 thousand metric tons of Fuji apple imports into the Japanese market or $83 million of imports. Thus, the removal of the fire blight protocol alone only accounts for 38 percent of the total trade impact of removing both the fire blight and codling moth protocols.

We close this section with brief consideration again of two studies that put the specific cases reviewed above into a broader empirical or analytic context. While the studies cited above introduce some elements of uncertainty into the analysis and present simulation results that reflect this uncertainty, they do not uniformly reflect a modeling framework incorporating uncertainty in a systematic manner. Waage et al. (2005) are more explicit in formulating such a model in their scoping study for DEFRA. In their framework, uncertainty about pest risks arises from unknown parameters affecting probabilities of pest entry, establishment, diffusion and density of infestations locally, and spread through long-distance dispersal. Additional uncertainty affecting the economic impacts of either invasive species infestations or established pests arise from the costs of control measures farmers take in production to limit their effects once a pest becomes established permanently, and from the impact of the established pest on crop yields or animal outputs. Waage et al. (2005) review the scientific literature to identify estimates of the parameters for a biological diffusion, density and spread model for numerous potential invasive species in six categories (terrestrial invertebrates, plant diseases, vertebrates, animal diseases, terrestrial plants and aquatic species). They then develop a static, stochastic, multi-year partial equilibrium economic model utilizing the @Risk computer software to incorporate the invasion-risk, biological and economic-cost uncertainties. For six invasive species (one from each category), they simulate such a model with 10,000 iterations to estimate the range of possible effects from that species. Waage et al. (2005) do not provide assessments of risk management strategies to reduce the probability of a pest invasion nor to reduce its spread or eradicate the pest, which would introduce additional uncertainties affecting both the choices of these strategies and the resulting pest prevalence and economic costs, along lines presented in some of the studies above. Instead, the simulations by Waage et al. (2005) only provide the range of possible outcomes for each pest for a "base case" where no such actions are taken by regulatory authorities and the pest becomes established. These values, they point out, would serve as upper bounds on the costs that would be justified for measures to exclude or eradicate the pest.

We will not repeat the results from the specific case studies presented by Waage et al. (2005) instead focusing on several methodological points that arise from their presentation. First, their review indentifies that scientific information on key parameters is often not available. One alternative they consider is converting expert opinion in qualitative terms into a range of numerical values for inclusion in their stochastic simulations. They present a table of such semi-quantifiable risk categories (their Table 3.1) that range from "high" with a probability of 0.7-1.0 to "negligible" with a probability of less than 1.0E-06. Second, they present their results for each case over a 20-year time horizon in three systematic graphs: one depicting the cumulative distribution of average expected yearly costs from the pest; one depicting the area or number of animals affected from the first to final year and confidence bounds around these annual estimates; and one depicting the expected costs per year and its confidence bounds. A detailed representation of both the distribution of total costs and their time path arise from these results. These vary substantially among pests of different types examined by Waage et al. (2005). The authors also discuss numerous limitations of their models for which extensions or additional sensitivity analysis could be developed: among these are the assumed form of the distribution of their unknown parameters, the assumption of fixed world prices for the products affected, and the effects on the environment for which they provide only qualitative assessments rather than incorporating costs of these impacts explicitly into their stochastic models.

The second paper adds perspective about the case studies reviewed above in a different dimension. Beghin et al. (2009) provides a conceptual framework for cost-benefit analysis for the whole range of non-tariff measures (NTMs) that countries might employ to address market failures and imperfections related to agro-food trade. This paper is part of an ongoing OECD project on NTMs that will eventually include identification of various cases for detailed study. Beghin et al. (2009) includes an appendix that presents a new classification scheme for sanitary and phytosanitary measures and other NTMs currently being developed by UNCTAD and the WTO. This classification scheme can be useful in categorizing invasive species prevention measures in specific studies for cross-study comparative purposes. The paper also provides a useful listing of data sources for supply and demand elasticities (from USDA, Economic Research Service and OECD) and existing NTM’s (from UNCTAD, WTO and several other sources) that can be informative for case studies. The analytic thrust of the paper by Beghin et al. (2009) is to recognize that market failures affecting consumers or producers, as well as global-commons environmental concerns and imperfect monitoring and implementation issues, should be incorporated in economic studies of NTMs. The authors specify partial equilibrium conceptual models that take these effects into account. For producer externalities specifically, the paper “follows Orden and Romano (1996), Wilson and and Antón (2006), and Peterson and Orden (2008)” in depicting the effects of invasive pests on the domestic supply curve, as shown above in Figure 2. This citation confirms the relevance of these studies to the emerging literature.

6. Some Studies on Controlling the Spread of Invasive Species

The part of the literature on the economics of invasive species that addresses control or eradication of invasive pests once they are introduced or become established is vast by itself. Some of the papers are very specific case studies not only in the U.S. but also in other countries. Some papers provide estimates of the potential negative economic effects of invasive species establishment and spread. Some studies analyze the existing control policies. Others extend further the analysis by suggesting ways to strategize the control measures so as to generate higher benefits not only at present but over time. This section does not provide an exhaustive review of this part of the literature but will only focus on four papers: Olson and Roy (2002), Burnett et al. (2007), Adams and Lee (2007) and Leuschner et al. (1996). The first paper is a theoretical paper that looks at the conditions under which it is optimal to eradicate the invasive species and the conditions under which it not optimal to eradicate. The other three papers are specific case studies. Focus is on choice of policies for controlling or eradicating an invasive pest regardless of the initial cause of its arrival. Thus, the concern over trade policy and risk-mitigation compliance measures to minimize invasive pest risk that is highlighted in the preceding section fades into the background in these control studies.

Optimal Control Models: When to Totally Eradicate an Invasive Species

It is clear in the literature that there is strong empirical evidence of considerable economic, environmental, and health costs from invasive species that warrant appropriate policy interventions. It is also clear from the literature that while the impact of unabated invasive species is significant, the cost of implementing species-population-reducing measures increases geometrically as shown in Figure 1. The cost of total and complete eradication of invasive species is substantial and can become prohibitive. Thus one of the challenges facing policy makers is: at what point should policy intervention stop, or is it economically optimal to completely eradicate the population of a particular invasive species?

In a theoretical paper Olson and Roy (2002) used a dynamic optimal control framework to analyze the conditions under which the control of invasive species is optimal. The framework has two major components: a function that specifies the growth of the invasive species and an objective function that contains the cost of control and the amount of damages that result from the invasion. The growth function incorporates general characteristics of the growth and spread of invasive species. It specifies an aggregate size of the invasion in terms of the population of the species or the area invaded at the beginning of the period. There is an existing control measure implemented during the period which reduces the population of the species but does not totally eradicate it. The remaining invasive species population will grow and regenerate depending upon climatic, geological, or ecological factors. Future costs and damages are discounted using a time preference factor in the objective function. The objective is to reduce the sum of the total cost of control and the amount of damages subject to the growth function of the remaining invasive species during the period.

Without going through the mathematical details of the arguments of Olson and Roy (2002) one of the key policy lessons that can be drawn from their theoretical results is that although a complete eradication is costly, it can be justified on efficiency grounds only for a special case where the population size of invasive species is small and the growth rate of the species population is high. In this case, the marginal benefits of avoiding the present and future damages from the invasive species can exceed the marginal cost of control. That is, total eradication of a small invasion avoids the rapid growth in future costs that accompany a high expansion rate of the invasion. However, if the invasion is large, the optimal policy choice on whether to eradicate or not will depend on the interaction of the cost of control, damages of the invasion species, and the growth rate of the invasion. Each of these parameters have to be looked at carefully, estimated and evaluated before an optimal policy is formulated.

Optimal Control Models: *Miconia calvescens* (purple plague) in Hawaii

The paper of Burnett et al. (2007) looks at how to control over time and space an invasive species called *Miconia calvescens* in Hawaii. *Miconia calvescens* is a flowering plant. It is invasive. In Hawaii it is commonly called the ‘purple plague’ which threatens to damage the ecosystem. It can grow to a height of 15 meters and has very large leaves that shade out the space below, thus preventing any other plant nearby from growing. Once it disperses into wet tropical forests, it takes hold vigorously and invades any spot in the understory that receives patches of sunlight. It has sweet fruits that are attractive to birds and other animals that disperse the seeds. *Miconia calvescens* has shallow system of roots, thus it exacerbates soil erosion.

Burnett et al. (2007) applies their analysis to the Island of Oahu in Hawaii. The current control management of *Miconia calvescens* in the island involves monitoring and response when the trees are discovered. Burnett et al. (2007) applies an optimal control framework, along the lines of Olson and Roy (2002), to understand the optimal treatment path. The study defines the control management as a minimization problem of the expected costs and damages from the presence of and control activities against *Miconia calvescens*. A contribution of the paper in terms of methodology is that it allows costs and damages that enter the objective function to vary across space and time.

The set up of the objective function is the discounted value of the difference between two functions which represent the cost of removing the invasive species (which is the product of the marginal cost and the number of removals) and the damages incurred. Both functions vary with the population of the species. The objective function is minimized subject to a function that defines the population growth of the species. The population of *Miconia calvescen* is a state variable in the optimal control problem. The first order condition (FOC) of the minimization problem describes the optimal management of *Miconia calvescen*. The FOC generates the equality between: (i) the opportunity cost of removing the marginal unit of the species in a particular location (or space) at the present period instead of one period later, and (ii) the net benefit of removing that unit of species. The net benefit is composed of two items: the decrease in the current-period damages and decrease in the costs of harvesting current-period growth, both of which are due to the marginal decline in the population of invasive species. One can observe that this analysis is within the framework presented in Figure 1.

The marginal cost function (where cost is composed of two components: search cost and treatment cost of *Miconia calvescen*) was parameterized using data generated by Geographical Information Systems (GIS). GIS was used to map the current and predicted future populations of the invasive. For purposes of the mapping, the island of Oahu was divided into 16-hectare cells. In each cell, there was information on habitat quality and the existence of *Miconia calvescen.* The study assumed that *Miconia calvescen* has been on the island for 37 years. Based on certain assumptions spelled out in detail in the study, it estimated the current population of *Miconia calvescen*. Also based on certain assumptions, the study estimated damages in the ecosystem: changes in the cycle that may affect freshwater supply and changes in forest composition that may reduce habitat for endangered species such as birds, plant species and invertebrate species.

Based on this information, the study arrived at the following conclusion: (a) over the next 40 years the cumulative damages caused by *Miconia calvescen* will amount to $627 million if its population is left unmanaged; (b) based on the optimal criterion derived from the analysis, the optimal population of *Miconia calvescen* in each cell will range from 40 to 700 trees per 16-hectares, which translated to densities of 1 percent to 18 percent cover; and (c) the optimal path for the control cost will involve higher expenditure during the first year of management in order to reduce current stock of *Miconia calvescen* and to slow its spread in the future; but after this initial expenditure outlay there will be lower present value of the net costs from *Miconia calvescen* management and at the same time there will be increasing present value of the difference between damages and costs over time.

One can observe the existence of an optimal control strategy based on assumptions used in the paper. The optimal control strategy does not contain measures that will totally eradicate the spread of the invasive species nor totally eliminate the damages from *Miconia calvescen*. In Figure 1, the optimal reduction in the population of the invasive species is at point N*, which is below point N_0.

Static Discounting Models: Invasive Aquatic Plants

The paper of Adams and Lee (2007) is also in the spirit of Figure 1 where total benefit is compared with total cost of controlling invasive species. This paper also contains cost-benefit analysis, but the method applied was different from the paper of Burnett et al. (2007) because the problem was not set up as an optimization where FOC for the solution are derived to guide the search for the optimal path of managing the invasive species. In Adams and Lee (2007), the cost of controlling invasive aquatic plants and the potential benefit derived if the control is effective were estimated using a bioeconomic model. The resulting net benefit is calculated and compared under three different scenarios. In terms of Figure 1, these scenarios could represent any point between N' and N_0.

The paper of Adams and Lee (2007) analyzed the harmful effects of three invasive aquatic plants (hydrilla, water hyacinth, and water lettuce) in 13 large Florida lakes. These invasives pollute 96 percent of Florida's public lakes and rivers. These invasives grow rapidly. They displace native flora and reduce recreational use of many water bodies in Florida. They affect summer activities such as camping, hiking, birding, and other nature-based activities. In the summer, these invasives cover aquatic areas and drive fish away. They also limit access to water. Thus, controlling the population of these invasives has become a high priority concern in Florida.

In the analysis, the paper used a bioeconomic model for invasive aquatic plants. The main components of the bioeconomic model were: (a) plant control and plant population; (b) plant populations and lake use; and (c) lake use and lake value.

Without going through the specifics of the model, the paper specified an equation for invasive aquatic plant coverage. Given this equation, a total budgetary cost function was specified, which was a function of invasive aquatic plant coverage. These two equations determined the extent of the invasives and the amount of resources needed to control their spread and population.

The paper specified a benefit equation which involved the total annual fishing activities in 13 lakes over 365 days. If the spread of the invasives is controlled, then fishing will improve, which in turn increases benefit. The net benefit equation was specified as the difference between total benefit and total cost. The model was used to simulate three different control scenarios presented in Table 6.

Table 6: Model Assumptions for Control Scenarios

Scenario	Treatment at day 60	Second Treatment
A (status quo)	All hydrilla and floating plant acreage	None
B	None in year 1, then maintenance control in subsequent year	None
C	Maintenance control in subsequent years	20 percent additional during mid-summer (actual date varies by lake), then maintenance control in subsequent years.

Source: Adams and Lee (2007)

The economic value of fishing activities in the 13 lakes was estimated to exceed $65 million per year while the control cost was estimated at $60 million. The simulation results indicated that: (a) a one-year lapse in control will result in 21 percent reduction in recreation activities and will increase the long-term control cost by 2.1 times; and (b) a one-year increase in control will increase fishing benefits by $4.9 million per year and will decrease maintenance control cost by $3.2 million (or 66 percent) and will generate net benefit of $6.6 million. Thus, based on these results, increased control activities against these invasives is the best control strategy among the three considered. A lapse in control will not only discourage activities, but will also increase the future control and maintenance cost.

Static Discounting Models: The Benefit of Controlling Gypsy Moth Spread

The objective of the paper of Leuschner et al. (1996) was to analyze the potential benefits of slowing down the spread of gypsy moth, *Lymantria dispar*. Gypsy moth was accidentally introduced in Boston, Massachusetts in 1869. Since then spread has intensified to as far away as Virginia, West Virginia and parts of northeast North Carolina.

Since information on gypsy moth was first recorded in 1924, this invasive has defoliated nearly 90 million acres nationwide. Based on facts presented in a Virginia Tech website (2009), gypsy moth has resulted in considerable cost to the state of Virginia. "In Virginia, historical defoliation is nearly 5.5 million acres with a suppression cost of over $17 million. These costs do not include the economics associated with tree mortality, reduced tourism, and adverse recreational and residential impacts due to defoliation and the nuisance of large numbers of caterpillars in and around dwellings and public areas. There also are human health impacts such as allergic reactions to gypsy moth larvae and their excrement as well as environmental impacts resulting from changes in the forest canopy."

To reduce the spread of these invasives, a gypsy moth containment program called 'Slow-The-Spread' (STS) was proposed in 1990. The paper of Leuschner et al. (1996) assesses the economic benefit of STS. In assessing the impact, the paper initially estimated the acres attacked by the invasives and the associated damages. Based on these estimates, the paper employed a spread simulation model using Geographical Information Systems (GIS) and projected the spread in the next 25 years (based on the 1990 base year). Furthermore, the paper used an economic model that incorporated control and management activities in the STS program. The economic model was used to estimate the impacts on timber, residential, and recreational activities.

In estimating the acres attacked, the paper utilized data on forest area covered with selected trees that are susceptible to defoliation[4]. The paper applied the assumption of 0.097 percent probability of a timber being infested in a year. Based on this information and other assumptions, the paper arrived at the estimated damage from gypsy moth invasion per acre. In the spread model, six rates of spread were selected which ranged from 2.5 to 15.0 miles per year in 2.4 mile increments in each county identified over a 25 year period. In the economic model, the paper assumed that the infested zone increases with the spread. However, the spread may be reduced through the STS program. The management cost through the STS program was affected by: (a) the increase in infested area as predicted by the spread model; (b) area in the county considered in the analysis; and (c) the average cost of $0.18 per acre (this was the 1988-1989 average cost per acre in the state of Pennsylvania).

Without going through the details of the various formulas used in the analysis to calculate the impact on management cost and timber, residential and recreation uses, we present the results of the calculations by Leuschner et al. (1996) in Table 7.

Table 7: Negative Impacts of gypsy moth spread over 25 years, in million 1990 dollars present value

	Rate of spread (miles per year)					
Impact	2.5	5.0	7.5	10.0	12.5	15.0
Management Activities	32.2	62.0	92.9	125.0	158.5	193.6
Timber	66.4	122.8	173.6	221.6	267.5	324.4
Recreational	46.9	94.7	143.0	195.0	241.7	389.3
Residential	649.7	1,203.6	1,820.7	2,463.6	3,131.3	3,789.6
Total	795.2	1,483.1	2,230.2	3,005.2	3,799.0	4,696.9

Source: Leuschner et al (1996)

[4] Oak-Pine, Oak-Hickory (except Yellow-poplar-Oak), Yellow-poplar-Oak, Oak-Gam-Cypress (except nonsusceptible types), and Maple-Birch-Beech.

This was how the authors interpreted the results. The results in the table indicate the potential damage under various rates of spread if the STS program was not implemented. However, if the program was successfully implemented, the rate of spread is slowed down considerably which will lead to significantly lesser economic damages. To analyze the potential benefits from the STS program, they considered the difference between the results under rate of spread of 15 miles per year and 2.5 miles per year as the scenario with the greatest benefit (in million 1990 dollars), i.e. \$4,696.9 – \$795.2 = \$3,900.8[5]. The medium case scenario was between 12.5 and 5.0 miles per year (\$3,798.9 – \$1,483.1 = \$2,315.9), while the least difference scenario was between 10 and 7.5 miles per year (\$3,005.1 – \$2,230.5 = \$775). The paper therefore concluded that the STS program could generate substantive benefit, of which about 83 percent of the impacts were due to delaying the residential effects.

7. Additional Methodological Concerns

The literature on the economics of invasive species is vast as illustrated by the selected studies and discussion presented in this review. There are a great number of issues tackled such as methodological modeling issues, identification and categorization of types of species, pathways of species introduction, estimates of potential damages, policy intervention through prevention measures (avoiding entry and establishment of species) and control programs (containing and mitigating the spread). In this section, we will discuss two interesting methodological issues: how to specify and model damage control agents such as pest control, immunization, fumigation etc., and how to model invasions under uncertainty. These issues are theoretical but have important implications for undertaking and interpreting studies of management of invasive species.

Policies that minimize the impact of invasive species generate benefits such as improvements in productivity (which will benefit the producers) and improvement in quality (which will benefit the consumers). Improved productivity will result in reduction in production cost and improvement in supply. Viewed in this way, reducing the pressure of invasive species is similar to improving production technology (Acquaye et al. 2005).

[5] There was a minor typographical error in the paper where the reported total was as \$4,597 when in fact the correct total was \$4,696.9.

In a theoretical paper, Lichtenberg and Zilberman (1986) considered two categories of factors of production. One set is the traditional factors such as land, labor and capital. Another set is composed of damage control agents. Unlike the traditional factors of production, these damage control agents do not increase potential output. "Instead, their distinctive contribution lies in their ability to increase the share of potential output that producers realize by reducing damage from both natural and human causes" (Lichtenberg and Zilberman, 1986, p. 261). That is, "damage control agents do not enhance productivity directly as do the standard types of production factors. To the contrary, they may even impede productivity somewhat. The application of a pesticide, for example, may be harmful to crop plants to a certain extent." (p. 262). Therefore, damage control agents cannot be considered to have similar characteristics as the traditional factor inputs.

Lichtenberg and Zilberman (1986) compared two production function specifications. One specification involves the following: Let G(X) be defined as an abatement function that is related to X which is the control agent. Let Z be the traditional factors of production. Let the production function be Q = F[Z,G(X)], where Q is output and F is the production function. The abatement function is a cumulative probability function defined over 0 and 1. G is equal to 1 if the destructive capacity of the invasive species is total eradicated, while G is equal to 0 if the invasive species have the maximum destructive capacity. The other production function is a simple one where X is treated in the same manner as Z, the tradition factors of production. That is, Q = F[Z,X].

Lichtenberg and Zilberman (1986) analyzed and compared the characteristics of each of these specifications. They observed that if the simple specification is used where the damage control agents are assumed to have the same characteristics as the traditional factors of production (i.e., Q = F[Z,X]), the productivity of damage control inputs will be overestimated and the productivity of the traditional factors will be underestimated. This will not be the case when an abatement function is specified together with the traditional factors.

This result has important policy implications. If the productivity of damage control agents is overestimated, chances are policy makers will be led to encourage more extensive and intensive use of the damage control agent. In the case of pesticides, for example, the policy maker could favor further application of pesticides at a time when they are already overutilized.

The other policy implication is that when damage control agents are considered the same as the traditional factors, the model will predict declining productivity of damage control agents over time, similar to the traditional factors. This suggests that as the spread of resistance of invasive species increases, there is reduction in the use of damage control agents. This will not happen if an abatement function with the characteristic described above is introduced. In this case, the use of damage control agents will intensify in response to the spread of resistance.

Applying the above framework of separating damage control agents from traditional factor inputs through a separate abatement function involving damage control agent variables, Babcock, Lichtenberg, and Zilberman (1992) analyzed the use of pesticides in apple production in North Carolina. One of their major policy conclusions was that damage control agents such as pesticides, antibiotics and irrigation (technologies which have gained growing public objections and concerns because of their environmental side effects) have both quality and quantity effects on production. Their results indicate that fungicides reduce yield losses and quality degradation. Insecticides reduce quality damage. The authors concluded that ignoring the effects of damage control agents on product quality as well as total output leads to underestimation of their productivity impact.

Another important methodological issue is with regard to invasive species risk management or management under uncertainty. A large part of the literature on the economics of invasive species under uncertainty is analyzed within an expected utility framework, including the studies cited in this review. This assumption may create serious problems because of the fact that while the probability of establishment and spread of invasive species is very low, once established and spread, the damages of invasive species can be very high Williamson (1996). But there is a tendency to assign higher probabilities to detrimental events with large social losses. Using insights from the Ellsberg's paradox in the expected utility maximization framework, people tend to make irrational choices between lotteries (Ellsberg, 1961). This may be explained by the fact that when probability of an event cannot be assessed, people tend to be averse to uncertainty. In this case, decision models based on standard expected utility theory may not be appropriate to analyze issues on invasive species under uncertainty and may not be suited for identifying efficient strategies in managing and controlling invasive species (Gren, 2008). There are two ways suggested in the literature of addressing this concern: (a) obtain more information; and (b) base decisions on rules other than maximization of expected utility.

Eisworth and van Kooten (2002) suggested methods for improving data assessment. They showed that expert judgment can be used for assessing various measures in controlling weeds and for identifying among these measures the most efficient management strategy.

Because of the limitation of the expected utility framework in analyzing invasive species issues, Horan, et al (2002) developed alternative decision rules on invasive species under uncertainty based on: (a) controlling invasion under full information (risk management); and (b) basing management decision rule on a framework with ignorance. Risk management under full information, however, may be infeasible because in most cases risk of invasion is unknown.

Three of their major assumptions are: (1) the impact of invasive species has a probability distribution; (2) there are *n* independent potential pathways of evasion, each treated as a Bernoulli event, i.e. an invasion either occurs or it does not; and (3) the decision maker that faces the control problem is adverse to uncertainty, meaning that events with high probability of occurrence will get relatively higher weights in the decision maker's preference function than other events.

Under both risk management with full information and ignorance, the optimal strategy of controlling invasive species is where marginal cost is equal marginal benefit. If there is no uncertainty, the expected value of the benefit may be identical with focus loss, where focus loss is defined as a decision that attracts the decision maker because it is where the loss is maximized. However, if there is no full information, extreme outcomes with low probability but nevertheless possible will be assigned more weight compared to the expected value approach. Therefore, "it is optimal to devote more resources to confronting high-damage events that are considered possible (low potential surprise) even if the probability is low, and to allocate few or no resources to confronting events that are considered less possible (higher potential surprise) – regardless of the expected damages of those events" Horan, et al (2002), p 1309. The policy implication of this result is that these outcomes will attract more attention in the decision process and therefore will be assigned more resources.

Furthermore, the theoretical results indicate that there is an optimal prevention effort addressing invasive species, which is found by weighing the costs and benefits of the control efforts. But the exact form of the weighting function and the specific weights that are applied have to be empirically estimated.

8. Insights

The literature has indicated prominently that although the probability of establishment and spread of invasive species is very low, once established and spread progresses, invasive species could bring substantial damage to the host region. Governments and other key institutions have recognized this potential damage and therefore have supported policy measures that can minimize the effects.

The risk of invasive species introductions is usually analyzed in the literature within the context of two influencing forces: economic activities that create risk and economic activities that reduce risk. A major concern in the economics of invasive species is to find the optimal balance or mix of these forces and to search for the right policy instruments that can maximize welfare of producers and consumers, net of the cost of implementing these policy measures.

One of the major pathways of invasive species entry is through foreign trade. There has been an unprecedented growth in world trade and an exponential increase in the establishment of alien species. This presents two key policy concerns: (a) how to minimize the possibility of entry of invasive species through the borders; and (b) how to minimize trade distortions so as to facilitate trade in goods and services across countries. In the literature on trade and invasive species, the primary challenge therefore is how to design a policy that will accommodate the dual concerns of minimum possibility of entry of invasive species and of minimum trade distortions. Much of the literature is focused on invasive species management under uncertainty in the expected utility framework.

Three policy instruments have been most widely analyzed for preventing introductions of invasive species through trade: import bans, import tariffs, and risk mitigating strategies. While a total ban can control entry of invasive species, it could result in significant cost to the consumers because of higher prices and limited availability and diversity of commodities in the market. Import tariffs can also reduce invasive species introduction but they are not the most desirable policy to address pest risks in principle, nor are they a policy instrument likely to be available to regulatory agencies. The optimal tariff can be prohibitive especially if there is high risk of invasion and high productivity loss of pest outbreaks. In other cases, because of its improved welfare implications the literature has strongly recommended use of mitigating measures to reduce invasive species risks. This includes use of a systems approach that involves a set of compliance and monitoring measures with mutually reinforcing risk-reduction effects that may be implemented in the countries exporting potentially tainted commodities as well as in the importing country.

Studies addressing the prevention of invasive species inherently involve substantial modeling of markets and trade, since both pest risks and economic consequences under alternative policies depend on the volume of trade that occurs. Moreover, the pests being given consideration are generally not established in the importing country, so scientific and field-based evidence about their impacts is often limited or speculative As a consequence, these studies have in some cases represented pest risks and the costs of risk mitigation or consequences of pest invasions in relatively simply and static terms, with limited sensitivity analysis provided concerning the uncertainty about the parameters of the pest-related risks and costs. The literature reviewed in this survey is illustrative that studies focused on control or eradication of established pests have generally focused in more depth on the biological modeling of pest spread and consequences, often in a dynamic framework.

A key point of focus for this review has been the model developed by Peterson and Orden (2008) that incorporates trade-related pest risks and the costs associated with mitigation measures and occurrence of invasive species outbreaks into the economic assessment of alternative regulatory policies. Several insights can be drawn from the review in terms of future development and uses of this modeling framework. The surveys by Gren (2008) and Costello, Lawley and McAusland (2008) call attention to additional policy instruments, such as a market for rights for risk creation or use of criminal/civil liability, that might be incorporated in the set of policies evaluated. The scoping monograph by Waage et al. (2005) highlights systematic stochastic assessment of the risks and costs associated with invasive pests over time, evaluated in a multi-period, static framework. Wilson and Antón (2006) and several other papers reviewed demonstrate the emergence of an increasingly sophisticated literature in terms of inclusion of mitigation strategies and assessments of their effects. And the pest control studies reviewed point toward the need for dynamic treatment of trade and the resulting effects from invasive species.

Policy-oriented economic benefit-cost analysis that integrates risk assessment and related mitigation and control costs has to incorporate three components into an inter-disciplinary framework. The first component is based purely on risk science, such as probabilities of pest risk of infestations or transmission, or procedures for control of pest outbreaks. The second component inherently involves a mixture of pest risk science and economic considerations, such as an assessment of the effectiveness of specific mitigation or pest control measures and their likely economic cost. The third component is based purely on economics in that it involves the construction of the economic model in which the specific and net effects of alternative policy decisions are evaluated, taking information from the first two components into account.

In any particular case in which regulation is being considered or re-evaluated, there can be gaps in knowledge in any one, or more than one, of these three components. The empirical results in the literature are sensitive to the level of risk and uncertainty of invasive species, unknown or uncertain efficacy and costs of potential intervention measures, and uncertainty about economic behavior of producers and consumers. The economic models developed can provide rich policy insights provided there is sufficient information available related to each of these necessary dimensions of the analysis. That is, the critical aspect in the design of policy that can accommodate the dual concerns of minimum possibility of entry of invasive species and of minimum trade distortions is uncertainty. Some consider uncertainty of invasive species as an exogenous variable. But uncertainty is an endogenous variable. Policy makers can allocate resources to learning more about invasive species and therefore increase knowledge about them. This can be done through data gathering, surveys, observation from trials and experiments, and other research. Likewise, investments in attaining knowledge of key economic parameters and the development of realistic economic models will contribute to better regulatory decision making.

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Appendix A: Synopsis Table of Main Studies Reviewed

Title	Authors(Year)	Synopsis
Recent Related Surveys		
The Economics of Terrestrial Invasive Species: A Review of the Literature	Olson (2006)	Summarizes studies of economic impact of invasive species; reviews dynamic programming models for optimal pest control; examines border measures and pest detection strategies; examines specific cases for different categories of pests
Economics of alien invasive species management – choices of targets and policies	Gren (2008)	Presents a general economic framework for optimal pest prevention and control efforts; examines command and control versus economic incentive policies; compares a range of measues including tariffs, border risk-mitigation measures, rights for risk creation, and dissemination of information about risks
Pre-empting NIS Introductions: Targeting Policy	Costello, Lawley and McAusland (2008)	Focuses on trade-related pest prevention measures; examines how characteristics of specific pests affect relative efficacy of different policy instruments including price-based, quantitative, process versus product, and criminal/civil liability
A New Agenda for Biosecurity	Waage, Fraser, Mumford, Cook and Wilby (2005)	Presents historical evidence of pest invasions and impacts in the UK and describes emerging market and social forces that will affect the future incidences and costs; develops stochastic, static bio-economic simulation model; presents results for seven invasive or established pests; provides strategic conclusions for UK regulatory agency (DEFRA)

Overviews and Perspective		
Food Regulation and Trade: Toward a Safe and Open Global System	Josling, Roberts and Orden (2004)	Examines the global trade regulatory regime for animal, plant and human health through the WTO; reviews dispute resolution and presents other case studies under the SPS and TBT agreements and other WTO provisions
A Cost-Benefit Framework for the Assessment of Non-Tariff Measures in Agro-Food Trade	Beghin, Marette and von Tongeren (2009)	Presents partial equilibrium cost-benefit models accounting for market failures affecting consumers or producers, global commons concerns, and imperfect monitoring and implementation of regulatory policies; presents detailed new classification scheme for NTMs developed by UNCTAD and the WTO and data sources for supply and demand elasticities and existing NTMs
The Econometrics of Damage Control: Why Specification Matters	Lichtenberg and Zilberman (1986)	Theoretic paper addressing econometric modeling of production function where traditional factor inputs are separated from damage-control inputs, and where damage-control inputs are specified in a separate abatement function
Impact of Damage Control and Quality of Output: Estimating Pest Control Effectiveness	Babcok, Lichtenberg, and Zilberman (1992)	Estimates pesticide productivity using damage control abatement function in production and applies the analysis to North Carolina apple production
Biological Pollution Prevention Strategies under Ignorance: The Case of Invasive Species	Horan, Perrings, Lupi and Bulte (2002)	Discusses alternatives to expected utility for evaluating optimal decision about invasive species management

Link between Trade and Invasive Species		
Economic Factors Affecting Vulnerability to Biological Invasions	Dalamazzone (2000)	Cross-country econometric study finds positive statistical correlation between trade flows and invasive species introductions
Forecasting Biological Invasions with Increasing International Trade	Levine and D'Antonio (2003)	Econometric study for the United States projects number of invasive species becoming established to be at least 120 during 2000-2020 based on expected trade volumes and estimated past effects of trade on pest invasions
Tariffs, Bans and Other Risk Mitigation Measures		
Import Restrictions in the Presence of a Health Risk: An Illustration Using FMD	Paarlberg and Lee (1998)	Evaluates optimal tariffs for U.S. against countries with FMD; finds that optimal tariff is prohibitive if pest risk is high, while optimal tariffs would not preclude all imports if risk is low
Combining Risk Assessment and Economics of Managing a Sanitary-Phytosanitary Risk	Wilson and Antón (2006)	Extends Paarlberg and Lee by introducing border risk mitigation strategies; finds optimal tariff is low even when risk is high if appropriate mitigation strategies can be implemented
Avoiding Invasives: Trade-Related Policies for Controlling Unintentional Exotic Species Introductions	McAusland and Costello (2004)	Evaluates the optimal combination of tariffs and port inspection in addressing trade-related invasive species
Economic Consequences of Invasive Species Policies in the Presence of Commodity Programs: Theory and Application to Citrus Canker	Acquaye, Alston, Lee, and Sumner (2005)	Examines effects of tariffs and farm subsidies on effects of pest infestations that reduce U.S. domestic citrus supply by an assumed 10 percent

Avocado Pests and Avocado Trade	Peterson and Orden (2008)	Models opening of U.S. market to avocados from Mexico taking pest risks, mitigation measures and costs of trade-related pest infestations into account; finds little pest risk and net economic gains to consumers exceeds losses to domestic producers with mitigation measures against avocado-specific pests retained; concludes there is too much uncertainty about pest risks to eliminate the pest-related import requirements completely
Technical Barriers Affecting Agricultural Exports from China: The Case of Fresh Apples	Orden, Gao, Xue, Peterson and Thornsbury (2007)	Models exports of fresh apples from China; finds that opening the U.S. market would result in limited imports with a net economic gain as long as pest risks are at a minimal level
On the Need for More Economic Assessment of Quarantine Policies	James and Anderson (1998)	Examines Australian ban on banana imports and concludes gains to consumers would exceed losses of producers if the ban were eliminated
Technical Barriers to Trade: A Case Study of Phytosanitary Barriers and the U.S.-Japanese Apple Trade	Calvin and Krissoff (1998)	Examines Japanese technical barriers to apple import from the U.S. and concludes these barriers are overly restrictive
Measuring the Costs and Trade Effects of Phytosanitary Protocols: A U.S.-Japanese Apple Example	Calvin, Krissoff and Foster (2007)	Investigates the impact of the 2005 Japanese decision to revise the Phytosanitary protocol for fire blight for U.S. apple imports and to retain the codling moth protocol
Controlling the Spread of Invasive Species		
The Economics of Controlling a Stochastic Biological Invasion	Olson and Roy (2002)	Theoretical paper describing objective function and pest infestation growth function for optimal control dynamic models; results imply complete eradication is only optimal in special circumstances of small initial pest population with rapid growth and consequent damages

Invasive Species Control over Space and Time: (*Miconia calvescens)* on Oahu, Hawaii	Burnett, Kaiser and Roumasset (2007)	Application of optimal control model to "purple plague" affecting ecosystem with damages estimated at $627 million in the absence of control measures; results suggest optimal strategy is higher initial control expenses but not eradication of the pest species
Estimating the Value of Invasive Aquatic Plant Control: A Bioeconomic Analysis of 13 Public Lakes in Florida	Adams and Lee (2007)	Multi-year (but not formal optimal control dynamic) model taking harmful effects and costs of three alternative control strategies into account; results suggest net gains of $6.6 million from initiating a one-year increase in control expenditures
Potential Benefits of Slowing Gypsy Moth's Spread	Leuschner, Young and Ravlin (1996)	Multi-year model estimating costs under different assumptions on rate of pest spread; results indicate benefits of program to slow spread primarily from increased residential use values