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Three Essays on the Economics of Controlling Invasive Species

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THREE ESSAYS ON THE ECONOMICS OF CONTROLLING INVASIVE SPECIES

by

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ABSTRACT

Three Essays on the Economics of Controlling Invasive Species

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This dissertation addresses issues pertinent to the control of an invasive species, issues that pertain both to a species' introduction at a country's international border and its spread within the country's border. In the first essay, tariffs and inspections are examined as a joint border control mechanism. In a deterministic setting, where the invasive species level is functionally related to a foreign (i.e., exporting) country's shipment size, a traditional tariff can be optimal for the home (i.e., importing) country in the short run, but distorts the entry condition for foreign firms and results in a suboptimal industry size in the foreign country in the long run. When the foreign country's abatement effort determines the invasive species level, an additional home-country tariff on the invasive-species level (which I call an "invasive-species tariff") is necessary to motivate the foreign firms to abate the invasive species at socially optimal level.

In the second essay I consider the case where the invasive species contamination level is jointly determined by the foreign countries' abating efforts and random environmental factors. The home country may use standard contracts to mitigate imperfect observability caused by the random factors. However, I show that the home country must provide risk-averse foreign countries with higher subsidy rates than the first-best rates with perfect information as compensation for partially bearing the risk. When risk-averse foreign countries face both individualistic and common random environmental factors, a standard tournament scheme is capable of attaining the home country's first-best invasive-species solution.

The third essay addresses the control of an established invasive species outbreak in the home country with multiple spatially-connected individuals. The optimal response to invasion (eradicating, stopping, or ignoring invasion) is determined by the incremental damage of invasion and the marginal control cost. Different spatial scales lead to a divergence between the control incentives of society and individuals, and result in a deficiency of individualistic control, which in turn results in a larger steady-state invasion area. Numerical analysis also demonstrates that the number, size, and spatial configuration of small and large individual land parcels influence the severity of the externality and the insufficiency of privately supplied control. I introduce a dynamic multiple-source-subsidy scheme to internalize the externalities, which prompts individuals to coordinate and follow the social optimal control path without a budget burden on the government.

(188 pages)

PUBLIC ABSTRACT

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Invasive species have caused notable economic damages in agriculture, fisheries, forestry, and other industries over the past several decades. Invasive species control must therefore be designed to prevent the both the introduction and spread of invasive species. This dissertation examines the efficiency and efficacy of tariffs and inspections as a joint control mechanism at a home (i.e., importing) country's border. I find that a traditional tariff can be optimal in the short run when the invasive species level is directly related to a foreign (i.e., exporting) country's shipment size. However, in the long run a traditional tariff results in a suboptimal industry size in the foreign country. When foreign countries can abate the invasive-species level prior to exportation, an additional tariff should be levied by the home country on the foreign country in order to induce the latter to choose the optimal abatement effort.

Next I discuss the case of uncertainty, where the invasive species contamination level is jointly determined by the foreign countries' abatement efforts and random environmental factors. The home country can no longer perfectly observe the foreign country's abatement efforts due to this randomness. A standard subsidy contract can nevertheless induce the foreign country to optimally abate the invasive species level

(from the home country's perspective). However, the home country must offer a higher subsidy rate than the corresponding rate under perfect information in order to compensate a risk-averse foreign country. I also find that a standard tournament scheme between two competing foreign countries can be effective in attaining the home-country's first-best outcome when risk-averse foreign countries face both individualistic and common random environmental factors.

For the control of an established invasive species outbreak within a home country that consists of multiple spatially-connected individuals, I find that individualistic (i.e., uncoordinated) control is suboptimal. The key reason for this outcome is the existence of uncompensated benefits associated with individualistic control. Individual participants with small spatial scales are only concerned with their own limited damages, which are subset of the social damages. I also find that the more individuals, and the smaller the average parcel size, the larger is the steady-state invasion area. The configuration of small and large individual land parcels also influences the severity of the externality and the result of individualistic control. I show that a dynamic, multi-source subsidy scheme can be optimal in these circumstances.

To my teachers

To my families

To my friends

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CHAPTER 1

INTRODUCTION

Invasive species include nonnative plants, animals, disease pathogens, and other organisms whose introduction cause, or are likely to cause, economic and environmental harm, e.g. to human, animal, plant, or environmental health (ISAC, 2006). Although some nonnative species are introduced for intentional beneficial purposes (Clout and Williams, 2009), many nonnative species are introduced unintentionally through contaminated commodities and packing materials, ballast water, and tourism. According to the Office of Technology Assessment (OTA), roughly 12% of intentionally introduced species and 44% of unintentionally introduced species cause harm basing on the examination (OTA, 1993).

Invasive species have been causing notable economic damages in agriculture, fisheries, forestry, and other industries over the past several decades. These damages, which are sometimes irreversible, materialize as commodity reduction, native species extinctions, biodiversity loss, human health threat, and diminishment of ecosystem services and aesthetics. Pimentel et al. (2005) estimate that invasive species cause roughly $120 billion of annual environmental damages and losses in the US. Wilcove et al. (1998) estimate that invasive-species invasions affect about a half of native imperiled species in the US. Levine and D' antonio (2003) use species-accumulation model and forecast that invasive species will increase in the future as international trade expands.

The urgency of prevention and control of invasive species has increasingly been recognized by regulatory authorities. Typical prevention measures include import bans, permits, tariffs, inspections, quarantine, and education. Measures receiving the most attention in the literature have been tariffs and inspections (Costello and McAusland, 2003; McAusland and Costello, 2004; Margolis et al. 2005; Mérel and Carter, 2008; Batabyal and Beladi, 2009). For the most part, this literature has ignored the abatement reactions of foreigns (henceforth foreign firms or countries). Exceptions include McAusland and Costello (2004), Amenden et al. (2007), Mérel and Carter (2008), and Jones and Corona (2008).[1] Further, random factors affect the establishment of invasive species and subsequent damages, and also influence the behaviors of foreign firms. Particularly when foreign firms are risk-averse, uncertainty is an important factor affecting the foreign firm's decision. The effect of uncertainty has also not been adequately addressed in the literature.[2]

Controlling the spread of an established invasive species within the home country is another important issue needing to be addressed. The spread of invasive species within a given region is ultimately a dynamic process. Therefore its control is an optimal control problem that includes multiple participants. A participant makes control decisions

[1] McAusland and Costello (2004) show that if inspection is not perfect, i.e., a positive unit cost of inspection with a less than 100% discovery rate, the optimal tariff rate comprises two parts - unit inspection cost and unit damage. If the infection rate is fixed, the combination of a tariff and inspection can realize optimal prevention. If the foreign firm can reduce the infection rate through abatement effort, the firm adjusts its abatement level according to its private interest with respect to the pre-determined tariff and inspection rates set by the home country. Since the foreign firm does not internalize the home country's marginal damage from invasive species infection, its abatement effort is inefficiently low. Consequently, the home country prefers to set tariff and inspection rates above their respective socially efficient levels. The authors also offer a specific policy where the tariff and inspection rates are contingent upon the infection rate and thus induce the foreign firm to abate at the socially efficient level. Mérel and Carter (2008) follow McAusland and Costello's (2004) structure and suggest a penalty on inspected contaminated goods in order to induce the foreign firm to correct its abatement effort. Amenden et al. (2007) discuss the foreign firm's reaction to border enforcements.

[2] Previous analysis of uncertainty has mostly focused on the introduction, establishment, and damage processes (Olson and Roy, 2002; Finnoff et al., 2005; Olson and Roy, 2005 etc.). Costello and McAusland (2003) also argue that the damage associated with an invasive-species invasion depends on the amount of agricultural activity.

according to his own interests, which in general is differs from what would be a social objective. Nevertheless, individual control creates benefit spillovers to other adjacent landholders and the public (i.e., positive spatial externalities), as well as negative spillovers, e.g., damage caused by the emigration of pests from high-density to low-density areas. The fundamental reason for this dual externality is that the social planner and the individual participants differ in their concerns for and jurisdiction over the damage caused by an invasive species. While previous work has acknowledged the existence of the positive externalities, far less attention has been devoted to this externality component. For a socially optimal solution to the problem, it is thus necessary to coordinate the individuals' respective interests with a social goal. An incentive scheme is required to overcome the deficiency of (or externality associated with) individual control.

This dissertation proposes various incentive schemes for controlling the spread of invasive species at or within the border of a home country. The first essay concerns control of the international spread of invasive species through an international trade mechanism. A modified tariff scheme is introduced to overcome the shortcomings of a traditional tariff scheme along the lines of McAusland and Costello (2004). Control in the presence of risk-averse foreigns and environmental uncertainty is the focus of the second essay. An optimal subsidy scheme is analyzed in the context of a standard principal-agent model. A tournament scheme is also developed, where risk-averse foreigns face both individualistic and common random factors. The third and final essay develops a dynamic optimal control analysis of the within-region spread of invasive species with multiple, private land owners. The deficiency of decentralized individual control is discussed and policy solutions are proposed. To illustrate the theoretical results, numerical analyses are conducted in each essay.

References

Ameden, Holly A., Cash, Sean B, and Zilberman, David, 2007. Border enforcement and firm response in the management of invasive species. Journal of Agricultural and Applied Economics 39, (October), 35-46.

Batabyal, Amitrajeet A., and Beladi, Hamid, 2009. Trade, the damage from alien species, and the effects of protectionism under alternate market structures. Journal of Economic Behavior & Organization 70, 389-401.

Clout, Mick N., and Williams, Peter A., 2009. Invasive species management. Oxford University Press.

Costello, Christopher, and McAusland, Carol, 2003. Protectionism, trade, and measures of damage from exotic species introductions. The American Journal of Agricultural Economics 85 (4), (November), 964-975.

Finnoff, David, Shogren, Jason F., Leung, Brian, and Lodge, David, 2005. Risk and nonindigenous species management. Review of Agricultural Economics 27 (3), 475–482.

ISAC, 2006. Invasive species definition clarification and guidance white Paper. Submitted by the Definitions Subcommittee of the Invasive Species Advisory Committee (ISAC),< http://www.invasivespeciesinfo.gov/docs/council/isacdef.pdf> (accessed 02.12.10).

Jones, Kristin, Roti, and Corona, Joel P., 2008. An ambient tax approach to invasive species. Ecological Economics 64, 534-541.

Levine, Jonathan M., and D'antonio, Carla M., 2003. Forecasting biological invasions with increasing international trade. Conservation Biology 17(1), (February), 322–326.

Margolis, Michael, Shogren, Jason F., and Fischer, Carolyn, 2005. How trade politics affect invasive species control. Ecological Economics 52, 305- 313.

McAusland, Carol, and Costello, Christopher, 2004. Avoiding invasives: trade-related policies for controlling unintentional exotic species introductions. Journal of Environmental Economics and Management 48, 954–977.

Mérel, Pierre R., and Carter, Colin A., 2008. A second look at managing import risk from invasive species. Journal of Environmental Economics and Management 56, 286-290.

Olson, Lars J., and Roy, Santanu, 2002. The economics of controlling a stochastic biological invasion. The American Journal of Agricultural Economics 84 (5), 1311–1316.

Olson, Lars J., and Roy, Santanu, 2005. On prevention and control of an uncertain biological invasion. Review of Agricultural Economics 27 (3), 491-497.

OTA, 1993. Harmful non-indigenous species in the United States. Office of Technology Assessment, United States Congress, Washington, DC.

Pimentel, David, Zuniga, Rodolfo, and Morrison, Doug, 2005. Update on the environmental and economic costs associated with alien-invasive species in the

United States. Ecological Economics 52, 273– 288.

Wilcove, David S., Rothstein, David, Bubow, Jason, Phillips, Ali, and Losos, Elizabeth, 1998. Quantifying threats to imperiled species in the United States. Bioscience 48 (8), 607– 615.

CHAPTER 2

HOW A TARIFF WORKS AS AN INVASIVE-SPECIES CONTROL POLICY

Abstract

This study investigates the efficacy of a traditional tariff and proposes an invasive-species tariff in a deterministic and perfectly-observability setting. The framework for this essay is provided by Spulber (1985) and McAusland and Costello (2004). When the invasive species level is functionally related to shipment size, the traditional tariff works well in the short term but distorts the entry condition of foreign commodity industry and results in a suboptimal industry size in the long term. A lump-sum subsidy or tax is necessary to correct the distortion. To the contrary, when the foreign firm's abatement effort determines the invasive species level (i.e., the invasive species level is not functionally related to shipment size), the traditional tariff alone cannot provide the correct incentive for abatement. An invasive-species tariff levied directly on the invasive species level is necessary to attain the home country's optimal invasive species level. Numerical analysis shows how the home country's damages are affected by shipment size and the tariff levels. As the foreign firm's abatement cost increases, total shipment size and the foreign industry shrinks, yet the shipment size per foreign, the invasive species level, the invasive-species tariff rate increase. As a result, the home country's welfare decreases.

1. Introduction

Invasive species outbreaks occur in three stages: the arrival, establishment, and spread phases. An invasive species becomes established when it has high population, wide distribution, and consequently very low possibility of extinction (Liebhold and Tobin, 2008). Therefore, prevention at the border is generally believed to be the most efficient way to prevent an invasive species outbreak from occurring. An unintentional introduction of an invasive species typically occurs through international trade, which therefore motivates exporting and importing countries to coordinate their prevention efforts.

Typical prevention measures include import bans, permits, tariffs, inspections, quarantine, and education. Tariffs and inspections are the common preventative measures, which are also at the core of discussion and debate in the literature. Because unintentional introductions of invasive species are byproducts of trade, coordinated intervention is necessary. However, as the real problem is not trade per se, intervention measures should not necessarily restrain the flow of international trade. Rather, foreigns need to be provided with direct incentives to decrease the contamination level of their shipments to the home country. A traditional tariff does not provide a direct incentive to abate the invasive species. This issue has not received enough attention in the literature, and is therefore addressed in this essay.

In the general frameworks of McAusland and Costello (2004) and Mérel and Carter (2008), we find that in the short run a traditional tariff can be an efficient instrument when the invasive-species contamination rate exhibits a fixed relationship with shipment size. This is essentially the same conclusion reached by McAusland and Costello (2004). However, we show that in the long run an additional lump-sum tax (subsidy) per firm is required to induce the optimal industry size in the foreign country. When this fixed relationship between contamination rate and shipment size is absent, a traditional tariff is shown to be inefficient. An "invasive-species tariff" levied directly on the invasive species level itself becomes necessary to convey the correct abatement incentive for the foreign firm. In this essay, both the "fixed" and "unfixed" cases are assumed to occur in a deterministic setting.

2. Literature Review

The problem of controlling the spread of invasive species between and within given regions is, in many respects, similar to the control of nonpoint source pollution. To begin with, only the aggregate level of an invasive species attack is observable. It is difficult (too costly) to identify which source contributes to which portion of the damage. Further, the establishment and damage of invasive species depends on stochastic environmental variables. The specific contribution of a given source does not in general result in one-for-one spread or damage. Nevertheless, invasive species have unique characteristics. First, with respect to the international spread of a species, it is possible to inspect imported goods, albeit imperfectly. Second, there is a time lag between the introduction of an invasive species and its associated damages. This entails having to discount expected future damages and control costs for optimal decision making (Kim et al, 2006; Olson and Roy, 2010). Consequentially the economics of invasive species is concentrated on when and how to control the spread in the long run.

Invasive-species economics research generally proposes either ex-ante or ex-post control policies (Gren, 2008). Ex-ante policies are concerned with preventive management, e.g. control of the international or interregional spread of invasive species. Ex-post policies focus on controlling invasive species that have already entered and spread within a country or region. Policies therefore generally target three components of an invasion: introduction, establishment and spread, and damages (Gren, 2008). Allocating resources efficiently between prevention and control activities requires the consideration of prevention and control costs, potential damages, the growth rate of invasive species, and the discount rate.

Mehta et al. (2007) discuss the role of detection activities in invasive-species management. They analyze the stochastic and dynamic factors governing the trade-off between allocating resources to the detection phase and the post-detection control phase. Using a constant detection strategy, they demonstrate that it is optimal to allocate more resources to detection efforts for species associated with high damages. However, for species with (1) a low efficacy of search, (2) low population densities, (3) low growth rate, or (4) where a cost-efficient control strategy is available, the optimal allocation of resources to search efforts will be lower than when the species causes high damages. Kim et al. (2006) argue that it is optimal to allocate more resources to what they call “exclusion activities” (prevention), before an invasive species is first discovered. They argue exclusion activities can be optimal if the invasive species population is initially beneath a threshold level. Above the threshold, exclusionary activities are no longer optimal. Finnoff et al. (2007) argue that a risk-averse social manager will prefer more control than prevention due to the uncertainty of exclusion activities. However, preventing the introduction of an invasive species has a profound impact on the subsequent control of the invasive-species spread.

Both intentional and unintentional introductions of invasive species can be thought of as market failures. Along these lines, Knowler and Barbier (2005) discuss the necessity of implementing policies, such as Pigovian tax, to control the size of breeding exotic species industry, which imports the breeding material of an exotic species and breeds through competitive nurseries for sale within a given region. The authors point out that without intervention the long-run equilibrium number of nurseries is higher than the socially optimal level. Excessive nurseries increase the risk of potential invasive species outbreaks. The authors also emphasize that a pollution evaluation on exotic species should be implemented before permitting their importation. Their numerical illustration of Tamarisk spread shows that horticultural introducers should be taxed at a roughly less than 1% rate of average profits to ensure an optimal industry size (and thus spread of Tamarisk). They conclude that (1) the higher the hazard rate (the probability that a commercial plant becomes invasive at a specific time), (2) the more sensitive is industry size vis-a-vis the hazard rate, and (3) the greater the extent of damages from invasion, the higher the optimal tax on the introducers.

Regarding unintentional introduction of invasive species, most studies assume that the invasive species level imported into a host country is exogenously determined (Costello and McAusland, 2003; McAusland and Costello, 2004; Margolis et al., 2005;

Olson and Roy, 2010).[3] For example, Margolis et al. (2005) assume a fixed contamination rate and a constant damage rate of each importing good. Olson and Roy (2010) assume a constant size of invasive-species introduction. In each of these papers, the prevailing assumption is that invasive species distribute uniformly among imported goods. Under these assumptions, the importing country can therefore decrease the risk of invasive-species introduction through implementation of a tariff or inspection measures.

A tariff decreases the volume of imports, and inspections provide a check on contaminated goods, each of which can reduce the incidence of invasive-species introductions. For example, Costello and McAusland (2003) utilize a two-sector balanced trade model of a small country that shows how increasing the tariff rate can decrease the rate of invasive-species introductions into the home country. As McAusland and Costello (2004) show, tariffs can work well in decreasing the risk of introducing an invasive species in a deterministic setting when the level of invasive species has a fixed relationship with the volume of the import good, i.e., there is a constant infection rate. The authors investigate a policy mix of tariff and inspection, where inspection can intercept a portion of the contaminated goods, which are then discarded at the foreign firm's expense. The authors find that the optimal tariff and inspection rates are both positive under the assumptions of an exogenous proportion of infected goods to total received goods.

Margolis et al. (2005) point out that trade politics can also affect the border control of invasive species. Using Grossman and Helpman's (1994) political economy model, they assume that interest groups care solely about their respective member's welfare,

[3] McAusland and Costello (2004) relax this assumption in Section 4 of their paper.

while the government cares about general welfare and contributions from the interest groups. Interest groups represent the interests of private owners of each respective factor of production. Rent to each factor depends on the price of the product for which the factor is used. The interest groups adjust their contribution schedules in an effort to secure high protection from imports. The authors show that an optimal tariff rate (from the perspectives of the government with respect to social welfare and political contributions) will always exceed the marginal damage associated with the species' spread.

In controlling the introduction of an invasive species, trade should not necessarily be restrained, as the real problem is not trade per se. For example, Peterson and Orden (2008) estimate that using alternative compliance measures to decrease pest risks, and removing seasonal and geographic restrictions on importing fresh avocados from approved orchards in Mexico, would increase U.S. net welfare by $77 million annually.

Rather, the negative externality associated with the introduction of an invasive species caused by international trade needs to be more directly internalized. Since a first-best externality policy generally applies the economic instrument (e.g., tax) directly on the invasive species level itself, tariffs levied on the import goods are therefore not generally a first-best instrument.[4] Thus, tariffs imposed directly on the imported goods are generally not an efficient way to achieve an environmental objective, especially when the invasive species level can be changed through the abatement effort of the foreigns

[4] As Spulber (1985) points out, "under an output tax the firm will have an incorrect input mix and the firm may not engage in the right amount of effluent pretreatment activities…… (A transfer is thus) needed to correct the Pigouvian tax per unit of output."

(McAusland and Costello, 2004).[5] Toward this end, Mérel and Carter (2008) extend McAusland and Costello (2004)'s model by imposing a penalty scheme, which is imposed directly on the detected contaminated units with a tariff levied on total imported goods. They find that a penalty-with-inspection scheme generally outperforms a tariff-with-inspection scheme. In the optimal solution, the tariff rate equals per-unit inspection cost.[6] The penalty is set equal to the expected marginal damage modified by the effectiveness of inspection.

Border enforcement is also addressed in the literature. Ameden et al. (2007) argue that increased inspection may result in decreased imports and increased or reduced "pre-entry treatment." The authors point out that pre-entry treatment technology and inspecting intensity can be crucial enforcement tools. Using a queuing theoretic model, Batabyal and Nijkamp (2005) find that a container policy (i.e. "inspects cargo upon the arrival of a specified number of containers") is superior to a temporal policy (i.e. "inspects cargo at fixed points in time"). However, empirical estimates suggest that border inspection affects only a small percentage of imported goods, since the cost of inspection is high. For example, APHIS (Animal and Plant Health Inspection Service, the

[5] As previously mentioned, McAusland and Costello (2004) show that the foreign firm reduces its abatement effort beneath the social optimal level if the foreign firm can mitigate its infection rate under the preset tariff-and-inspection scheme. The abatement effort of the foreign firm is not fully compensated when the tariff and inspection rates are preset. The home country can correct for the foreign firm's incentive to lower its abatement effort before setting its trade policy, i.e., the home country can manipulate the tariff and inspection rates to induce more abatement from the foreign firm. The authors also offer a firm-specific infection-contingent policy which internalizes the invasive species damage to the home country. However, the policy-making cost may increase and compromise the benefit associated with the lowered infection rate. The tariff-and-inspection scheme is not necessarily efficient because it does not target the externality directly.

[6] This result is the same as in McAusland and Costello (2004).

U.S. Department of Agriculture) examines only roughly 2% of U.S. international cargo (Haack, 2001).

Sanitary and phytosanitary trade policies as prevention measures are discussed in several papers, such as Wilson and Antón (2006), Cook and Fraser (2008), and Olson and Roy (2010). Olson and Roy (2010) argue that if the marginal cost of sanitary and phytosanitary policy at fully protecting level is lower than the current and future marginal damage and marginal control cost, then fully protective trade policy will be efficient. Otherwise, partial or no protection is preferable. Cook and Fraser (2008) show that a country may choose the same outcome through WTO compliance or a unilateral welfare-maximizing policy. Sanitary and phytosanitary measures taken by the importing country should meet the SPS Agreement. [7]

As mentioned previously, the control of invasive species is similar in some respects to the control of nonpoint source pollution. Segerson (1988) initially proposed a linear ambient tax to control nonpoint source pollution. She shows that this scheme can give the correct incentive for polluters to abate at an ex ante socially optimal level for single or multiple polluters.[8] Jones and Corona (2008) apply Segerson's (1988) ambient tax mechanism to the ballast-water invasive species problem and argue without vessel-specific information an ex-ante tax scheme can be used to induce vessels to choose the optimal abatement effort in the short-run. However, vessel-specific information is needed in a long-run optimal tax scheme, with a lump-sum subsidy provided to each vessel. Then they propose an adjusted ambient tax with random exclusions.

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[7] The Agreement on the Application of Sanitary and Phytosanitary Measures (the "SPS Agreement") concerns the application of food safety and animal and plant health regulations (WTO, 1998).

[8] Horan et al. (1998) investigate the use of a nonlinear ambient tax, as well as an ex post tax rate scheme.

Finally, Horan and Lupi (2005) propose a tradable risk permit system to motivate foreigns to control the contamination level of invasive species. However, the permit measure may be compromised to high transactions and administrative costs. Also, decentralized bargaining is unsuitable due to the complexity associated with multiple participants, as well as the inherent uncertainty associated with the spread of a species.

3. Fixed Relationship between Contamination Level and Shipment Size

3.1 Theoretical Analysis

To simplify the tariff model, a partial equilibrium setup is considered. We assume a single commodity is traded internationally, which is contaminated by an invasive species. The home country, which does not have a domestic production of the commodity, is large and therefore exerts pricing power in the international market. Its objective is to maximize its own welfare (consumer surplus) net of invasive species damage. Also it is assumed there is no consumption of this commodity in the foreign country. We begin by assuming that a deterministic function describes the relationship between the level of invasive-species contamination (henceforth invasive-species size) and shipment size of the international commodity. In the section 4, this 'functional relationship' assumption is relaxed.

Following McAusland and Costello (2004), we assume the importing sector is perfectly competitive. There are *n* atomistic, identical, risk-neutral foreign firms that take the price determined by the home country as given. To concentrate on the effect of the tariff, the home country is assumed to inspect each shipment and to be able to detect the corresponding invasive species size accurately. Since the optimal tariff induces the foreign firms to fully internalize the damages incurred by the home country, it follows that in cases where a non-zero invasive species level is optimal, and the home country does not necessarily discard the shipment.[9]

Let s represent a representative foreign firm's shipment size of the traded commodity, and I the corresponding invasive-species size imported by the home country from the firm. To begin, we assume $I = I(s)$, with $\partial I(s)/\partial s > 0$. $D(nI(s))$ represents the aggregate financial damage (incurred by the home country) caused by an invasive-species invasion, where $\partial D(nI)/\partial(nI) > 0$ and $\partial^2 D(nI)/\partial(nI)^2 > 0$. P is the per-unit price of the traded good. W represents the welfare level of the home country, and $B(ns)$ is the benefit gained by the home country via consumption of the imported good, $\partial B(ns)/\partial(ns) > 0$ and $\partial^2 B(ns)/\partial(ns)^2 \leq 0$. Since $B(ns)$ can be thought of as a total surplus measure, it can be represented as $\int_0^{ns} P(x)dx$, i.e., the area beneath the home country's (inverse) market demand curve. Let τ^s represent a uniform tariff rate on shipment size s, a the constant marginal cost of inspecting each shipment, π each foreign firm's profit level, and $c(s)$ each foreign firm's shipment cost function, with $\partial c(s)/\partial s > 0$ and $\partial^2 c(s)/\partial s^2 \geq 0$.

Taking the number of firms, n, as given, the home country's objective is therefore,

$$\underset{\tau^s}{\text{Max}}\, W = \int_0^{ns(\tau^s)} P(x)dx - ns(\cdot)P\big(ns(\cdot)\big) - nas(\tau^s)$$

[9] McAusland and Costello (2004) do not make as simplifying an assumption as this. In their case, the home country is unable to perfectly inspect each shipment, and thus their optimal tariff is supplemented with a penalty for any discarded portion of the shipment. The tariff and penalty together induce the foreign firm to fully internalize the control costs incurred by the home country. Further, McAusland and Costello (2004) assume a linear damage function. The damage function used in this paper is more general than McAusland and Costello's (2004).

$$-D(nI(s(\cdot))) + n\tau^s s(\cdot) \tag{2.1}$$

Totally differentiating (2.1) with respect to τ^sresults in,

$$\frac{dW}{d\tau^s} = -n\frac{\partial P\big(ns(\tau^s)\big)}{\partial(ns)}\frac{\partial s(\tau^s)}{\partial\tau^s}s(\tau^s) + s(\tau^s)$$

$$+\tau^s\frac{\partial s(\tau^s)}{\partial\tau^s} - \frac{\partial D(\cdot)}{\partial(nI)}\frac{\partial I(\cdot)}{\partial s}\frac{\partial s(\tau^s)}{\partial\tau^s} - a\frac{\partial s(\tau^s)}{\partial\tau^s} = 0 \tag{2.2}$$

Each foreign firm earns zero profit in long-run equilibrium. Therefore,

$$\pi = P\big(ns(\tau^s)\big)s(\tau^s) - c\big(s(\tau^s)\big) - \tau^s s(\tau^s) = 0 \tag{2.3}$$

where the commodity price P is taken as given by each firm. Totally differentiating equation (2.3), obtain,

$$\frac{\partial s(\tau^s)}{\partial\tau^s} = \frac{1}{n[\partial P(ns)/\partial(ns)]} \tag{2.4}$$

Substituting (2.4) into (2.2) and reducing (2.2), we obtain,

$$\tau^s = \frac{\partial D(\cdot)}{\partial(nI)}\frac{\partial I(\cdot)}{\partial s} + a \tag{2.5}$$

The optimal tariff rate is thus composed of two parts. The first part is the marginal invasive species damage incurred by the home country per shipment, where the damage and invasive-species functions, $D(\cdot)$ and $I(\cdot)$, respectively, are evaluated at the optimal shipment and industry (n) sizes. The second is the marginal inspection cost per shipment. Although τ^s fully internalizes the damage incurred by the home country per foreign firm, it does not provide firms in the foreign sector the correct entry incentive, i.e. given $P(ns)s - c(s) - (\partial D(nI)/\partial(nI))\,I(s) - as = 0$, τ^s alone cannot simultaneously determine optimal n as well.

As shown in Appendix A, an additional lump-sum tax (subsidy) per firm is required to induce the optimal industry size (Spulber, 1985). This tax (subsidy) is shown to equal s $\left[\frac{\partial D(\cdot)}{\partial(nI)}\frac{I(s)}{s} - \frac{\partial D(\cdot)}{\partial(nI)}\frac{\partial I(s)}{\partial s}\right]$. Thus, only when the invasive-species size has a linear relationship with shipment size, is this lump-sum tax (subsidy) equal to zero, i.e., the traditional tariff levied on a firm's shipment size determines both the optimal shipment and industry sizes. A nonlinear relationship between the invasive-species and shipment sizes therefore implies that if $\frac{\partial I(s)}{\partial s} > 0$, when $\frac{I(s)}{s} > \frac{\partial I(s)}{\partial s}$ at the optimal solution, a lump-sum tax is necessary to decrease the number of foreign firms to an optimal level. When $\frac{I(s)}{s} < \frac{\partial I(s)}{\partial s}$, a lump-sum subsidy is needed to optimally increase the number of foreign firms.

3.2 Numerical Analysis

In this section, numerical simulation is undertaken in order to illuminate how the traditional tariff policy derived in Section 3.1 works in the short run, and how it does not work as well in the long run when the invasive-species size is not linearly related to shipment size. As in Section 3.1, the home country is able to levy a tariff to jointly control the shipment and invasive-species sizes that accompany the imported good. In general, this type of traditional tariff results in a suboptimal number of foreign firms, a suboptimal total shipment size, and lower social welfare in the long run, thus necessitating the levying of a lump-sum subsidy in concert with the tariff. This numerical analysis is undertaken using GAMS 23.7.

Assume the price of the traded commodity is determined according to the simple linear relationship,

$$P(ns) = b_1 - b_2 ns \tag{2.6}$$

Initially, the relationship between the representative firm's shipment and invasive-species sizes is represented by the linear function,

$$I(s) = is \tag{2.7}$$

Later, this relationship follows the increasing non-linear form,

$$I = is^{1.05} \tag{2.7'}$$

The home country's damage function is represented by,

$$D\big[n\big(I(s)\big)\big] = d_1[n(I(s))]^2 \tag{2.8}$$

Therefore, the home country's social welfare can be expressed as,

$$W = \int_0^{ns}(b_1 - b_2x)dx - n(b_1 - b_2ns)s$$

$$-nas - d_1[n(I(s))]^2 + n\tau^s s \tag{2.9}$$

The representative foreign firm's cost function is,

$$c(s) = c_1 + c_2s^2 \tag{2.10}$$

Therefore, its profit can be written as,

$$\pi = Ps - (c_1 + c_2s^2) - \tau^s s \tag{2.11}$$

The parameter values for this simulation exercise are set at $b_1 = 10,000,\ b_2 = 5, a = 2,$ $d_1 = 1,\ i = 2\ ,\ c_1 =\ 5,000$, and $c_2 = 5$. Results for the case of a linear relationship between shipment and invasive-species size are summarized in Table 2.1.[10]

As indicated in Table 2.1, the optimal shipment is roughly 32 units per firm, and the optimal industry size is 24 firms, with a total shipment size of 745 units. The invasive species size is 1490 units, which causes more than two million dollars of damage in the home country. Based on the theoretical analysis presented in Section 3.1, the approximate

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[10] Because the representative firm obtains zero profit in equilibrium, the home country's social welfare is effectively total social welfare.

tariff level of $188,500 per firm results in the socially optimal solution for the case of a linear relationship between the invasive-species and shipment sizes. These results are benchmark values for the subsequent analysis. Through a simple comparative statics analysis, we can show how damage caused by invasive-species affects the shipment sizes, the price of the traded commodity, the tariff rate, and the invasive-species sizes (shown in Figures 2.1 to 2.4).

Table 2.1
Simulation results for the socially optimal outcome and associated tariff assuming a linear relationship between *I* and *s* (equation (2.7)).

Variables	Values
Total shipment size per firm(*s*)	31.62
Number of foreign firms (*n*)	23.55
Total amount of traded commodity(*ns*)	744.75
Per-unit price of the commodity (*P*)	$ 6,276.25
Invasive-species size (*nI*)	1,489.50
Total Damage level (*D*)	$ 2,218,620.44
Tariff level per firm ($\tau^s s$)	$ 188,472.18
Total home country welfare (*W*)	$ 3,605,258.22

In Figures 2.1- 2.4, the invasive-species sizes, tariff rates, total shipment sizes, and the commodity prices are compared when the parameter of the home country's damage function, d_1, changes from 1.0 to 2.0. The higher d_1, the more serious the damage caused by a given invasive species level in the home country. If invasive species damage is higher, the optimal invasive-species size is lower, and consequently the tariff rate increases, total shipment size decreases, and the commodity price increases.

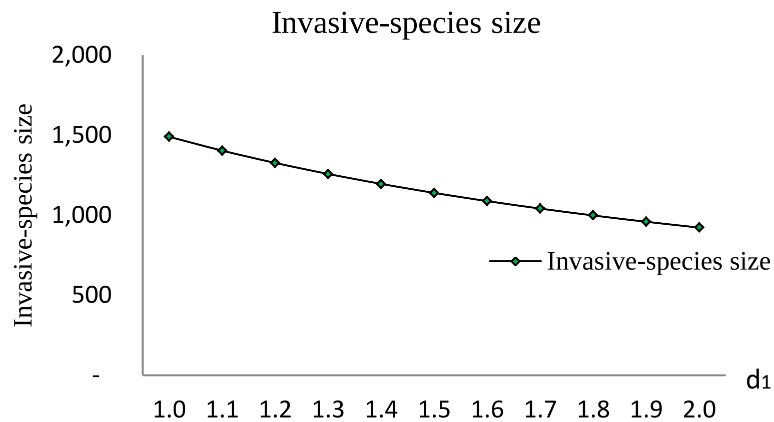

Figure 2.1. The optimal invasive-species size with different invasive species damage level on the home country.

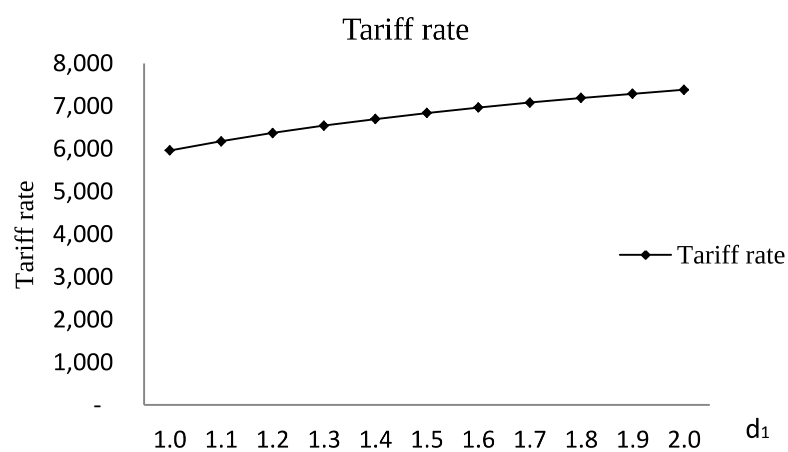

Figure 2.2. The tariff rate with different invasive species damage level on the home country.

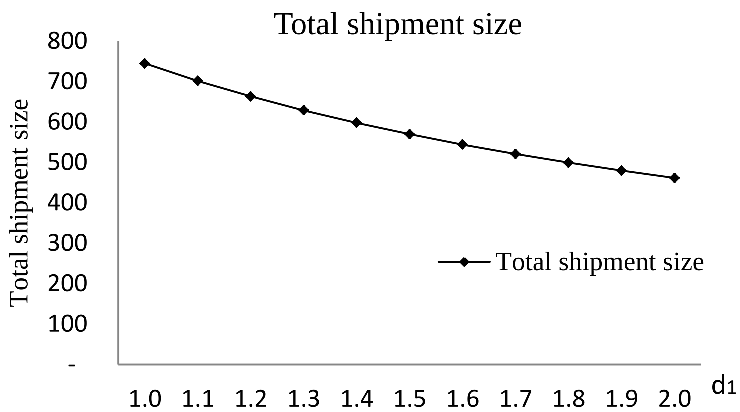

Figure 2.3. The total shipment size with different invasive species damage level on the home country.

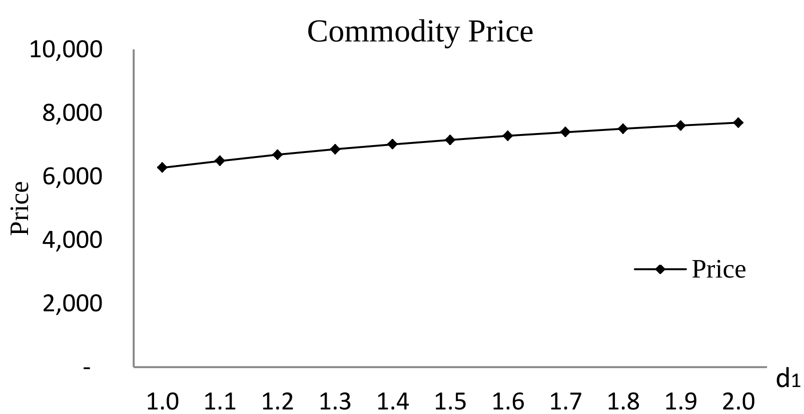

Figure 2.4. The commodity price with different invasive species damage level on the home country.

As shown in Table 2.2, however, if the relationship between shipment and invasive-species sizes is instead nonlinear (e.g., according to equation (2.7')), then the traditional tariff derived above results in a suboptimal number of foreign firms, shipment size, and invasive-species size. Under the traditional tariff, the number of foreign firms decreases from the corresponding socially optimal level of 48 firms to only 18. In contrast, the representative foreign firm's shipment size increases from approximately 13 to 32 units. Combining these results, the total imported commodity level equals 574 units, which is less than the socially optimal level of 623 units. Further, the total invasive-species and damage levels are lower than their respective corresponding socially optimal levels. But social welfare is lower in the traditional tariff scheme.

Table 2.2
Simulation results assuming a nonlinear relationship between *I* and *s* (equation (2.7')).

Variables	Values	
	Tariff Scheme	Social Optimal
Shipment size (*s*)	31.62	12.94
Number of foreign firms (*n*)	18.15	48.11
Total importing commodities (*ns*)	574.06	622.58
Invasive-species size (*nI*)	1,364.55	1,415.22
Damage level (*D*)	$1,862,004.74	2,002,844.26
Tariff level/per foreign firm ($s\tau^s$)	215,460.26	83,281.57
Total home country welfare (*W*)	2,872,079.21	2,971,866.69
Price of the commodity (*P*)	7,129.68	6,887.09

As shown in the Section 3.1, although τ^s fully internalizes the damage incurred by the home country per foreign firm, it does not provide firms in the foreign sector the correct entry incentive, i.e., τ^s alone cannot simultaneously determine optimal *n* as well. This tax (subsidy) was shown to equal $\left[\frac{\partial D(\cdot)}{\partial(nI)}\frac{I(s)}{s} - \frac{\partial D(\cdot)}{\partial(nI)}\frac{\partial I(s)}{\partial s}\right] s$. If $\frac{I(s)}{s} > \frac{\partial I(s)}{\partial s}$, a lump-sum tax is necessary to decrease the number of foreign firms to an optimal level; and if $\frac{I(s)}{s} < \frac{\partial I(s)}{\partial s}$, a lump-sum subsidy is needed to optimally increase the number of foreign firms. For our particular simulation exercise, the lump-sum subsidy would need to be

$ 132,179 per firm, which in turn would induce the optimal number of foreign firms in the foreign industry.

4. Non-Fixed Relationship between Contamination Level and Shipment Size

In the previous section, where invasive-species size depends non-linearly on the shipment size, optimal social welfare cannot be realized solely through the implementation of a traditional tariff by the home country. In the long run, a lump-sum tax/subsidy is also needed to ensure optimal industry size. In fact (i.e., in a broader sense), invasive-species size is not fully determined by a foreign firm's shipment size, i.e. invasive-species size depends upon the abatement effort of the foreign firm and other random variables. A tariff imposed directly on the volume of imported goods will generally not attain an optimal level of prevention (Spulber, 1985).[11] Therefore, we turn to a case where a foreign firm can exert abatement effort to control the invasive-species level in its shipment, and, initially, the home country has perfect information as to the extent of this effort level. We also begin by assuming that there are no random factors affecting the invasive-species level. The third chapter of the dissertation will examine the consequences of relaxing these perfect information and certainty assumptions.

4.1 Theoretical Analysis

Here we assume a representative foreign firm can exert costly abatement effort, such as implementing a cleaner production process, using detective equipment, and adopting packing technologies that decrease the incidence of invasive-species

[11] McAusland and Costello (2004) design "firm-specific contamination-contingent policies" where the firm can choose to alter the contamination level of its shipment. This policy can induce the firm to implement optimal abatement effort in the short run.

contamination. Therefore, in addition to setting τ^s, the home country must induce each foreign firm to choose optimal abatement effort (from the home country's perspective) by setting a tariff rate on the invasive species level directly. Hereafter, I call this tariff an "invasive-species tariff", denoted by τ^I. τ^I is imposed directly on the level of invasive-species contamination, I, which initially is assumed to be detected with certainty upon inspection. The home country's objective function is therefore,

$$\max_{\tau^I,\tau^s} W = \int_0^{ns(\tau^s,\tau^I)} P(x)dx - nP\big(ns(\cdot)\big)s(\tau^s,\tau^I) - nas(\tau^s,\tau^I)$$

$$-D\big(nI(\tau^I)\big) + n\tau^s s(\tau^s,\tau^I) + n\tau^I I(\tau^I) \tag{2.12}$$

The first-order conditions for this problem are,

$$\frac{dW}{d\tau^s} = -n\frac{\partial P(\cdot)}{\partial(ns)}\frac{\partial s(\cdot)}{\partial\tau^s}s(\cdot) + s(\cdot) + \tau^s\frac{\partial s(\cdot)}{\partial\tau^s} - a\frac{\partial s(\cdot)}{\partial\tau^s} = 0 \tag{2.13}$$

$$\frac{dW}{d\tau^I} = -n\frac{\partial P(\cdot)}{\partial(ns)}\frac{\partial s(\cdot)}{\partial\tau^I}s(\cdot) + I(\cdot) + \tau^I\frac{\partial I(\cdot)}{\partial\tau^I} + \tau^s\frac{\partial s(\cdot)}{\partial\tau^I} - \frac{\partial D(\cdot)}{\partial(nI)}\frac{\partial I(\cdot)}{\partial\tau^I} - a\frac{\partial s(\cdot)}{\partial\tau^I} = 0 \tag{2.14}$$

Again, each foreign firm earns the zero profit in the long-run equilibrium, therefore,

$$\pi = P\big(ns(\cdot)\big)s(\cdot) - c(s(\cdot),I) - \tau^s s(\cdot) - \tau^I I(\cdot) = 0 \tag{2.15}$$

where $c(s,I)$ is an foreign firm's total cost associated with shipment size and the corresponding invasive-species size, $\partial c(\cdot)/\partial s > 0$ and $\partial^2 c(\cdot)/\partial s^2 \geq 0$, $\partial c(\cdot)/\partial I < 0$ and $\partial^2 c(\cdot)/\partial I^2 \geq 0$. Totally differentiating zero-profit condition (2.15) we obtain,

$$\frac{\partial s(\cdot)}{\partial\tau^s} = \frac{1}{n[\partial P(\cdot)/\partial(ns)]} \tag{2.16}$$

$$\frac{\partial s(\cdot)}{\partial\tau^I} = \frac{I(\cdot)}{ns(\cdot)[\partial P(\cdot)/\partial(ns)]} \tag{2.17}$$

Substituting (2.16) and (2.17) to equations (2.13) and (2.14) reduces the home country's first-order conditions to,

$$\tau^{S} = a \tag{2.18}$$

$$\tau^{I} = \frac{\partial D(\cdot)}{\partial (nI)} \tag{2.19}$$

As shown by (2.19), the invasive-species tariff rate is set equal to the marginal damage with respect to the total invasive-species size (evaluated at the optimal invasive species size). Equation (2.18) likewise reveals the traditional tariff (set directly on shipment size) is set equal to the inspection cost per unit shipment. The invasive-species tariff is therefore based directly on the marginal damages associated with the invasive-species level. Through the invasive-species tariff, the foreign firm fully internalizes the damage cost associated with the invasive species level in the home country. As Spulber (1985) helps us understand, the invasive-species tariff corrects for the traditional tariff's inability to control the externality directly as a sole policy instrument.

Together, the traditional and invasive-species tariffs ensure an efficient invasive-species incidence in the home country.[12] Similar to Section 3.2 for the fixed-relationship case, a numerical simulation is now presented to demonstrate at what level the home country should levy an invasive-species tariff to induce the representative foreign firm to optimally control its invasive-species level per shipment in a deterministic setting.

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[12] As shown in Appendix A, this policy scheme indeed achieves the same shipment and invasive-species sizes that result from the social planner's problem.

4.2 Numerical Analysis

Assume the price and damage functions are the same as in Section 3.2. The production and abatement cost function of the representative foreign firm is

$$c(s) = c_1 + c_2 s^2 + c_3 I^{-1} \qquad (2.20)$$

Table 2.3
Simulation results assuming a non-fixed relationship between *I* and *s* with different marginal abatement cost parameters.

Variables	Values			
	Low	Medium	Medium high	High
	c_3=100,000	c_3=200,000	c_3=350,000	c_3=500,000
Shipment size (*s*)	66	77	89	97
Number of foreign firms (*n*)	28	24	21	19
Total importing commodities (*ns*)	1,868	1,845	1,822	1,806
Invasive species level (*I*)	12	16	20	24
Total invasive species level (*nI*)	343	385	420	442
Damage level (*D*)	117,836	148,255	176,210	195,711
Invasive species tariff rate (τ^I)	687	770	840	885
Sum of traditional and invasive species tariff levels per foreign firm	8,417	12,565	17,319	21,227
Total home country welfare (*W*)	8,843,573	8,659,651	8,478,369	8,345,794
Price of the commodity (*P*)	659	774	888	972

The parameters are again the same as in Section 3.2, namely $b_1 = 10,000$, $b_2 = 5$, $a = 2$, $d = 1$, $i = 2$, $c_1 = 5,000$, and $c_2 = 5$. For this analysis, the parameter c_3 is set at four different levels- low, medium, medium high, and high - in order to assess the sensitivity of the invasive-species control decision relative to increases in marginal abatement cost. Results for the corresponding social optima are summarized in Table 2.3.

As shown in this table, as the marginal abatement cost of invasive-species control increases, the optimal invasive-species level correspondingly increases, as do the invasive-species damage levels and the corresponding invasive-species tariff rates. Along with the increasing socially optimal invasive-species damage level, the home country's social welfare decreases. The optimal invasive species control level is determined by the tradeoff between the home country's invasive species damages and the foreign firms' abatement costs. Once the abatement cost begins to increase, the home country concedes to accept more invasive species to counteract the now higher control cost.

This numerical simulation exercise confirms the analytical findings in Section 4.1, in particular that when confronted with a non-fixed relationship between the shipment and invasive-species sizes, a tariff levied by the home country directly on the foreign country's invasive-species size is needed in concert with a traditional tariff levied on the shipment size. As mentioned in Section 4.1, Spulber (1985) shows that a lump-sum subsidy is no longer required to maintain the optimal number of foreign firms in this type of scenario, where the home country is now able to levy a tariff directly on the invasive-species level. The joint traditional and invasive-species tariffs provide adequate control for both the invasive-species size per foreign firm and the number of firms in the industry.

5. Conclusion

This essay investigates the efficacy of a traditional tariff when the invasive species contamination level is functionally vs. non-functionally related to shipment size, and the analysis of the invasive-species tariff that directly influence a foreign country's abatement effort. The modeling framework for this essay is provided by McAusland and Costello (2004) and Spulber (1985).

As taught by McAusland and Costello (2004), a joint tariff and inspection scheme can be implemented to control invasive species at the border. This essay shows that when the invasive species level is functionally related to shipment size, a traditional tariff can optimally determine the shipment size and concomitant invasive species level. However, in the long run the industry's entry condition is distorted, resulting in a suboptimal industry size. As Spulber (1985) informs us, a lump-sum subsidy or tax is necessary to correct the distortion. Further, if the invasive species level is not functionally related to shipment size (i.e., is influenced by the abatement effort of foreign firms), a traditional tariff alone cannot provide adequate incentive on the abatement endeavor. Therefore, a policy instrument targeted directly on the invasive species level is needed. We derive the optimal tariff in the context of the invasive species problem.

In addition, we numerically analyze our conceptual results. We begin with the case of a functional relationship between shipment size and invasive species level, and analyze the effectiveness of a traditional tariff. We find that when the functional relationship is linear, the traditional tariff alone can attain the optimal shipment, invasive-species, and foreign industry sizes. When the relationship is non-linear, a lump-sum subsidy is needed to correct for industry size in the long term. We also find that increases in the home country's marginal damage parameter leads to increases in both the tariff rate and commodity price, and decreases in shipment size and invasive species level.

For the case of a non-functional relationship between shipment and invasive-species sizes, we assess the effectiveness of a separate “invasive species tariff” in achieving the home country’s optimal solution to the invasive species control problem at the border. Our main finding is that the invasive species tariff can motivate the foreign firms to abate the invasive species at socially optimal level. Numerical analysis demonstrates that when the foreign firm’s marginal abatement cost parameter increases, total shipment and foreign industry sizes shrink, but shipment size per firm, the invasive species level, and the optimal invasive-species tariff rate increase. As a result, the home country’s welfare decreases.

The study of invasive species border control is complex. In reality, a given invasive-species size is determined not only by the foreign firm’s abatement effort, but also as a consequence of random environmental factors. In addition, the home country is precluded from perfectly observing the abatement effort undertaken by the foreign country. Regarding this randomness and imperfect observability in the context of invasive species problem, we develop a principal-agent model in the next chapter to accommodate the inherent randomness and imperfect observability. We also develop a tournament framework in order to address the more general setting of both individualistic and common random environmental factors.

References

Ameden, Holly A., Cash, Sean B, and Zilberman, David, 2007. Border enforcement and firm response in the management of invasive species. Journal of Agricultural and Applied Economics 39, (October), 35-46.

Batabyal, Amitrajeet A., and Nijkamp, Peter, 2005. On container versus time based Inspection policies in invasive species management. Stochastic Environmental Research and Risk Assessment 19, 340-347.

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

Costello, Christopher, and McAusland, Carol, 2003. Protectionism, trade, and measures of damage from exotic species introductions. The American Journal of Agricultural Economics 85 (4), (November), 964-975.

Finnoff, David, Shogren, Jason F., Leung, Brian, and Lodge, David, 2007. Take a risk: preferring prevention over control of biological Invaders. Ecological Economics 62, 216 -222.

Gren, Ing-Marie, 2008. Economics of alien invasive species management-choices of targets and policies. Boreal Environment Research 13, 17-32.

Grossman, Gene M., and Helpman, Elhanan, 1994. Protection for sale. The American Economic Review 84 (4), (Sep.), 833-850.

Haack, Robert A., 2001. Intercepted Scolytidae (Coleoptera) at U.S. ports of entry: 1985–2000. Integrated Pest Management Reviews 6, 253–282.

Horan, Richard D., and Lupi, Frank, 2005. Tradeable risk permits to prevent future introductions of invasive alien species into the Great Lakes. Ecological Economics 52, 289– 304.

Horan, Richard D., Shortle, James S., and Abler, David G., 1998. Ambient taxes when polluters have multiple choices. Journal of Environmental Economics and Management 36, 186–199.

Jones, Kristin Roti, and Corona, Joel P., 2008. An ambient tax approach to invasive species. Ecological Economics 64, 534-541.

Kim, C.S., Lubowski, Ruben N., Lewandrowski, Jan, and Eiswerth, Mark E., 2006. Prevention or control: optimal government policies for invasive species management. Agricultural and Resource Economics Review 35 (1), (April), 29–40.

Knowler, Duncan, and Barbier, Edward, 2005. Importing exotic plants and the risk of invasion: are market-based instruments adequate? Ecological Economics 52, 341-354.

Liebhold, Andrew M., and Tobin, Patrick C., 2008. Population ecology of insect invasions and their management. Annual Review of Entomology 53, 387–408.

Margolis, Michael, Shogren, Jason F., and Fischer, Carolyn, 2005. How trade politics affect invasive species control. Ecological Economics 52, 305- 313.

McAusland, Carol, and Costello, Christopher, 2004. Avoiding invasives: trade-related policies for controlling unintentional exotic species introductions. Journal of Environmental Economics and Management 48, 954–977.

Mehta, Shefali V., Haight, Robert G., Homans, Frances R., Polasky, Stephen, and Venette, Robert C., 2007. Optimal detection and control strategies for invasive species management. Ecological Economics 61, 237-245.

Mérel, Pierre R., and Carter, Colin A., 2008. A second look at managing import risk from invasive species. Journal of Environmental Economics and Management 56, 286-290.

Olson, Lars J., and Roy, Santanu, 2010. Dynamic sanitary and phytosanitary trade policy. Journal of Environmental Economics and Management 60, 21–30.

Peterson, Everett B., and Orden, David, 2008. Avocado pests and avocado trade. The American Journal of Agricultural Economics 90 (2), (May), 321-335.

Segerson, Kathleen, 1988. Uncertainty and incentives for nonpoint pollution control. Journal of Environmental Economics and Management 15, 87-98.

Spulber, Daniel F., 1985. Effluent regulation and long-run optimality. Journal of Environmental Economics and Management 12, 103-116.

Wilson, Norbert L.W., and Antón, Jesús, 2006. Combining risk assessment and economics in managing a sanitary–phytosanitary risk. The American Journal of Agricultural Economics 88 (1), (February), 194–202.

WTO, 1998. Understanding the WTO agreement on sanitary and phytosanitary measures. < http://www.wto.org/english/tratop_e/sps_e/spsund_e.htm > (accessed 05.03.14)

CHAPTER 3

AN INVASIVE-SPECIES SUBSIDY AND TOURNAMENT UNDER UNCERTAINTY

Abstract

This paper addresses the issue of invasive species control when the importing (home) country has imperfect information about the abatement efforts of foreign countries (henceforth, the foreigns). The control of invasive species at the home country's border depends not only upon a foreign's abatement effort, but also on random environmental variables. Holmstrom's (1979) framework is adopted for the initial design of a set of contracts between the home country and foreigns that account for individualistic random factors affecting the effectiveness of the foreigns' respective abatement efforts. We show that a contract's subsidy (provided by the home country to the foreign), is in general higher than the home country's first-best subsidy under perfect information. Numerical analysis demonstrates the extent of the difference between the first- and second-best subsidies and the sensitivity of the optimal subsidy to the foreign's reservation welfare level and marginal abatement cost. Following Nalebuff and Stiglitz (1983), we then develop a standard tournament scheme for the case where risk-averse foreigns face both individualistic and common random factors. We find that a rank-order tournament is capable of attaining the home country's first-best solution. Numerical analysis suggests that tournament risk as a percentage of the loser's subsidy (i.e., downside risk for the foreign) is sensitive to the foreign's opportunity cost of participating in the tournament, but not its marginal cost of abating the invasive species.

1. Introduction

Invasive species have caused extensive economic damages in agriculture, fisheries, forestry, and other industries over the past several decades (Pimentel et al., 2005). By one estimate, more than half of native imperiled species in the US have resulted from invasive-species invasions (Wilcove et al., 1998). Although nonnative species are sometimes introduced for intentional beneficial purposes (Clout and Williams, 2009), many species are introduced unintentionally through contaminated commodities and packing materials, ballast water, or tourism. Levine and D' antonio (2003) forecast that invasive species outbreaks will increase in the future as international trade expands. The need for trade policy to incorporate effective control instruments to halt the spread of invasive species is therefore urgent.

As we argue in this paper, the prevention of invasive species depends not only upon the foreign's abatement effort, but also on random environmental variables, such as local weather, location, etc. The concomitant unobservability of the foreign's abatement effort complicates the ability of the home country to control for the introduction of an invasive species at its border. Typical prevention measures include import bans, permits, tariffs, inspections, quarantine, and education. However, these instruments do not convey a direct incentive on the foreign's abatement effort. Neither do they account for the effects of imperfect observability of abatement effort in the design of optimal policy.

This paper addresses the issue of imperfect observability of the foreign's abatement efforts. Initially, Holmstrom's (1979) framework is adopted for the design of a contract between the home country and a single or multiple foreigns that accounts for individualistic random factors affecting the foreigns' respective abatement efforts. Later, the assumption of independence of each foreign's stochastic factors is relaxed through the introduction of a common random factor. A standard tournament scheme based on the framework developed by Nalebuff and Stiglitz (1983) is then examined in the context of two risk-averse foreigns facing individualistic and common random factors.

We find that, in an effort to control the introduction of the invasive species in the home country, a bilateral contract scheme conveys optimal ex ante incentives from the home country to the foreigns through second-best subsidies when there are only individualistic random factors affecting abatement. Numerical analysis demonstrates the extent of the difference between the first- and second-best subsidies (where "first-best" means optimal subsidies under perfect observability), in particular the sensitivity of this difference to both a foreign's reservation welfare level (or, opportunity cost of participating in the subsidy scheme) and marginal cost of abatement. We find that a rank-order tournament is capable of attaining the home country's first-best solution in the presence of individualistic and common random factors. Numerical analysis suggests that tournament risk as a percentage of the loser's subsidy (i.e., downside risk for the foreign) is sensitive to the foreign's opportunity cost of participating in the tournament, but not its marginal cost of abating the invasive species.

The next section provides a brief review of the invasive-species control literature. Section 3 presents our basic modeling framework and the results for the foreign-specific contracts in the presence of solely individualistic random factors. In this section we consider the cases of a single and multiple foreigns. Section 4 introduces a common random factor and investigates the efficacy of a rank-order tournament in controlling the introduction of an invasive species in the home country. Section 5 summarizes and concludes.

2. Literature Review

It is important to note that the level of invasive-species contamination is, in general, not functionally related to shipment size. The contamination level may also depend on the mitigation effort of foreign countries, as well as on other random variables such as geographic location, rainfall, and temperature. Stochastic factors also play important roles at each stage of an invasive species outbreak (from introduction to establishment to spread to damage). With respect to damages, a linear damage function cannot adequately represent the complicated relationship between contamination rates and damages incurred.[13] Consequently, uncertainty is an important factor in making prevention and control decisions. To date, the uncertainty literature has only cursorily addressed the wide-ranging effects of invasive species' introduction, establishment, spread, and damage in the home country. Similar to the literature on tariffs and inspections, research addressing these stochastic issues is still in its infancy.

Olson and Roy (2005) find that prevention and control policies naturally depend upon the invasive-species introduction size, its growth rate, uncertainty associated with the species' introduction, and the damage suffered by the home country. Finnoff et al. (2005) discuss the effect of feedback and risk aversion on private and regulatory manager

[13] For example, Jones and Corona (2008) assume a constant marginal damage rate in designing a Segerson (1988) type ambient tax mechanism for ballast water control problem. Similar to McAusland and Costello (2004), Mérel and Carter (2008) assume a linear damage function and constant marginal damage rate.

decision making in a setting of random invasion and stochastic growth processes. The authors show that the stochastic characteristics associated with an invasive-species introduction and its spread ultimately determine the (random) amount of damage. Similarly, Olson and Roy (2002) assign a random parameter to scale an invasive species spread, and discuss when eradication of an invasive species is optimal.

Costello and McAusland (2003) consider different characteristics of uncertainty associated with an invasive-species' introduction, establishment and associated damage. The authors show that, when accounting for uncertainty, the enforcement of a tariff can decrease the risk of introducing an invasive species, but possibly increase the potential range of damages due to increased crop production in the home country. They classify damages according to three different categories: augmented damages, neutral damages, and diminished damages. The categories are distinguished by the responsiveness of damages to the level of agricultural activity. In particular, as agricultural activity increases, crop damage is likely to increase due to a larger area now susceptible to the spread of invasive species. Also, as more lands are tilled, ecosystems are more disturbed, thus precipitating ecological damage. This is what the authors call augmented damages. Damage from marine and aquatic systems is considered as neutral with respect to agricultural activities.[14]

Costello and McAusland (2003) find that an increase in the (traditional) tariff rate reduces expected neutral and diminished-typed damages unambiguously for a small agricultural-good importing economy. However, if the responsiveness of damages to the level of agricultural activity is high enough, raising the tariff rate in turn increases

[14] The authors do not provide an example of diminished damage.

expected augmented-typed damages. For a small agricultural good exporting economy, an increase in the tariff rate reduces expected augmented and neutral damages. Therefore, the responsiveness of damages to the level of agricultural activity should be considered in tariff policy making.

Burnett (2006) finds that regions do not invest enough in prevention of invasive species outbreaks when facing a "weaker link public good technology." The transparency of information concerning other regions' respective prevention costs affects the efficient prevention level in the home region. Feng et al. (2008) suggest a tradable risk permit system using the log of firm success probabilities as the risk instrument for weakest link technology. Prevention measures receiving the most attention in the broader invasive-species literature have been tariffs and inspections (Costello and McAusland, 2003; McAusland and Costello, 2004; Margolis et al. 2005; Mérel and Carter, 2008; Batabyal and Beladi, 2009). However, in general, a traditional tariff scheme does not provide a sufficient incentive for foreigns to undertake optimal abatement effort, as shown in Chapter 2.

Horan et al. (2002) find that the marginal control cost should equal the marginal expected benefit at an optimal abatement level, which is also optimal for the home country. However, the home country cannot perfectly observe the foreign's abatement effort, similar to the classic case where a principal employs an agent and provides a reward based upon the agent's performance. Holmstrom (1979) develops the seminal theoretical structure whereby the principal determines a payoff scheme based upon stochastic profit in order to motivate the agent to act according to the principal's best interest. In international trade, the home country must incorporate these factors in the formulation of its compensation scheme, or contract, in order to prevent the spread of invasive species when trading with foreigns, especially with risk-averse foreigns.

The existence of a common random factor generally precludes individualistic contracts from obtaining an ex ante optimum from the home country's perspective. Green and Stokey (1983) and Nalebuff and Stiglitz (1983) show that if (1) there is a common random shock to the output of each agent, (2) the common shock's distribution is diffuse enough, or (3) the number of agents is large, individualistic contracts are generally dominated (in terms of the principal's welfare) by a tournament scheme. Holmstrom (1982) shows how a contest can reveal information about the respective agents. McLaughlin (1988) compares tournaments in a variety of model frameworks, such as Lazear and Sherwin (1981), Nalebuff and Stiglitz (1983), Green and Stokey (1983) and O'Keeffe et al. (1984), and validates the efficiency of a tournament in the presence of a more risky common stochastic factor.

In the case of a common random factor, a subsidy scheme based upon a foreign's relative rather than absolute performance is required. In the case of invasive-species border control, this means that each foreign's invasive-species size is a stochastic function of its own abatement effort, a country-specific random factor, and random shocks common to all foreigns (e.g. climate change, extreme weather events.). As Nalebuff and Stiglitz (1983) and Green and Stokey (1983) show, a tournament generally outperforms adjusted contracts in the presence of a common random factor. As mentioned in Section 1, this paper explores the implementation of a contract and a tournament in the context of the invasive-species control problem.

3. Individualistic Invasive Species Contracts

3.1 The Basic Model and its Benchmark Solution

We begin by assuming that the effect of the foreign's abatement effort on a potential invasive species level in the home country is partially determined by a random state of nature, denoted by random variable θ, which nevertheless has a commonly known probability distribution. For simplicity, we refer to θ as the composite level of random factors instead of a vector of separate stochastic factors. Thus, the invasive-species level can be defined as $I = I(g, \theta)$ with $I_g = \partial I(\cdot)/\partial g < 0$ and $I_{gg} = \partial^2 I(\cdot)/\partial g^2 > 0$, where g represents the abatement effort undertaken by the foreign.

Following Mirrlees' (1976) and Holmstrom's (1979) parameterized distribution formulation, θ is suppressed and I is viewed directly as a random variable, with a conditional cumulative distribution function defined over the invasive-species contamination level, $F(I|g)$, and corresponding conditional density function $f(I|g)$. Density function $f(I|g)$ is everywhere non-negative and continuously differentiable in g. Because $I_g < 0$ and $F_g(I|g) \geq 0$, it is further assumed that $F(I|g^L)$ under low abatement effort, g^L, first-order stochastic dominates $F(I|g^H)$ under high abatement effort, g^H. This in turn implies that the home country's expected invasive-species level from imported goods when the foreign chooses g^L is never less than that which results from g^H.

The foreign is assumed strictly risk-averse. Its total welfare depends upon three components: net revenue from the sale of its commodity, the subsidy offered by the home country (through a contract), and its abatement cost. Let $c(s)$ represent the foreign's total cost associated with shipment size, with $\partial c(s)/\partial s > 0$ and $\partial^2 c(s)/\partial s^2 > 0$. The function $U(Ps - c(s))$ represents net welfare obtained from its exported commodity, $U' > 0, U'' \leq 0$, and $V(t(I))$ represents welfare obtained from the home country's subsidy, $V' > 0, V'' < 0$. [15] [16] Let $Z(g)$ represent the foreign's abatement cost, or disutility from abatement. This disutility may reflect both monetary and non-monetary expenses, e.g., expenses associated with harmful effects and the corresponding inconvenience caused by the control efforts.[17] The disutility function satisfies $Z' > 0$ and $Z'' > 0$.[18]

Let $t^a(I)$ represent the lump-sum invasive-species subsidy under perfect information, or observability. Assume the home country offers the foreign a contract specifying s, g, and $t^a(I)$, which the foreign can either accept or reject. If the foreign rejects the contract, $s = 0$ and $t^a(I) = 0\ \forall I$. To induce the foreign to accept the contract, the home country must provide the foreign with at least its reservation expected welfare level $\bar{u}$. This constraint on the home country's choice of the subsidy is commonly known

[15] The concave transformation of net revenue and subsidy of the foreign is to describe the risk-aversion of foreign country (Malik, 1990; Silberberg and Suen, 2001).
[16] $U'(\cdot)$ refers to the first derivative of $U(\cdot)$ with respect to commodity revenue. $V'(\cdot) > 0$ represents the first derivative of $V(\cdot)$ with respect to the subsidy offered by the home country. The corresponding second derivatives of the two functions, $U'' \leq 0$ and $V'' < 0$, ensure that the foreign is risk averse.
[17] For example, pesticides, which are used in controlling insects, may cause polluting effects harmful to human health. Oceanic ballast water exchange is commonly considered to be an unsafe action for vessels (Horan and Lupi, 2005).
[18] We therefore effectively assume separability in shipment and abatement costs, which greatly simplifies the ensuing analysis.

as a "participation constraint." The optimal invasive-species subsidy scheme for the home country then solves,

$$\underset{s,t^a(I)}{\text{Max}}\ W = \int_0^s P(x)dx - P(s)s - as$$
$$- \int D(I)f(I|g)dI - \int t^a(I)f(I|g)dI \qquad (3.1)$$
$$\text{s.t. } U(P(s)s - c(s)) + \int V\big(t^a(I)\big)f(I|g)dI - Z(g) \geq \bar{u}.$$

where a is the constant marginal inspection cost at the home country's border. To simplify notation, we henceforth suppress the lower and upper limits of integration associated with the level of I. This problem can be analyzed in two stages. In the stage one, the home country determines the optimal invasive-species subsidy to include in its contract for any given level of g. In stage two, the home country likewise determines the optimal contract's level of g.

Since it gains nothing by providing the foreign expected welfare in excess of $\bar{u}$, the home country adjusts $t^a(I)$ to a level at which the foreign just accepts its contract offer. Therefore, the constraint in (3.1) binds at any solution to the home country's problem. Let λ represent the multiplier associated with this constraint, $\lambda \geq 0$. The Lagrangian function is then,

$$L\big(s, t^a(I)\big) = \int_0^s P(x)dx - P(s)s - as - \int D(I)f(I|g)dI - \int t^a(I)f(I|g)dI$$
$$+\lambda\big\{U(P(s)s - c(s)) + \int V\big(t^a(I)\big)f(I|g)dI - Z(g) - \bar{u}\big\} \qquad (3.2)$$

and the associated first-order conditions are:

$$\frac{\partial L(\cdot)}{\partial s} = -\frac{\partial P(s)}{\partial s}s - a + \lambda\left[U'(\cdot)\frac{\partial P(s)}{\partial s}s\right] = 0 \qquad (3.3)$$

$$\frac{\partial L(\cdot)}{\partial t^a(I)} = -f(I|g) + \lambda V'(t^a(I))f(I|g) = 0 \qquad (3.4)$$

which implies,

$$\frac{1}{V'(t^a(I))} = \lambda > 0 \tag{3.5}$$

Since the foreign is strictly risk averse (recall that $U'' \leq 0$ and $V'' < 0$), the optimal lump-sum subsidy $t^a(I)$ is constant, or fixed, with respect to s and I. However, $t^a(\cdot)$ is not constant with respect to g, as we show below. In the context of international invasive-species control, the fixed subsidy is a classic result indicating that the home country's optimal strategy is to fully insure the risk-averse foreign against the uncertain level of invasive-species associated with its shipments (Holmstrom, 1979).

Under perfect observability, the optimal subsidy therefore depends directly on the foreign's observable abatement effort, g, and solves

$$U(P(s)s - c(s)) + V\big(t^a(I)\big) - Z(g) = \bar{u} \tag{3.6}$$

We label this subsidy level $t^a(g) = V^{-1}\{\bar{u} + Z(g) - U(P(s)s - c(s))\}$. Optimal abatement effort, g^*, in turn maximizes the home country's welfare, $\int_0^s P(x)dx - P(s)s - as - \int D(I)f(I|g)dI - V^{-1}\{\bar{u} + Z(g) - U(P(s)s - c(s))\}$, which via the inverse function rule, results in the first-order condition,

$$-\int D(I)f_g(I|g)dI - \frac{1}{V'(\cdot)}Z'(g) = 0 \tag{3.7}$$

where all choice variables are evaluated at their optimal levels. The optimal subsidy is therefore represented as

$$t^a(g^*) = V^{-1}\{\bar{u} + Z(g^*) - U(P(s^*)s^* - c(s^*))\} \tag{3.8}$$

To induce the foreign to choose optimal abatement level g^*, the home country can set the invasive-species subsidy scheme according to,

$$t^a(I) = \begin{cases} t^h = V^{-1}\{\bar{u} + Z(g^*) - U\big(P(s^*)s - c(s^*)\big)\} & g \geq g^* \\ t^l = 0 & g < g^* \end{cases} \tag{3.8'}$$

where t^h is a specific subsidy level that maximizes the home country's welfare and also satisfies the foreign's "participation constraint" at optimal abatement level g^*. t^l is determined by t^h, with $t^l < t^h$. In this case, t^l is set equal to zero. Being able to perfectly observe the foreign's abatement effort, the home county should therefore set an invasive-species subsidy scheme at one of two different levels to induce the foreign to select optimal effort level, g^*. If g is not less than g^*, the home country offers the foreign subsidy t^h, otherwise it offers subsidy t^l. Ultimately the foreign voluntarily chooses g^*, which provides it with reservation expected welfare level $\bar{u}$.

3.2 Unobservable Abatement Effort and a Single Foreign

As shown in the previous section, when abatement effort is perfectly observable the home country specifies in its contract an optimal effort choice by fully insuring the foreign against risk. However, when abatement effort is unobservable, optimal effort can only be induced at the cost of the foreign bearing some risk. This is a standard result in the principal-agent literature (Holmstrom, 1979).

Because the foreign's abatement effort is unobservable, the home country needs to ensure that the effort level specified in the contract is optimal from the foreign's perspective given the offered subsidy. To do this, the home country must satisfy an additional "incentive-compatibility constraint" in specifying its contract offer. Letting $t^u(I)$ denote the invasive-species subsidy in this case, the optimal contract for implementing g solves,

$$\underset{s,t^u(I)}{\text{Max}}\ W = \int_0^s P(x)dx - P(s)s - as - \int D(I)f(I|g)dI$$

$$- \int t^u(I)f(I|g)dI \tag{3.9}$$

s.t. $(i)\ U(P(s)s - c(s)) + \int V\big(t^u(I)\big)f(I|g)dI - Z(g) \geq \bar{u}.$

(ii) g and s jointly solve

$$\max_{g,s} U(P(s)s - c(s)) + \int V\big(t^u(I)\big)f(I|g)dI - Z(g)$$

Constraint (*i*) is the familiar participation constraint introduced previously in Section 3.1, while constraint (*ii*) is the incentive-compatibility constraint. Again, constraint (*i*) binds at the solution to this problem. Constraint (*ii*) insures that the contracted g and *s* levels are optimal from the foreign's perspective.[19] Using Holmstrom's (1979) first-order approach, constraint (*ii*) is represented by the following two equations,

$$P - \frac{\partial c(s)}{\partial s} = 0 \tag{3.10}$$

$$\int V(\cdot)f_g(I|g)dI - Z'(g) = 0 \tag{3.11}$$

Letting $\lambda \geq 0$ be the multiplier for constraint (*i*), and $\nu \geq 0$ and $\omega \geq 0$ the multipliers for constraints (3.10) and (3.11), respectively, the Lagrangian function for this problem is specified as

$$L(\cdot) = \int_0^s P(x)dx - P(s)s - as - \int D(I)f(I|g)dI - \int t^u(I)f(I|g)dI$$

$$+\lambda\left\{U\big(P(s)s - c(s)\big) + \int V(t^u(I))f(I|g)dI - Z(g) - \bar{u}\right\}$$

$$+\nu\left\{P(\cdot) - \frac{\partial c(s)}{\partial s}\right\}$$

[19] Shipment price *P* is taken as given in the constraint for this problem.

$$+\omega\left\{\int V(\cdot) f_g(I|g)dI - Z'(g)\right\} \tag{3.12}$$

First-order conditions for an interior solution are: [20]

$$\frac{\partial L(\cdot)}{\partial s} = -\frac{\partial P(s)}{\partial s}s - a + \lambda U'(\cdot)\frac{\partial P(s)}{\partial s}s + \nu\left\{\frac{\partial P(s)}{\partial s} - \frac{\partial c^2(s)}{\partial s^2}\right\} = 0 \tag{3.13}$$

$$\frac{\partial L(\cdot)}{\partial t^u(I)} = -f(I|g) + \lambda V'(\cdot)f(I|g) + \omega V'(\cdot)f_g(I|g) = 0 \tag{3.14}$$

which implies

$$\frac{1}{V'(\cdot)} = \lambda + \omega\frac{f_g(I|g)}{f(I|g)} \tag{3.15}$$

and

$$\frac{\partial L(\cdot)}{\partial g} = -\int D(I)f_g(I|g)dI - \int t^u(I)f_g(I|g)dI$$

$$+\omega\left[\int V(t^u(I))f_{gg}(I|g)dI - Z''(g)\right]=0 \tag{3.16}$$

$$\frac{\partial L(\cdot)}{\partial \lambda} = U\big(P(s)s - c(s)\big) + \int V(t^u(I))f(I|g)dI - Z(g) - \bar{u} = 0 \tag{3.17}$$

$$\frac{\partial L(\cdot)}{\partial \nu} = P(\cdot) - \frac{\partial c(s)}{\partial s} = 0 \tag{3.18}$$

$$\frac{\partial L(\cdot)}{\partial \omega} = \int V(\cdot)f_g(I|g)dI - Z'(g) = 0 \tag{3.19}$$

where condition (3.16) uses equation (3.11).We begin by noting that $\lambda > 0$ and $\omega > 0$. This result then enables us to derive the condition under (and the degree to) which the subsidy in this problem is “inefficient” from the perspective of its deviating from the home country’s optimal subsidy under perfect observability. The subsidy, $t^u(I)$, is

[20] Equation (3.13) is a condition the home country must satisfy in order to ensure the optimal shipment size. At the same time, the home country takes the first-order condition (equation (3.10)) as one of its constraints in its welfare-maximizing decision. This condition ensures the home country’s optimal shipment size is also the optimal shipment size from the point of view of the foreign. It aligns decisions of the home country and foreign through the change in the price of the tradable commodity.

therefore a second-best solution due to the home country's need to satisfy the incentive constraint.

Lemma 3.1. Assume $V'(\cdot) > 0$ and $\partial F(\cdot)/\partial g > 0$, then $\lambda > 0$ and $\omega > 0$. Therefore both constraints are binding. (Proof is provided in the Appendix B.)

Corollary 3.1. Lump-sum subsidy $t^u(I)$ has the following relationship with $t^a(I)$:

$$\begin{cases} t^u(I) > t^a(I) & I \in I' \\ t^u(I) = t^a(I) & I \in I''' \\ t^u(I) < t^a(I) & I \in I'' \end{cases} \tag{3.20}$$

where $I' = \{I|\, f_g(I|g)dI > 0\}$, $I'' = \{I|f_g(I|g)dI < 0\}$, such that $I''' = \{I|f_g(I|g)dI = 0\}$ respectively.

Given $\lambda > 0$ and $\omega > 0$, Corollary 3.1 follows directly from condition (3.15). It says that subsidy $t^u(I)$ is higher than the first-best subsidy $t^a(I)$ when I is lower than the mean level obtained under $t^a(I)$, i.e., the probability of the foreign exerting high abatement effort exceeds that of exerting low level abatement effort.

Using Lemma 3.1 again, we can state a second corollary,

Corollary 3.2. The second-best solution (i.e., the solution with $t^u(I)$) is strictly inferior to the first-best solution (i.e., the solution with $t^a(I)$) .

The proof of this corollary follows Holmstrom (1979), which states that because $\omega > 0$ and $f_g(I|g)/f(I|g)$ is non-constant in I, the second-best solution is therefore strictly inferior to the first-best solution.

Table 3.1
Simulation functions assuming a single foreign.

No.	Function Name	Description	Function
1	$P(x)$	Price of the tradable commodity	$P(s) = b_1 - b_2 s$
2	$D(I)$	Home country's total damage from the invasive species	$D(I) = d_1 I^2$
3	$U(\cdot)$	Foreign's welfare function from its shipment profit [21]	$U(\cdot) = b_3\big(P(s)s - c(s)\big)$
4	$V(\cdot)$	Foreign's welfare function from the subsidy	$V\big(t^u(I)\big) = 2\sqrt{t^u(I)}$
5	$C(s)$	Foreign's production cost function	$c(s) = c_1 + c_2 s^2$
6	$Z(g)$	Foreign's abatement cost function	$Z(g) = z_1 g^2$
7	$f(I\|g)$	Conditional probability density function for I	$f(I\|g) = ge^{-gI}$

Finally, equation (3.15) suggests that the optimal invasive-species subsidy schedule is not likely to have a simple linear relationship with the invasive species level, i.e., the schedule $t^u(I)$ is a potentially complicated function of I. To demonstrate this feature of the subsidy scheme, we now provide a simple numerical analysis of the problem. The corresponding functions used in this analysis are summarized in the Table 3.1.

The probability density function for this exercise, $f(I|g)$, is defined as an exponential function over abatement effort level g. For the remaining functions, quadratic and linear functional forms are adopted in order to make the simulation exercise tractable. Initially, the parameters are set as $\bar{u} = 100,\ a = 2,\ b_1 = 2{,}000,\ b_2 = 10,\ b_3 = 0.005,\ c_1 = 22{,}000,\ c_2 = 20,\ d_1 = 1000,$ and $z_1 = 5$. Corresponding results are then calculated for the cases of three different foreign reservation utility levels (assuming marginal abatement cost is fixed at $z_1 = 5$), and three different marginal

[21] The assumption of a linear function defined over the foreign's profit facilitates computation without sacrificing the more general implications of the central results. Risk-aversion is captured by the non-linear function defined over the subsidy, i.e., the expression for $V(\cdot)$.

abatement cost parameters (assuming reservation utility is fixed at 100). Results are presented in Table 3.2.

As shown in Table 3.2, the foreign exports a 40-unit shipment to the home country, which is unaffected by changes in the foreign's reservation welfare and marginal abatement cost. The reason for this is that the optimal shipment size is determined by the equality of marginal production cost with the price of the traded commodity (condition (3.10)). However, these changes nevertheless influence the foreign's abatement effort.

Table 3.2
Simulation results for the single foreign.

Variables	Welfare Constraint (when z_1=5)			Abatement Cost (when $\bar{u}$=100)		
	Low $\bar{u}$=80	Medium $\bar{u}$=100	High $\bar{u}$=110	Low z_1=5	Medium z_1=10	High z_1=15
Tradable commodity shipment size (s)	40	40	40	40	40	40
Tradable commodity equilibrium price (P)	1,600	1,600	1,600	1,600	1,600	1,600
Abatement effort level (g)	1.680	1.621	1.595	1.621	1.310	1.155
Multiplier λ	22.053	31.573	36.36	31.573	33.581	35
Multiplier ν	7.078	6.697	6.506	6.697	6.617	6.56
Multiplier ω	23.691	21.316	20.289	21.316	22.483	23.094
Expected subsidy ($E(t^u(I))$)	685	1,170	1,484	1,170	1,422	1,625
First-best subsidy (t^a)	486	997	1,322	997	1,128	1,225
Expected welfare ($E(W)$)	6,526	5,989	5,650	5,989	5,332	4,796
First-best welfare (W)	6,725	6,162	5,812	6,162	5,627	5,196

As both $\bar{u}$ and z_1 increase, the foreign's abatement effort decreases. In contrast, its expected subsidy increases in both $\bar{u}$ and z_1. Because $\bar{u}$ is the foreign's participation constraint, the home country must provide the foreign with at least $\bar{u}$ (in fact, just $\bar{u}$) to accept the contract. In the case of larger reservation welfare, the home country must provide a higher subsidy for the foreign to sign the contract with a fixed optimal shipment size. As discussed above, the optimal control level is determined by the tradeoff between the home country's invasive species damage level and the foreign's abatement costs. Once the foreign's marginal abatement cost increases, the home country must concede to accept a larger invasive species spread, all else equal. The participation and incentive-compatibility constraints now require the home country to provide the foreign with a higher subsidy to achieve an optimal invasive species size. In each case for this simulation, the expected second-best subsidy exceeds the first-best subsidy (under perfect observability). As a result, expected home-country welfare under imperfect observability is lower than under perfect observability.

For the case of imperfect observability, the foreign's abatement effort directly determines the distribution of the ex post invasive-species size, and subsequently the subsidy level. Figure 3.1 depicts the case for the medium welfare constraint ($\bar{u} = 100$) and low marginal abatement cost ($z_1 = 5$). In this figure, the solid line represents the optimal invasive-species subsidy at different levels of invasive-species size. The dashed line represents the benchmark subsidy under perfect observability. Note that the solid line crosses the dashed line at the conditional mean invasive-species size, $E(I|g = 1.621) = 0.617$. At this point the first- and second-best subsidies equate.

For invasive-species sizes less than 0.617, the home country awards the foreign with a subsidy larger than the first-best level. In this case, the home country interprets the lower invasive species size as implying a higher likelihood of high abatement effort on the part of the foreign for any given draw from the distribution of random environmental factors. To the contrary, for invasive-species sizes larger than 0.617, the home country provides the foreign with a subsidy lower than the first-best level. The subsidy falls to zero for invasive-species sizes greater than 2.098. From the point of view of the foreign, with a welfare constraint of 100 and a relatively low marginal abatement cost of 5, it is ex ante optimal to choose an abatement effort of 1.621. Therefore, the home country induces the foreign to choose the ex-ante effort level and shipment size at which the home country maximizes its welfare.

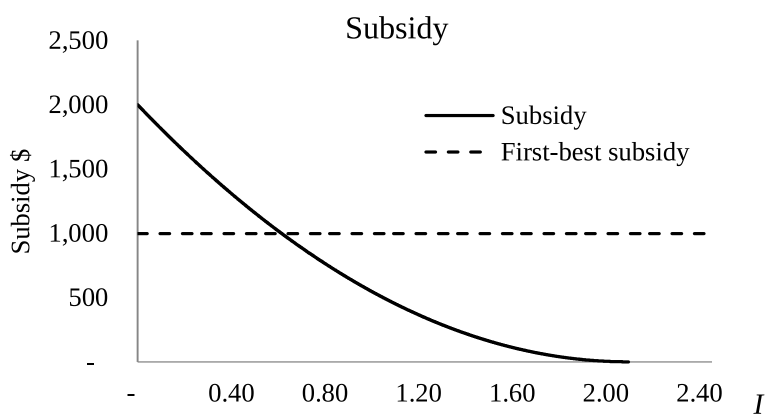

Figure 3.1. The subsidy scheme with $\bar{u}$=100 and z_1=5.

Figure 3.2 displays the distribution of invasive-species size when the foreign chooses an abatement effort level of 1.621. The mean invasive species level is 0.617.

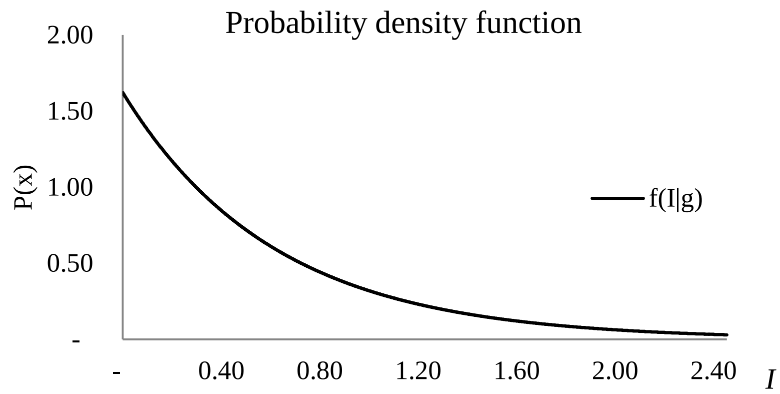

Figure 3.2. The probability density function for invasive species size when $g = 1.621$.

Figure 3.3, shows how changes in the foreign's reservation welfare level shifts the optimal invasive-species subsidy curve in Figure 3.1. As reservation welfare increases from 80 to 110, for example, the corresponding optimal invasive-species subsidy line shifts upward, indicating that the home country must provide the foreign with a higher subsidy at each ex post invasive-species size.

Figure 3.4 similarly shows how a change in the foreign's marginal abatement cost shifts the optimal invasive-species subsidy curve. As marginal abatement cost increases, the optimal invasive-species subsidy line shifts upward, implying that the home country must provide a larger subsidy to the foreign for any given invasive-species size.

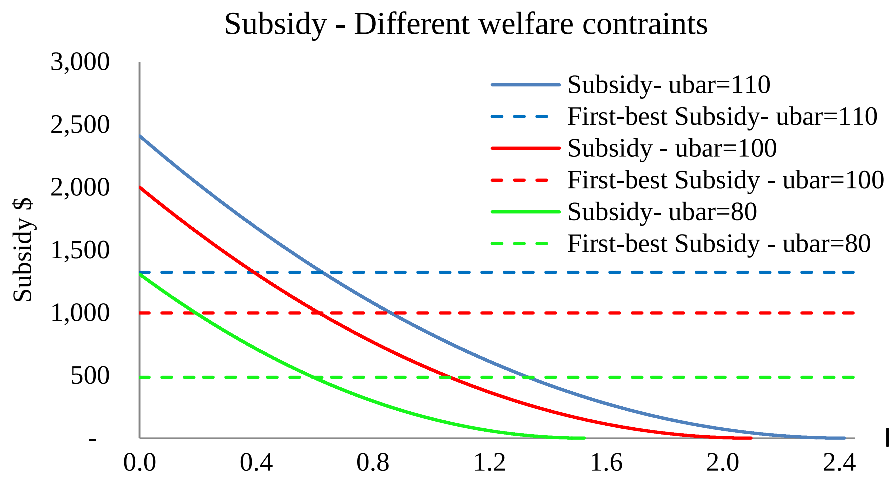

Figure 3.3. The optimal subsidy with different welfare constraints.

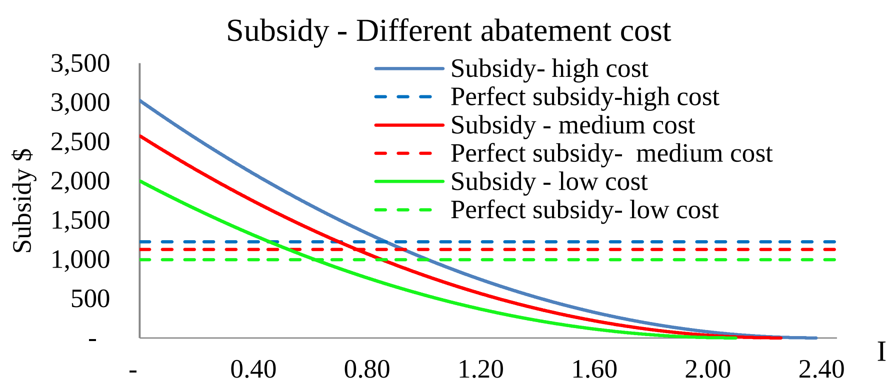

Figure 3.4. The optimal subsidy with different marginal abatement costs.

This simulation exercise therefore demonstrates how the optimal invasive-species subsidy can be used to encourage the foreign to control the invasive species at a specific expected level consistent with the home country's ex ante optimum. As shown, this subsidy's expected value under uncertainty exceeds the first-best subsidy under perfect observability.

3.3 Unobservable Abatement Effort and Multiple Foreigns

The next step in our analysis is to investigate the case of two foreigns, each with unobservable abatement effort. Here, the home country designs separate contracts with each foreign, subject to the foreigns' respective "participation" and "incentive-compatibility" constraints. The random factors affecting the respective foreigns are initially assumed to be independent of each other. This assumption is relaxed in Section 4 with the addition of a common random factor.

The home country derives separate contracts for the foreigns by solving the following problem,

$$
\begin{aligned}
\max_{s^1, s^2, t_1^u, t_2^u} W = \int_0^{s_1+s_2} P(x)dx - P(s_1+s_2)\,(s_1+s_2) - a(s_1+s_2) \\
- \int D(I_1+I_2) f^1(I_1|g_1) f^2(I_2|g_2) dI_1 dI_2 \\
- \int t_1^u(I_1) f^1(I_1|g_1) dI_1 \\
- \int t_2^u(I_2) f^2(I_2|g_2) dI_2
\end{aligned}
\tag{3.21}
$$

$$s.t.(i)\;\; U_i[P(s_1+s_2)s_i - c_i(s_i)] + \int V_i(t_i^u(I_i)) f^i(I_i|g_i) dI_i - Z_i(g_i) \geq \bar{u}_i$$

(ii) g_i and s_i jointly solve

$$\max_{g_i, s_i} U_i[P(s_1+s_2)s_i - c_i(s_i)] + \int V_i(t_i^u(I_i)) f^i(I_i|g_i) dI_i - Z_i(g_i)$$

$$i = 1,2.$$

Again using the first-order approach (Holmstrom, 1979), constraints (ii) are represented by the following four equations,

$$P - \frac{\partial c_i(s_i)}{\partial s_i} = 0, i = 1,2 \tag{3.22}$$

$$\int V_i(\cdot) f_{g_i}^i(I_i|g_i) dI_i - Z_i'(g_i) = 0, i = 1,2 \tag{3.23}$$

Letting $\lambda_i \geq 0$ be the multipliers for constraints (*i*), and $\nu_i \geq 0$ and $\omega_i \geq 0$ the multipliers for constraints (3.22) and (3.23) respectively, the Lagrangian function for this problem can be written as

$$\begin{aligned} L(\cdot) = &\int_0^{s_1+s_2} P(x)dx - P(s_1+s_2)(s_1+s_2) - a(s_1+s_2) \\ &- \int D(I_1+I_2) f^1(I_1|g_1) f^2(I_2|g_2) dI_1 dI_2 \\ &- \int t_1^u(I_1) f^1(I_1|g_1) dI_1 - \int t_2^u(I_2) f^2(I_2|g_2) dI_2 \\ &+ \sum_{i=1}^2 \nu_i \left\{P(\cdot) - \frac{\partial c_i(s_i)}{\partial s_i}\right\} \\ &+ \sum_{i=1}^2 \omega_i \left\{\int V_i(\cdot) f_{g_i}^i(I_i|g_i) dI_i - Z_i'(g_i)\right\} \\ &+ \sum_{i=1}^2 \lambda_i \left\{\begin{matrix} U_i[P(s_1+s_2)s_i - c_i(s_i)] \\ + \int V_i(t_i^u(I_i)) f^i(I_i|g_i) dI_i - Z_i(g_i) - \bar{u}_i \end{matrix}\right\} \end{aligned} \tag{3.24}$$

First-order conditions for an interior solution are $(i = 1,2, j = 1,2, \text{and } i \neq j)$,

$$\begin{aligned} \frac{\partial L(\cdot)}{\partial s_i} = &-\frac{\partial P(\cdot)}{\partial s_i}(s_1+s_2) - a + \lambda_i U_i'(\cdot)\frac{\partial P(\cdot)}{\partial s_i} s_i + \lambda_j U_j'(\cdot)\frac{\partial P(\cdot)}{\partial s_i} s_j \\ &+\nu_i \left\{\frac{\partial P(\cdot)}{\partial s_i} - \frac{\partial c_i^2(s_i)}{\partial s_i^2}\right\} + \nu_j \left\{\frac{\partial P(\cdot)}{\partial s_i}\right\} = 0 \end{aligned} \tag{3.25}$$

$$\frac{\partial L(\cdot)}{\partial t_i^u(I)} = -f^i(I_i|g_i) + \lambda_i V_i'(\cdot) f^i(I_i|g_i) + \omega_i V_i'(\cdot) f_{g_i}^i(I_i|g_i) = 0 \tag{3.26}$$

which implies

$$\frac{1}{V_i'(\cdot)} = \lambda_i + \omega_i \frac{f_{g_i}^i(I_i|g_i)}{f^i(I_i|g_i)} \tag{3.27}$$

and

$$\frac{\partial L(\cdot)}{\partial g_i} = -\int D(I_i + I_j) f_{g_i}^i(I_i|g_i) f^j(I_j|g_j) dI_i dI_j - \int t_i^u f_{g_i}^i(I_j|g_j) dI_i$$

$$+\omega_i\left[\int V_i(\cdot)f^i_{g_ig_i}(I_i|g_i)dI_i - Z_i''(g_i)\right]=0 \tag{3.28}$$

$$\frac{\partial L(\cdot)}{\partial \lambda_i} = U_i[P(s_1+s_2)s_i - c_i(s_i)] + \int V_i(t_i^u(I_i))f^i(I_i|g_i)dI_i$$

$$-Z_i(g_i) - \bar{u}_i = 0 \tag{3.29}$$

$$\frac{\partial L(\cdot)}{\partial v_i} = P(\cdot) - \frac{\partial c_i(s_i)}{\partial s_i} = 0 \tag{3.30}$$

$$\frac{\partial L(\cdot)}{\partial \omega_i} = \int V_i(\cdot)f^i_{g_i}(I_i|g_i)dI_i - Z_i'(g_i) = 0 \tag{3.31}$$

Following the proof of Lemma 3.1, $\lambda_i > 0$ and $\omega_i > 0$. This result can then be used to derive the condition under (and the degree to) which the subsidies in this problem are "inefficient" from the perspective of their deviation from what would be the optimal subsidies under perfect observability. The subsidies, $t_i^u(I_i)$, are therefore second-best solutions due to the home-country's need to satisfy the respective incentive constraints. Equations (3.27) suggest that the optimal invasive-species subsidy schedules for the two respective foreigns are not likely to have simple linear relationships with the foreigns' respective contributions to the invasive species level, i.e., the schedules $t_i^u(I_i)$ are potentially complicated functions of $I_i, i = 1,2$.

Similar to the simulation exercise undertaken in section 3.2, we now demonstrate how separate invasive-species control subsidies can be used to induce the two foreigns to (ex ante) optimally control their respective contributions to the home country's invasive species level. The two foreigns are assumed to be identical. This symmetry assumption does not alter the qualitative findings of the simulation exercise. Instead, it enables a nice comparison with the previous simulation analysis for the single foreign case. The corresponding functions are summarized in the Table 3.3.

Table 3.3
Simulation functions for the two foreigns (i=1,2.).

No.	Function Name	Description	Function
1	$P(x)$	Price of the tradable commodity	$P(s) = b_1 - b_2(s_1 + s_2)$
2	$D(I)$	Home country's damage from the invasive species level	$D(I) = d_1(I_1 + I_2)^2$
3	$U_i(\cdot)$	Foreign's welfare from the profit of exporting shipment s_i	$U_i(\cdot) = b_3^i\big(P(s_1 + s_2)s_i - c_i(s_i)\big)$
4	$V_i(\cdot)$	Foreign's welfare from the subsidy	$V_i\big(t_i^u(I)\big) = 2\sqrt{t_i^u(I)}$
5	$C_i(s)$	Foreign's producing cost	$c_i(s) = c_1^i + c_2^i s_i^2$
6	$Z_i(g)$	Foreign's abatement cost	$Z(g) = z_1^i {g_i}^2$
7	$f^i(I_i \mid g_i)$	Probability distribution functions for invasive species	$f^i(I_i \mid g_i) = g_i e^{-g_i I_i}$

Table 3.4
Simulation results for the two foreign cases.

Items	Welfare constraint (when z_1=5)			Abatement cost (when $\bar{u}$=100)		
	Low $\bar{u}$=80	Medium $\bar{u}$=100	Low $\bar{u}$=110	Low z_1=5	Medium z_1=10	High z_1=15
Tradable commodity shipment size s_i	33.3	33.3	33.3	33.3	33.3	33.3
Tradable commodity equilibrium price P	1,333	1,333	1,333	1,333	1,333	1,333
Abatement effort level g_i	1.683	1.639	1.619	1.639	1.336	1.183
Multipliers λ_i	46.523	56.164	61.001	56.164	58.373	59.948
Multipliers ν_i	8.493	7.958	7.689	7.958	7.835	7.747
Multipliers ω_i	23.823	22.034	21.237	22.034	23.861	24.862
Expected subsidy $E(t^u(I))$	2,365	3,335	3,893	3,335	3,726	4,035
First-best subsidy t^a	2,164	3,154	3,721	3,154	3,407	3,594
Expected welfare $E(W)$	15,241	13,185	12,013	13,185	11,274	9,730
First-best welfare W	15,641	13,546	12,357	13,546	11,912	10,614

To begin, the parameters are set as $\bar{u} = 100,\ a = 2,\ b_1 = 2{,}000,\ b_2 = 10,\ b_3 = 0.005,\ c_1 = 22{,}000,$ and $c_2 = 20, d_1 = 1000,$ and $z_1 = 5$. Next, corresponding results are derived based upon two different levels of the foreign's reservation welfare constraints and marginal abatement costs. Results are summarized in Table 3.4.

As expected, the symmetry assumption results in identical variable values across the two foreigns. In the optimal solution, the foreigns export approximately a total of 67 commodity units per shipment to the home country. Due to the downward-sloping aggregate demand and increasing production cost assumptions in this model, each foreign exports less than that in the single foreign case. Yet the total amount exported increases from 40 to roughly 67 units.

The corresponding equilibrium price decreases from $1600 (the price in the single foreign case) to $1333. Compared to the single foreign case, both foreigns s offer higher respective abatement efforts. But the mean invasive species size arriving at the home country is nevertheless larger with two foreigns than with one. This result comes about because with the lower equilibrium price per shipment, the home country gains greater welfare through the importation of more commodities, and, all else equal, is therefore willing to bear higher invasive-species damage. At the same time, the home country offers higher subsidies to each foreign than in the single foreign case. As a result, the increase in welfare from larger importation of the tradable commodity offsets the decrease in welfare from the higher level of invasive species damage and the higher abatement subsidy. The home country's welfare based on trade with two foreigns, rather than with only one, increases.

As in the single foreign case, changes in the foreign's respective reservation welfare levels and marginal abatement cost parameters do not affect their respective optimal shipment sizes. However, these changes do influence their abatement effort levels. In particular, as $\bar{u}_i, i = 1,2$, increases, each foreign's abatement effort decreases. Also, each foreign chooses a lower level of abatement when confronted with a higher marginal abatement cost parameter. In these cases, their expected subsidies increase as well.

In Figure 3.5, the solid line again represents the optimal subsidy (provided per foreign) for different levels of invasive species size. The dashed line is a benchmark representing the first-best (perfect observability) subsidy. The solid line crosses the dashed line at the conditional mean of the invasive-species size, $E(I_i|g_i = 1.639) = 0.610$. At this point the first-best and second best subsidies are equated. Compared to the single foreign case, each of the two foreign's abatement efforts increases to 1.639 from 1.621, and the mean invasive species level decreases to 0.61 from 0.617, respectively. But the total potential expected invasive species level increases for the home country.

Figure 3.6 displays the invasive-species size distribution when foreign country *i* chooses abatement effort at 1.639. The mean invasive species size at this abatement level is 0.610.

Figure 3.7 shows how a change in the foreign country's reservation welfare level shifts the optimal invasive-species subsidy curve. When reservation welfare increases from 80 to 110 units, the optimal subsidy lines shift upward. This means that the home country must provide the foreign country with a larger subsidy at each invasive-species size as reservation welfare increases.

Figure 3.8 similarly shows how the change in marginal abatement control cost shifts the optimal invasive-species subsidy curve. When an foreign country faces a higher marginal abatement control cost, the home country's optimal subsidy line shifts upward, i.e., the home country must compensate the foreign country with a higher subsidy at each invasive-species size in order to encourage the foreign country to control the invasive species size at the optimal level.

This simulation exercise shows that when trading with multiple foreigns in the face of independent random factors, an optimal set of invasive-species subsidies can still be implemented by the home country. However, the home country must offer a higher subsidy per foreign than first-best in order to compensate for the risk incurred by the foreigns. In the next section, a common random factor is also assumed to affect the abatement-effort/invasive-species relationships for each of the foreigns along the lines of Nalebuff and Stiglitz (1983). A tournament scheme is investigated as a possible solution to the invasive-species problem.

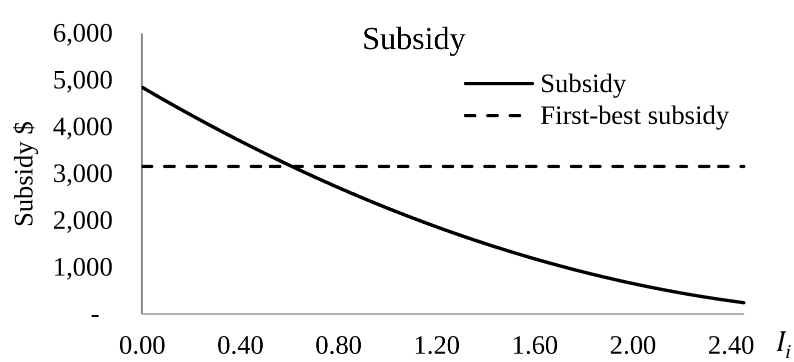

Figure 3.5. The optimal subsidy schedule for foreign *i* with $\bar{u}_i$=100 and $z_1^i = 5$.

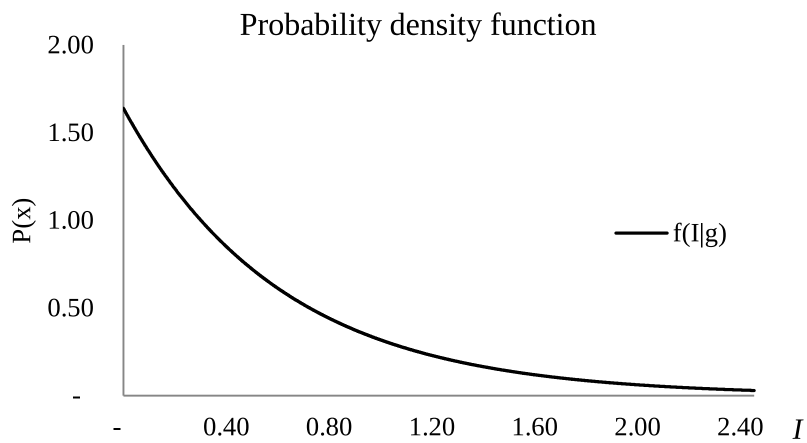

Figure 3.6. The conditional probability density function for I_i given $g_i = 1.639$.

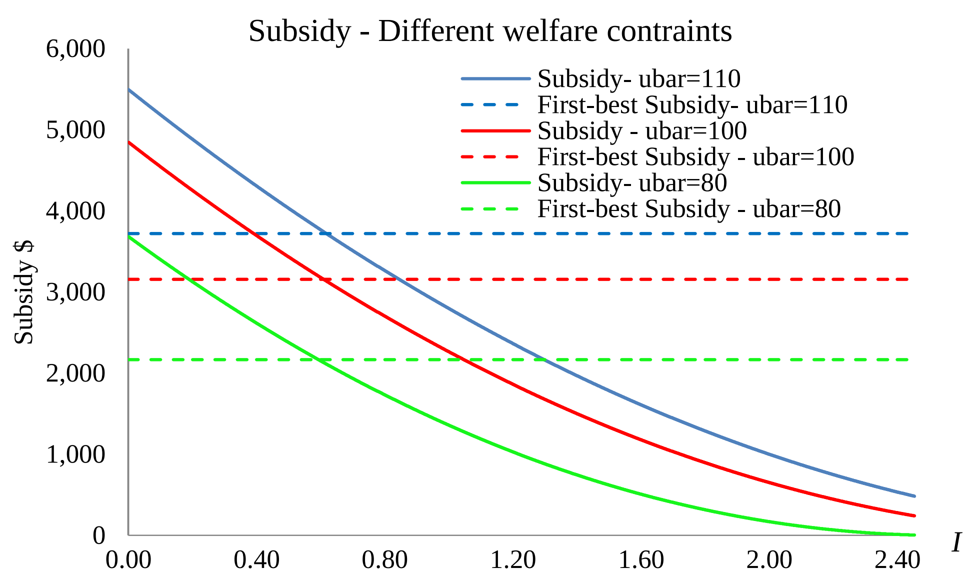

Figure 3.7. The optimal subsidy for foreign *i* for different reservation welfare levels.

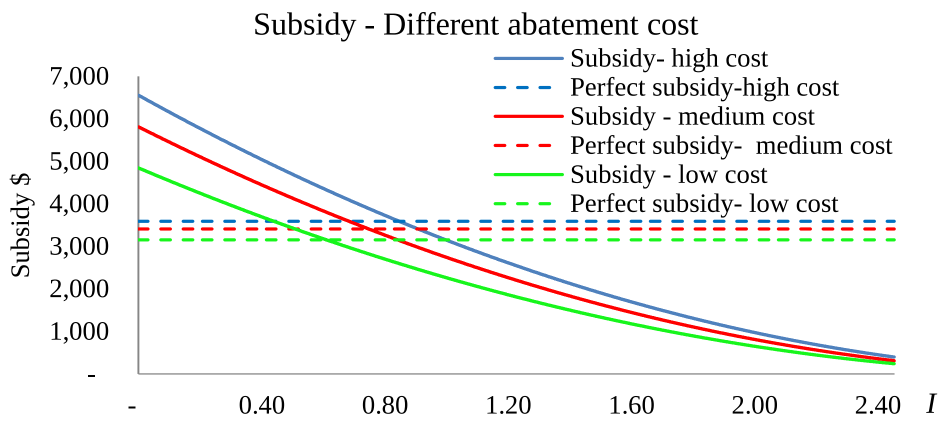

Figure 3.8. The optimal subsidy for foreign *i* with different marginal abatement cost parameters.

4. The Case of a Common Random Factor

As Theorem 1 in Nalebuff and Stiglitz (1983) shows, separate contracts are indeed ex ante optimal in the presence of independent random effects. In a more general setting, however, not only independent, but also common random factors, such as climate change, technological progress, and transitions in the global economic environment, can simultaneously affect the ability of a group of foreigns' abatement efforts to impact an invasive species size. These types of global or regional factors are examples of the common random factors considered in a more general framework by Green and Stokey (1983) and Nalebuff and Stiglitz (1983).

We begin with the assumption of two identical, risk-averse foreigns that export a homogeneous commodity to the home country.[22] In addition to an individualistic random factor that determines the effectiveness of each foreign's control effort, θ_i ($i = 1{,}2.$), an "environmental" factor, η, accounts for common randomness in both foreigns' control effectiveness. For instance, η can represent general weather patterns across both foreigns, and θ_i the particular weather conditions faced by foreign i. The home country is capable of observing each foreign's invasive-species contamination level, I_i, which is nevertheless a random function of its unobserved abatement effort, g_i, as a result of θ_i and η. We further assume that,

$$I_i = I_i(\eta g_i) + \theta_i \tag{3.32}$$

where $\frac{\partial I_i(\eta g_i)}{\partial(\eta g_i)} < 0$, $\frac{\partial^2 I_i(\eta g_i)}{\partial(\eta g_i)^2} \geq 0$, and $\partial^2 I_i(\eta g_i)/\partial\eta\partial g_i \neq 0$. As in Section 3, the greater the abatement effort, the smaller the invasive species size (nevertheless at a decreasing rate of return), all else equal.

Following Nalebuff and Stiglitz (1983), the home country and foreigns sign either bilateral or multilateral (i.e., tournament) contracts, whichever the case may be, before $\theta_i$and η are known (but given that the distributions of θ_i and η are common knowledge). In designing the tournament's prizes, the home country anticipates the reactions of the foreigns with respect to their respective choices of optimal shipment sizes and abatement efforts. Assume $E(\theta_i) = 0$, $E(\theta_i\theta_j) = 0$, and $\sigma^2(\theta_i) > 0$ $(i, j = 1{,}2;\ i \neq j)$, where

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[22] In keeping with Nalebuff and Stiglitz (1983), we again assume identical exporters. When the home country faces heterogeneous exporters, the basic conclusions reached here may be unchanged in a qualitative sense.

$E(\cdot)$ and $\sigma^2(\cdot)$ represent the expectation and variance operators, respectively. [23] Further, $E(\eta) = 1$, and $\sigma^2(\eta) > 0$. Let $f(\theta_i)$ and $F(\theta_i)$ represent the probability density and cumulative probability functions for θ_i, respectively.[24] Let $\zeta(\eta)$ be the probability density function for η. It is assumed that the variances of θ_i and η are both large enough to have sufficient effects on optimal invasive-species control undertaken by the two foreigns, respectively.

As implied by the analysis in Section 3.1, if the home country can perfectly observe both g_i and η, a first-best optimum can be determined by providing foreign-specific subsidies, which are determined solely by the respective foreigns' abatement efforts.[25] Appealing to the analysis of Section 3, optimal subsidies are ultimately determined by equation (3.8), $t_i^a(g_i) = V_i^{-1}\{\bar{u}_i + Z(g_i) - U_i(P(s_1, s_2)s_i - c_i(s_i))\}$ (which is explicitly derived below).

As discussed in that section, the home country sets the subsidies such that foreign i just obtains its reservation welfare level, $\bar{u}_i$. With the optimal subsidy included as a constraint, optimal abatement effort, g_i^*, is solved by maximizing the home country's welfare,

$$\max_{s_i, g_i} W = \int_0^{s_1+s_2} P(x)dx - P(s_1, s_2)(s_1 + s_2) - a(s_1 + s_2)$$

$$- \int\int\int D\left(\textstyle\sum_{i=1}^{2}(I_i(\eta g_i) + \theta_i)\right) f(\theta_1) f(\theta_2) \zeta(\eta)\, d\theta_1 d\theta_2 d\eta$$

$$- \textstyle\sum_{i=1}^{2} V_i^{-1}\{\bar{u}_i + Z_i(g_i) - U_i(P(s_1, s_2)s_i - c_i(s_i))\},$$

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[23] We assume that θ_i and θ_j are independent random variables, i.e. foreign *i*' s random factor does not affects foreign *j*'s, therefore the covariance of two random factors is zero.

[24] Because the two exporters are identical, the distributions of θ_i and θ_j are per force assumed to be the same as well.

[25] This result follows because with perfect observability η effectively becomes a constant in the home country's problem.

$$\text{s.t. } P(s_1, s_2) - \frac{\partial c_i(s_i)}{\partial s_i} = 0.\text{ [26]} \tag{3.33}$$

Letting λ_i represent the multipliers on the foreigns' respective first-order constraints, the Lagrangian function for this problem may be written as,

$$L(\cdot) = \int_0^{s_1+s_2} P(x)dx - P(s_1, s_2)(s_1 + s_2) - a(s_1 + s_2)$$

$$- \int\int\int D(\textstyle\sum_{i=1}^{2}(I_i(\eta g_i) + \theta_i))f(\theta_1)f(\theta_2)\zeta(\eta)\, d\theta_1 d\theta_2 d\eta$$

$$- \textstyle\sum_{i=1}^{2} V_i^{-1}\{\bar{u}_i + Z(g_i) - U_i(P(s_1, s_2)s_i - c_i(s_i))\}$$

$$+\lambda_i \left(P(s_1, s_2) - \frac{\partial c_i(s_i)}{\partial s_i}\right)$$

which, via the inverse function rule, results in the following first-order conditions for the choice of g_i,

$$-\eta \int\int\int \frac{\partial(I_i(\cdot))}{\partial(\eta g_i^*)} D'(\cdot)f(\theta_1)f(\theta_2)\zeta(\eta)\, d\theta_1 d\theta_2 d\eta\, (\cdot^*)V_i'(\cdot)$$

$$-Z_i'(g_i^*) = 0, i = 1{,}2 \tag{3.34}$$

i.e., $-\eta E\big(D'(\cdot)\big)V_i'(\cdot) = Z_i'(g_i^*)$.

At foreign i's optimal abatement level, determined by (3.34), its marginal abatement cost equals expected marginal damage from the invasive species level in the home country caused by foreign i, valued in foreign i's welfare units. Again, by facing the foreigns' respective reservation welfare constraints, the home country takes the foreigns' respective reactions into consideration upfront. Equation (3.34) is therefore the condition for optimal abatement effort for both the home country and foreigns. The optimal shipment size from foreign i is determined by

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[26] For the home country, the invasive species damage is determined by the random invasive-species size, which is decided by the exporters' abatement efforts and the random variables. Therefore, the home country only can make a decision based upon expected damage.

$$-\frac{\partial P(\cdot)}{\partial s_i}(s_1+s_2)-a+\frac{\left[U_i'(\cdot)\frac{\partial P(\cdot)}{\partial s_i}s_i\right]}{V_i'(\cdot)}+\frac{\left[U_j'(\cdot)\frac{\partial P(\cdot)}{\partial s_i}s_j\right]}{V_j'(\cdot)}$$

$$+\lambda_i\left(\frac{\partial P(\cdot)}{\partial s_i}-\frac{\partial^2 c_i(s_i)}{\partial s_i^2}\right)=0,\ (i,j=1,2\ ),\text{ and } i\neq j \tag{3.35}$$

The home country takes account of the foreigns' respective optimal shipment sizes to satisfy

$$P(\cdot)-\frac{\partial c_i(s_i)}{\partial s_i}=0 \tag{3.36}$$

The first-best subsidy can therefore be written as,

$$t_i^a(g_i)=\begin{cases} t_i^{a*}(g_i^*)=V_i^{-1}\begin{Bmatrix} \bar{u}_i+Z_i(g_i^*) \\ -U_i(P(s_1^*,s_2^*)s_i^*-c_i(s_i^*)) \end{Bmatrix} & g_i\geq g_i^* \\ 0 & g_i<g_i^* \end{cases} \tag{3.37}$$

As this condition shows, in the benchmark solution with a risk-neutral home country and risk-averse foreign foreigns, the foreigns are provided with full insurance.[27] Realistically, however, the home country can observe neither the foreigns' abatement efforts nor the individualistic and common random factors. In the face of this uncertainty, the home country can instead design a tournament scheme along the lines of Nalebuff and Stiglitz (1983).

As Nalebuff and Stigliz (1983) and Green and Stokey (1983) have shown, a rank-order tournament generally dominates individualistic contracts in the presence of a common random factor. A rank-order tournament is an incentive scheme in which participants' rewards or penalties are based upon an ordinal ranking of their respective performances (in our case invasive-species contamination levels), not on the actual

[27] As in Section 3, foreign *i* chooses exactly g_i^*, thus obtaining the subsidy at the lowest possible cost to itself in terms of abatement effort.

performances themselves. Tournaments tend to be preferable when the risk associated with the common environmental variable, i.e., η, is relatively large, or when the number of agents is large. In this section, a rank-order tournament is developed along the lines of Nalebuff and Stigliz (1983) for invasive species border control in the presence of unobservable abatement efforts among the foreigns.[28]

Let the "winner" foreign's subsidy be denoted t^w, and the "loser's" t^L, where the winner is the foreign with the lower invasive-species size. As shown by Nalebuff and Stiglitz (1983), in this case the winner is rewarded more than its performance would otherwise merit, in an attempt to motivate greater abatement efforts among both agents. The winner and loser are determined by both their respective abatement levels and the draws of both the individualistic and common random factors. Even in the case of symmetric agents, the tournament will distinguish a winner and a loser. However, the expected prize is the same for each agent.

For uniformity with the individualistic subsidy scheme in Section 3, let $t^w + t^L$ equal the sum of the expected subsidies calculated under perfect observability. That is,

$$t^w + t^L = \sum_{i=1}^{2} t_i^{a*}(g_i^*)$$

$$= \sum_{i=1}^{2} V_i^{-1}\{\bar{u}_i + Z_i(g_i^*) - U_i(P(s_1^*, s_2^*)s_i^* - c_i(s_i^*))\} \tag{3.38}$$

Following Nalebuff and Stiglitz (1983), let

$$\bar{t} = \frac{t^w + t^L}{2}$$

$$r = \frac{t^w - t^L}{2} \tag{3.39}$$

[28] We do not derive ex ante optimal individual contracts in this case of both individualistic and common random factors due to (1) the more general results of Nalebuff and Stiglitz (1983) and Green and Stokey (1983) showing the superiority of tournaments, and (2) space limitations.

where $\bar{t}$ is the average subsidy, or "safe income," and r is the risk associated with participating in the tournament.

The foreigns' expected welfares are, respectively, functions of the probabilities of their winning the tournament. A foreign's winning probability depends not only on its abatement effort, but also on its opponent's abatement effort, as well as η and θ_i. For given distributions of θ_i and η, let $q_i(g_1, g_2, \eta)$ represent foreign i' s probability of winning the tournament. Foreign i's expected welfare function can then be written as,

$$\max_{s_i, g_i} \mathrm{W}_i = U_i\big(P(s_1, s_2)s_i - c_i(s_i)\big) + q_i(\cdot)V_i(\bar{t} + r)$$

$$+\big(1 - q_i(\cdot)\big)V_i(\bar{t} - r) - Z_i(g_i) \qquad (3.40)$$

As before, the foreign will choose its optimal shipment size, s_i, according to equation (3.36), i.e.,

$$P(\cdot) - \frac{\partial c(s_i)}{\partial s_i} = 0 \qquad (3.41)$$

As Nalebuff and Stigliz (1983) point out, by rewarding agents on the basis of a contest, the individualistic random term, θ_i , is effectively replaced in the agent's expected welfare function by the new disturbance term r. In the context of our problem, θ_i is by definition uncorrelated with abatement effort g_i, but r is not. If a foreign implements more abatement effort, the probability of winning r increases. After observing η, foreigns choose their respective abatement efforts according to,

$$\frac{\partial q_i(\cdot)}{\partial g_i} \Delta V_i - Z_i'(g_i) = 0 \qquad (3.42)$$

where $\Delta V_i = V_i(\bar{t} + r) - V_i(\bar{t} - r)$.

This equation represents the rule followed by the foreign in choosing its abatement effort. ΔV is the welfare surplus associated with winning the competition. Thus, $\frac{\partial q_i(\cdot)}{\partial g_i}\Delta V$ represents the marginal welfare surplus associated with abatement effort. The foreigns therefore choose their respective optimal abatement efforts up to the point where the marginal disutility (or cost) of abatement effort equals the marginal welfare surplus from participating in the tournament.

As Nalebuff and Stiglitz (1983) point out, these equations can be thought of as the reaction functions for the two agents, i.e., $g_1(g_2)$ and $g_2(g_1)$, which, under certain circumstances, lead to a symmetric equilibrium, i.e, $E(g_1) = E(g_2)$ (see footnote 3 in Nalebuff and Stiglitz (1983) for further discussion). In our case, each foreign chooses g_i based upon its observation of θ_i and η. Thus, g_i will not necessarily equal $g_j,\ i,j = 1,2,\ i{\neq}j$, for any given tournament.

If foreign 1 is to “beat” foreign 2, it must satisfy

$$I_1(\eta g_1) + \theta_1 < I_2(\eta g_2) + \theta_2 \tag{3.43}$$

The probability of this occurring for a given θ_2 is

$$F(I_2(\eta g_2) - I_1(\eta g_1) + \theta_2) \tag{3.44}$$

To calculate the probability of foreign 1 winning the tournament, we therefore solve,

$$q_1(\cdot) = \int F(I_2(\eta g_2) - I_1(\eta g_1) + \theta_2) f(\theta_2) d\theta_2 \tag{3.45}$$

Thus, as Nalebuff and Stiglitz (1983) show, at the symmetric equilibrium, $E(g_1) = E(g_2) = g_i^*,\ q_1 = q_2 = ½$. In our case, a symmetric equilibrium means that both the probability of winning the prize, t^w, and the expected subsidy are the same for each foreign. However, due to the identical-foreign assumption, the foreign with higher abatement effort is more likely to win. However, the winning foreign will incur higher abatement cost at the same time.

Using (3.45), foreign *1*'s probability of winning changes with respect to its abatement effort according to,

$$\frac{\partial q_1(\cdot)}{\partial g_1} = -\eta \frac{\partial I_1(\eta g_1)}{\partial(\eta g_1)} \int f(\theta_1) f(\theta_2) d\theta_2 = -\eta \frac{\partial I_1(\eta g_1)}{\partial(\eta g_1)} \bar{f} \tag{3.46}$$

where $\bar{f} = E[f(\theta)]$.

Substituting (3.46) into (3.42) yields

$$-\eta \frac{\partial I_1(\eta g_1)}{\partial(\eta g_1)} \bar{f} \Delta V = Z'(g_1) \tag{3.47}$$

Equation (3.47) is identical to fundamental equation (17) in Nalebuff and Stigliz (1983), given the non-linearity of function $I_i(\eta g_i)$. Given this non-linearity, each foreign's abatement effort is dependent upon η after observing η and θ_i. However, the two identical foreigns have the same winning probabilities, and each foreign's expected subsidy will be the same. If *r* is now set according to,

$$\bar{f} \Delta V = E\big(D'(\cdot) V'(\cdot)\big) \tag{3.48}$$

then equation (3.34) is replicated and first-best abatement efforts are chosen by both foreigns. Any t^W and t^L that together determine the *r* satisfying (3.48) and (3.38) are optimal from the home country's perspective. As shown by Nalebuff and Stiglitz (1983), due to the risk associated with participating in the tournament, each agent's welfare does not equate with its first-best level, but expected welfare is the welfare obtained under the first-best subsidy. Further, the higher the tournament risk, *r*, the more incentive each agent has to increase their abatement effort. This leads to Lemma 3.2.

Lemma 3.2 . The foreign's abatement effort is positively correlated with the size of the winning prize.

The proof for this lemma is readily seen. Applying the implicit function theorem to (3.47) at equilibrium results in

$$\frac{dg_i^*}{dr} = \frac{-\eta \frac{\partial I(\eta g_i^*)}{\partial(\eta g_i^*)} \bar{f}\left(V'(\bar{t}+r)+V'(\bar{t}-r)\right)}{\eta^2 \frac{\partial^2 I(\eta g_i^*)}{\partial(\eta g_i^*)^2} \bar{f}\Delta V + Z''(g_i)} > 0 \qquad (3.49)$$

and via (3.39), in particular the definition of r, the winning prize is in turn positively correlated with r.

For purposes of numerical simulation, let the home country's welfare and invasive species damage functions, the foreigns' welfare and cost functions, as well as the invasive-species size with respect to the abatement effort functions be as shown in Table 3.5.

Table 3.5
Functions for a tournament simulation (i=1,2.).

No.	Function Name	Description	Function
1	$P(s)$	Price of the tradable commodity	$P(s) = b_1 - b_2(s_1 + s_2)$
2	$D(I)$	Home country' damage from an invasive species [29]	$D(I) = d_1(I_1 + I_2)$
3	$U_i(\cdot)$	ForeignForeign's welfare from the profit of exporting its commodity	$U_i(\cdot) = b_3^i\left(P(s_1 + s_2)s_i - c_i(s_i)\right)$
4	$V_i(\cdot)$	Foreign's welfare from the home country's subsidy	$V_i\left(t_i^a(I)\right) = 2\sqrt{t_i^a(I)}$
5	$C_i(s)$	Foreign's producing cost	$c_i(s) = c_1^i + c_2^i s_i^2$
6	$Z_i(g)$	Foreign's abatement cost	$Z_i(g_i) = z_1^i {g_i}^2$
7	$I_i(\eta g)$	Foreign's invasive-species size [30]	$I_i(\eta g_i) = h_i - \beta_i\sqrt{\eta g_i} + \theta_i,\ g_i \in \left[0, \frac{25}{54}\left(\frac{h_i}{\beta_i}\right)^2\right].$

[29] To simplify the calculation, a linear damage function is adopted here.
[30] The up bound of the abatement effort is set to guarantee the nonnegative invasive species size.

The probability density function defined over the common factor is assume to be uniform with a mean of 1,

$$\zeta(\eta) = \begin{cases} 1 & \frac{1}{2} \leq \eta \leq \frac{3}{2} \\ 0 & \eta < \frac{1}{2} \ or\ \eta > \frac{3}{2} \end{cases}.$$

Similarly, the probability density functions of the respective individualistic random factors are assumed to be uniform with zero means,[31]

$$f(\theta_i) = \begin{cases} \frac{3}{h_i} & -\frac{h_i}{6} \leq \theta_i \leq \frac{h_i}{6} \\ 0 & \theta_i < -\frac{h_i}{6} \ or\ \theta_i > \frac{h_i}{6} \end{cases}.$$

The expected invasive species size is therefore,

$$E\big(I_i(\eta g_i)\big) = \int_{\frac{1}{2}}^{\frac{3}{2}} \int_{-\frac{h_i}{6}}^{\frac{h_i}{6}} \big(h_i - \beta_i\sqrt{\eta g_i} + \theta_i\big)\frac{3}{h_i} d\theta_i d\eta.$$

Here, the maximum mean of invasive species size from foreign i is represented by h_i, i.e., the size corresponding to zero abatement effort on the part of foreign i. As i's abatement effort increases, its expected invasive species size decreases, but at a decreasing rate. Letting $h_i = 5$ and $\beta_i = 1$, the green line in Figure 3.9 illustrates how the expected invasive species size from foreign i changes with respect to the its abatement effort.

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[31] In Section 3, we assumed exponential density functions for the two exporters. Uniform densities are assumed here for tractability purposes.

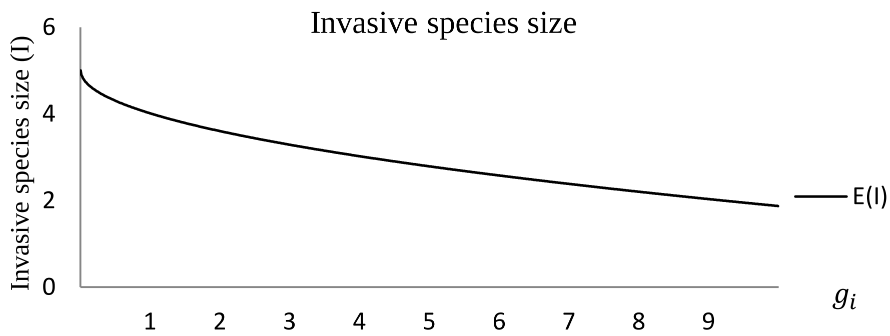

Figure 3.9. Expected invasive species size with respect to abatement effort.

The parameter values for this simulation exercise are set at $\bar{u}_i = 100,\ a = 2,\ b_1 = 2{,}000,\ b_2 = 10,\ b_3^i = 0.005,\ c_1^i =\ 22{,}000,\ c_2^i\ = 20,\ d_1 = 1000,\ h_i = 5,\ \beta_i = 1,$ and $z_1^i = 5$. Corresponding results for the benchmark case of perfect observability (using individualized contracts) are then calculated for the cases of three different foreign reservation utility levels (assuming marginal abatement cost is fixed at $z_1 = 5$) and three different marginal abatement cost parameters (assuming reservation utility is fixed at 100). Results are presented in Table 3.6.

When $\bar{u}_i = 100$ and $z_1^i = 5$, optimal (symmetric) shipment size is 33. The home country effectively determines the optimal abatement levels, at which the marginal damage of the invasive species level, valued in the foreigns' welfare units, equals the foreigns' respective marginal costs of abatement. Optimal abatement efforts are 0.970, and the subsidy is set at $2,683 per foreign. As expected, higher reservation welfare levels lead to a decrease in optimal abatement effort (referring to columns 2-4), as does a higher marginal abatement cost parameter.

Tournament risk for this simulation exercise, r, is derived from Equation (3.48). Corresponding winning and losing rewards, or subsidies, are then calculated for the same three foreign reservation utility levels (assuming marginal abatement cost is fixed at $z_1 = 5$) and three marginal abatement cost parameters (assuming reservation utility is fixed at 100) as in Table 3.6. The tournament results are presented in Table 3.7.

Similar to previous results, as foreigns increase their abatement efforts, the expected invasive-species size, and thus damage suffered by the home country, decreases. As shown above, the home country can choose a risk level for the foreigns such that a simple tournament between the foreigns results in the first-best level of abatement efforts. Comparing Table 3.7 with Table 3.6, the home country, without observation of the foreigns' abatement efforts, can realize the first-best level of welfare by using a tournament, indicating that a tournament scheme reveals more information about the individualistic and common random factors.

Table 3.6
Simulation results for the first-best benchmark solution (i=1,2.).

Variables	Minimum welfare (when z_1=5)			Abatement cost (when $\bar{u}_i = 100$)		
	Low $\bar{u}_i = 80$	Medium $\bar{u}_i = 100$	Low $\bar{u}_i = 110$	Low $z_1^i = 5$	Medium $z_1^i = 10$	High $z_1^i = 15$
Tradable commodity shipment size (s_i)	33	33	33	33	33	33
Abatement effort level (g_i)	1.106	0.970	0.915	0.970	0.614	0.470
Mean invasive species size $E(I_i)$	3.960	4.026	4.054	4.026	4.225	4.322
Subsidy $t_i^a(g_i)$	1,807	2,683	3,196	2,683	2,635	2,612
Expected welfare $E(W)$	10,726	8,627	7,470	8,627	7,968	7,763

Table 3.7
Simulation results for the tournament scheme (i=1,2.).

Variables	Minimum welfare (when z_1=5)			Abatement cost (when $\bar{u}_i = 100$)		
	Low $\bar{u}_i = 80$	Medium $\bar{u}_i = 100$	High $\bar{u}_i = 110$	Low $z_1^i = 5$	Medium $z_1^i = 10$	High $z_1^i = 15$
Tradable commodity shipment size (s_i)	33	33	33	33	33	33
Abatement effort level (g_i)	1.106	0.970	0.915	0.970	0.614	0.470
Mean invasive species size E(I_i)	3.960	4.026	4.054	4.026	4.225	4.322
Expected welfare $E(W)$	10,726	8,627	7,470	8,627	7,968	7,763
Tournament risk (r)	810.87	823.22	826.22	823.22	822.85	822.66
Subsidy $t_i^a(g_i)$	1,807	2,683	3,196	2,683	2,635	2,612
Winning subsidy $t_i^a(g_i) + r$	2,617	3,506	4,023	3,506	3,458	3,434
Losing subsidy $t_i^a(g_i) - r$	996	1,859	2,370	1,859	1,812	1,789

It is interesting to note from Table 3.7 that the tournament risk necessary to achieve the first-best solution values is relatively large, as indicated by the gaps between the winning and losing subsidies. For example, when $\bar{u}_i = 100$ and $z_1^i = 5$ the gap is approximately 811 units. Similar-sized gaps are reported for the other parameter combinations included in the table. However, as indicated the table, the gaps as percentages of the losing subsidies decrease quite dramatically with increases in reservation utility levels, reflecting the need for the home country to lower the downside risk of the tournament as the opportunity costs of foreigns' increases. To the contrary, the gaps as percentages of losing subsidies are relatively unchanged with increases in the marginal abatement cost parameter, suggesting that the home country does not need to be as sensitive to changes in downside risk associated with increases in the foreigns' marginal abatement costs.

5. Conclusion

This paper's main contribution to the invasive species border control literature – a literature that has heretofore focused almost exclusively on the use of tariffs and inspection as predominant control policies – is the investigation of two alternative policies that directly influence a foreign country's abatement effort – contracts and tournaments. Our framework for contracts is provided by Holmstrom (1979), while the framework for tournaments is provided by Nalebuff and Stiglitz (1983) and Green and Stokey (1983). Both frameworks accommodate uncertainty in the abatement process of a foreign country.

As taught by Nalebuff and Stiglitz (1983) and Green and Stokey (1983), the type of uncertainty faced by the home country governs its choice of policy instrument. When the environmental randomness that inhibits the home country's ability to observe a foreign's abatement effort is specific to that foreign (and thus strictly independent across foreigns), bilateral contracts between the home country and respective foreigns are sufficient for obtaining an ex ante optimal invasive species level in the home country. However, when the randomness has both independent and common components, a rank-order tournament is able to leverage the common component and induce first-best abatement efforts by the foreigns. We derive these analytical results in the specific context of the invasive species problem.

In addition, we numerically analyze the contract and tournament models in this context by considering three general cases. In the first two cases, where the random factor is foreign-specific and independent across foreigns, we analyze bilateral contracts provided by the home country to a single and to two foreigns, respectively. In the single foreign case, we find that the home country's subsidy is increasing in both the foreign's marginal abatement cost and reservation welfare level. These results also hold in the case of two foreigns, however the home country imports a larger quantity of the tradable commodity (and thus a larger quantity of the invasive species) as the commodity's equilibrium price falls. In each case, the expected second-best subsidy exceeds the first-best subsidy (under perfect observability). As a result, expected home-country welfare under imperfect observability is lower.

In the third case we assess the effectiveness of a tournament in achieving the home country's first-best solution to the invasive species problem in the face of both foreign-specific and common random factors. Our main finding is that the tournament risk (or gap between the winning and losing subsidies) as a percentage of the losing subsidy decreases quite dramatically with increases in the reservation utility levels of the foreigns, reflecting the need for the home country to lower the downside risk of the tournament as the opportunity costs of foreigns increases. To the contrary, the gap as a percentage of the losing subsidy is relatively insensitive to increases in the marginal abatement cost parameter, suggesting that in designing its tournament scheme the home country does not need to be as sensitive to changes in the downside risk associated with increases in the foreigns' marginal abatement costs.

The study of invasive species border control is complex, and as a result several issues remain for future research. Nalebuff and Stigliz (1983) show that introducing a threshold gap (in our case between the respective foreigns' contributions to the home country's invasive species level), with a subsidy bonus contingent upon meeting this threshold gap, can improve the tournament scheme. In the spirit of Nalebuff and Stiglitz (1983), a natural "next step" would therefore be to determine the optimal "threshold gap" in an invasive-species tournament.

A second logical step would be to link the contract and tournament schemes, which are border control policies, with policies aimed at reducing the spread of an invasive species once it has been introduced in the home country. It is important to note that the border-control policies explored in this paper assume a non-zero optimal invasive species size. Our model therefore abstracts from explicit mechanisms that are required to optimally contain the spread of the invasive species within the home country's borders. Presumably a joint policy that explicitly accounts for the dynamics of the invasive species spread, both temporally and spatially, is ultimately required. This policy would include schemes such as contracts, tournaments, or tariffs to control the invasive species level at the border, and then perhaps taxes or subsidies levied on private and public landowners within the home country to control the species' spread internally. Models addressing the spread of invasive species are in the early stages of development (see for instance, Sharov and Liebhod, 1998; Horan and Wolf, 2005; Rich et al., 2005; Kim et al., 2006; Wilen, 2007; Burnett et al., 2008; Olson and Roy, 2010; Finnoff et al., 2011; Homans and Horie, 2011; Sims and Finnoff, 2012). These models are likely candidates for linkage with the border control models developed in this paper.

References

Batabyal, Amitrajeet A., and Beladi, Hamid, 2009. Trade, the damage from alien species, and the effects of protectionism under alternate market structures. Journal of Economic Behavior & Organization 70, 389-401.

Burnett, Kimberly M., Evelyn, Sean. D, Kaiser, Brooks A., Nantamanasikarn, Porntawee, and Roumasset, James A., 2008. Beyond the lamppost: optimal prevention and control of the Brown Tree Snake in Hawaii. Ecological Economics 67, 66 –74.

Burnett, Kimberly M., 2006. Introductions of invasive species: failure of the weaker link. Agricultural and Resource Economics Review 35(1), (April), 21–28.

Clout, Mick N., and Williams, Peter A., 2009. Invasive species management. Oxford University Press.

Costello, Christopher, and McAusland, Carol, 2003. Protectionism, trade, and measures of damage from exotic species introductions. The American Journal of Agricultural Economics 85(4), (November), 964-975.

Feng, Hong L., and Hennessy, David A., 2008. Least-cost tradeable risk permit scheme for controlling risk of introducing invasive alien species by shipping. Ecological Economics 68, 532 –535.

Finnoff, David, Horan, Rick, McDermott, Shana, Sims, Charles, and Shogren, Jason F., 2011. Economic Control of Invasive Species. Working Paper.

Finnoff, David, Shogren, Jason F., Leung, Brian, and Lodge, David, 2005. Risk and nonindigenous species management. Review of Agricultural Economics 27 (3), 475–482.

Green, Jerry R., and Stokey, Nancy L., 1983. A comparison of tournaments and contracts. Journal of Political Economy 91 (3), 349-364.

Holmstrom, Bengt, 1979. Moral hazard and observability. The Bell Journal of Economics 10 (1), (Spring), 74-91.

Holmstrom, Bengt, 1982. Moral hazard in teams. The Bell Journal of Economics 13 (2), Autumn, 324-340.

Homans, Frances, and Horie, Tetsuya, 2011. Optimal detection strategies for an established invasive pest. Ecological Economics 70, 1129–1138.

Horan, Richard D., and Lupi, Frank, 2005. Tradeable risk permits to prevent future introductions of invasive alien species into the Great Lakes. Ecological Economics 52, 289– 304.

Horan, Richard D., and Wolf, Christopher A., 2005. The economics of managing infectious wildlife disease. The American Journal of Agricultural Economics 87 (3), (August), 537–551.

Horan, Richard D., Perrings, Charles, Lupi, Frank, and Bulte, Erwin H., 2002. Biological pollution prevention strategies under ignorance: the case of invasive species. The American Journal of Agricultural Economics 84 (5), Proceedings Issue (Dec.), 1303-1310.

Jones, Kristin Roti, and Corona, Joel P., 2008. An ambient tax approach to invasive species. Ecological Economics 64, 534-541.

Kim, C.S., Lubowski, Ruben N., Lewandrowski, Jan, and Eiswerth, Mark E., 2006. Prevention or control: optimal government policies for invasive species management.

Agricultural and Resource Economics Review 35 (1), (April), 29–40.

Lazear, Edward P., and Sherwin, Rosen, 1981. Rank-order tournaments as optimum labor contracts. Journal of Political Economy 89 (5), (Oct), 841- 864.

Levine, Jonathan M., and D'antonio, Carla M., 2003. Forecasting biological invasions with increasing international trade. Conservation Biology, 17 (1), (February), 322–326.

Malik, Arun S., 1990. Markets for pollution control when firms are noncompliant. Journal of Environmental Economics and Management 18, 97-106.

Margolis, Michael, Shogren, Jason F., and Fischer, Carolyn, 2005. How trade politics affect invasive species control. Ecological Economics 52, 305- 313.

McAusland, Carol, and Costello, Christopher, 2004. Avoiding invasives: trade-related policies for controlling unintentional exotic species introductions. Journal of Environmental Economics and Management 48, 954–977.

Mclaughlin, Kenneth J., 1988. Aspects of tournament models: a survey. Research in Labor Economics 9, 225-256.

Mérel, Pierre R., and Carter, Colin A., 2008. A second look at managing import risk from invasive species. Journal of Environmental Economics and Management 56, 286-290.

Mirrlees, James A., 1976. The optimal structure of incentives and authority within an organization. The Bell Journal of Economics 10 (1), (Spring), 105-131.

Nalebuff, Barry J., and Stiglitz, Joseph E., 1983. Prizes and incentives: towards a general theory of compensation and competition. The Bell Journal of Economics 14 (1), (Spring), 21-43.

O'Keeffe, Mary, Viscusi, W. Kip, and Zeckhauser, Richard J., 1984. Economic contests: comparative reward schemes. Journal of Labor Economics 2 (1), (Jan.), 27-56.

Olson, Lars J., and Roy, Santanu, 2002. The economics of controlling a stochastic biological invasion. The American Journal of Agricultural Economics. 84 (5), 1311–1316.

Olson, Lars J., and Roy, Santanu, 2005. On prevention and control of an uncertain biological invasion. Review of Agricultural Economics 27 (3), 491-497.

Olson, Lars J., and Roy, Santanu, 2010. Dynamic sanitary and phytosanitary trade policy. Journal of Environmental Economics and Management 60, 21–30.

Pimentel, David, Zuniga, Rodolfo, and Morrison, Doug, 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecological Economics 52, 273– 288.

Rich, Karl M., Winter-Nelson, Alex, and Brozović, Nicholas, 2005. Modeling regional externalities with heterogeneous incentives and fixed boundaries: applications to foot and mouth disease control in South America. Review of Agricultural Economics 27 (3), 456–464.

Sharov, Alexei A., and Liebhold, Andrew M., 1998. Bioeconomics of managing the spread of exotic pest species with barrier zones. Ecological Applications 8 (3), (Aug.), 833-845.

Silberberg, Eugene, and Suen,Wing, 2001. The structure of economics - a mathematical analysis. The third edition, McGraw-Hill.

Sims, Charles, and Finnoff, David, 2012. The role of spatial scale in the timing of uncertain environmental policy. Journal of Economic Dynamics and Control 36, 369-382.

Wilcove, David S., Rothstein, David, Bubow, Jason, Phillips, Ali, and Losos, Elizabeth, 1998. Quantifying threats to imperiled species in the United States. Bioscience 48 (8), 607– 615.

Wilen, James E., 2007. Economics of spatial-dynamic processes. The American Journal of Agricultural Economics 89 (5), 1134–1144.

CHAPTER 4

SPATIAL-DYNAMIC EXTERNALITIES AND COORDINATION IN INVASIVE SPECIES CONTROL

Abstract

Invasive species are causing tremendous losses in the US, while several billions of dollars in control costs are spent on decreasing the spread of invasive species. Since species invasions impact large spatial areas, these control costs and damages are incurred by multiple participants, e.g., land owners, regional government, countries. We integrate ecological and economic processes to study a spatial externality common in the control of an established invasive species. The model considers an invasive species spreading across a number of individual participants who each engage in costly control actions that lower the rate of spread. The individualistic optimum control strategy is solved through backward induction by a chain of individual optimal control process. We find that the optimal response to invasion (eradicating, stopping, or ignoring invasion) is determined by the incremental damage of invasion and the marginal control cost. In the stopping case, the steady-state invasion area is positively related to the discount rate and the marginal control cost, negatively related to marginal damage, but not related to the initial invaded area. The change in the optimal control rate directly relates to the state of the invasion and its shadow cost. The fundamental reason for the spatial externality is that society and the individual participants differ in concern to the damage caused by an invasive species. Specifically, different spatial scales lead to a divergence between the control incentives of society and individuals, and result in a deficiency of the individual's control

accompanying with a larger steady-state invasion area. I introduce a dynamic multiple-source-subsidy scheme to internalize the externalities, which expands Wilen's (2007) chained bilateral negotiation system. A numerical analysis demonstrates these theoretical results and then illustrates how the number, size, and spatial order of small and large parcel influence the severity of the externality and consequently the sufficiency of privately supplied invasive species control.

1. Introduction

Invasive species are causing tremendous losses in the US, while several billions of dollars in control costs are spent on decreasing the spread of invasive species (Pimentel et al., 2005). Invasive species control is a long-term trade-off between the flow of damages and relative control costs for the established invasive species. This trade-off critically depends on the ecological and economic factors that dictate the evolution of the invasion and subsequent damages (Olson and Roy, 2008). The spread of invasive species usually involves multiple individuals (e.g., land owners, regional government, countries), who may have different perspectives and actions to the invasion.[32] According to Mas-Colell and others' (2009) definition of externality, an individual's control action is a partial public good due to the direct effect on other individual's and social welfare. Therefore, invasive species control distinguishes itself in the integration of the invasive species' dynamics, biological interaction, environmental characteristics, and the participants' dynamic behaviors.

[32] In this paper, individuals are all the land owners who are affected by the invasive species' invasion. Decision makers refer to the social planner and the individual who is controlling the spread. Other individuals, who are not controlling spread at that time, are called participants or other land owners.

Invasive species control is a spatial-dynamic process with multiple affected individuals. Although an individual focuses on his/her private benefit of control, other individuals and society benefit from it, e.g., the delay and reduction of other individual's damages and impairment on the environment. The externality is driven by different spatial scale considerations which drive a wedge between an individual's and the society's damages and consequentially different shadow costs of invaded land. This leads to a divergence between the control incentives of society and individuals, and at last results in a deficiency of the individual's control, which requires regulatory intervention.

For example, Emerald Ash Borer (EAB), an invasive species that originated from Asia, was introduced to the US in cargo imported from Asia in 2002 (McCullough and Usborne, 2011). It first established in southeastern Michigan, but has since been detected in Illinois, Indiana, Iowa, Kentucky, Maryland, Minnesota, Missouri, New York, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, Wisconsin, Ontario and Quebec (McCullough and Usborne, 2011). EAB has caused the death and decline of tens of millions of U.S. ash trees. It can cause the infested ash tree to lose 30 to 50% of canopy 2 years after infestation and die within 3 to 4 years (USDA, 2010).

According to Sydnor et al. (2007), the complete loss of Ohio's urban ash is estimated to be about $7.5 billion. It includes the loss of landscape value of the existing tree, the removal cost of the dead or declining tree, and replacement costs. These losses are considered as the direct damages from EAB in this paper. Another indirect damage, market damage, occurs in the invaded regions at the same time. According to Federal Regulations and Quarantine Notices 7 CFR 301.53-1 through 301.53-9, areas where EAB has been detected may be quarantined. Therefore, ash trees are not permitted to be traded from quarantined areas and other ash products from infested areas are receiving a lower price than from uninvaded areas. Based on EAB's spread dynamics and the environmental conditions of the region, the coordination of each state's control actions play a crucial role in the control process, which requires the understanding of spatial externality and corresponding intervention.

The next section provides a brief review of the invasive-species control literature. Section 3 presents a basic modeling framework. The social optimal control process is illustrated in Section 4 as a benchmark for the comparison between the individual control relay which is set out in section 5. The comparison of individual and social control paths indicates the deficiency of decentralized individual control. Section 6 discusses the feasibility of internalizing the spatial externality of individualistic control through a multiple-source subsidy scheme. Section 7 demonstrates the numerical results and verifies the efficacy of the subsidy. Section 8 summarizes and concludes.

2. Literature Review

The biological growth of the invasion, the discount rate, the control costs, and the damages are necessary factors in the fundamental model of invasive species control (Olson and Roy, 2008). Here a brief survey of the literature is provided with respect to the invasion pattern, damage, control process, and externality. Previous economic research has characterized the degree of invasion in two ways. One is based on population density, in which the effectiveness of control is measured as a reduction in invasive species numbers (Bhat et al., 1993; Bhat et al., 1996; Bicknell et al., 1999;

Horan and Wolf, 2005; Kim et al., 2006; Bhat and Huffaker, 2007; Burnett et al., 2008; Olson and Roy, 2010; Finnoff et al., 2011; Homans and Horie, 2011). Population is generally assumed to follow a growth process within a fixed area, such as a logistic growth process. For example, Burnett et al. (2008) suggest that the authority should make efforts to acquire an estimating number of the Brown Tree Snake existing in Hawaii in order to make an optimal long-term prevention and control decision.

Another way to describe the impact of invasive species is spatial spread represented by an expansion of invaded area (Sharov and Liebhod, 1998; Rich et al., 2005; Hastings et al., 2005; Wilen, 2007; Olson and Roy, 2010; Sims and Finnoff, 2012). In this case, control is manifested as a reduced rate or spatial area of the invasive species spread. Wilen (2007) shows that ignoring the invasion is preferred if the discounted marginal damage is less than marginal control cost; slowing down or eradicating the spread is optimal if the discounted marginal damage is higher than marginal control cost in a spatial dynamic bio-invasion model.

Sharov and Liebhold (1998) investigate the conditions which determine the best spread rate for managing an invasive species with a barrier zone, which focuses on controlling the invasion rate in the area nearest the invasion front. In the case of an infinite rectangular strip, they show the optimal spread rate is determined by the marginal barrier zone control cost and the discounted marginal damage. They find that control may either slow the spread of the species or reverse spread such that the species is eradicated but do not consider the case where the control stops the invasion. In another case of a limited or fixed boundary rectangular area, they find the initial invasion area determines the optimal control strategy. Also they point out "stopping the spread is never an optimal strategy." Due to the concavity of the control cost function and linear damage function in their model, control will swing from zero to the optimal control rate. The model presented herein considers alternative specifications of the control cost and damage functions which allows for stopping, slowing, or eradication of spread in the region. As a result, the damage and control cost (and not the initial invasion) plays a larger role in the control results. [33]

While Sharov and Liebhold (1998) focus on a single decision maker, spatial externalities and the deficiency of individual abating efforts are important issues since species invasions impact large spatial areas with multiple participants.[34] Externalities in invasive species control can be characterized into two types. A negative externality arises when encourages spread from neighboring areas, such as the emigration of pests from high-density to less-density areas (Bhat et al., 1993; Bhat et al., 1996; Bhat and Huffaker, 2007). A positive externality arises when benefits from the individualistic control spillover to others, such as the decrease or delay of other individuals' damages (Wilen, 2007).[35]

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[33] Similar to Sharov and Liebhold (1998), my model also allows for the case where individuals ignore the invasion and perform no control.

[34] This is true of many ecological disturbances. Hansen and Libecap (2004) study the Dust Bowl of the 1930s and reveal the abundance of small farms in the 1930s compromised the control of wind erosion. The limited scale of small farmers encouraged less erosion control than larger farmers. Small farms with intensive cultivation and less erosion control cause increased blowing of sand to the leeward farms and reduce their benefits of control. The collective control necessitated the establishment of soil conservation districts and improved the coordination of farmer's erosion control. In the same way, the number and size of participants will also influence invasive species control.

[35] In some cases, the positive externality may include the uncompensated decrease in prevention cost which non-invaded individuals incur. For example, in the Chicago Sanitary and Shipping canal an electrical barrier has been built to prevent the spread of Asia carps into the Great Lakes (Oregon Sea Grant). If the control of Asian carp is implemented effectively on invaded areas of the river, the cost of preventing invasion into the Great lakes may decrease.

Rich et al. (2005) investigate the negative regional externalities associated with control of foot and mouth disease (FMD) in South America. They find regional control of FMD spread is influenced by the spatial spillover from neighboring regions which perform less control. Their simulation shows how neighbors with low incentive to control encourage the high incentive individuals to switch their high-effort strategy to low-effort. Bhat et al. (1996) provide an overview of three scenarios about controlling nuisance wildlife (beaver) which can migrate from high to low population-density. In scenario one, one parcel owner takes the beaver population level of the neighbor as a second state variable and performs "unilateral management" while another adjacent parcel owner does not control beavers and free-rides on the control of the neighbor. In scenario two, two owners with different optimal control levels may choose zero trapping rates in a non-cooperative process or Pareto efficient trapping rates through a compensating transfer between two owners under a binding cooperative contract. In scenario three, Bhat et al. (1993) show that multiple landowners necessitate a centralized control strategy incorporating the effect of species diffusion on control.[36]

When managing natural resources, internalizing an externality must connect the biological and spatial dispersal features between parcels. Sanchirico and Wilen (1999) investigate effects of the biological and the economic linkages, which originate from the spatial and economic heterogeneity, on the dynamic equilibrium of open access

[36] Bhat and Huffaker (2007) expand the bilateral strategy of control a nuisance and show the instability of ex ante self-enforcing cooperative contracts. The existence of maximum payoffs from breaking the contract after cooperating causes the termination of contract. This termination decision is determined by the trapping technology, the preferred population level, and the discount rate. They propose a variable transfer payment agreement, which is attained through renegotiating and aiming at compensating the owners who gain less with cooperative control.

exploitation. They show that the economic behavior can be influenced by biological systems nested within patches, which can be independent from other patches or partially or fully interacted with other patches. Sanchirico and Wilen (2005) prove that spatially uniform policies (such as a landing tax and tax on effort) on patches with different biological dispersal patterns, result in lower rent, non-optimal effort distribution, and inefficient biomass levels.

Though Wilen (2007) points out the existence of a spatial externality in invasive species control he does not provide a formal analysis. The fundamental reason for the externality is that the social planner and the individual participants differ in concern to the damage caused by an invasive species. As discussed previously, the outbreak of invasive species may cause economic losses and environmental damages (Pimentel et al., 2005). Economic damages represent the pecuniary losses from the reduction in production and market value of commodities and the expense of a remediation cost (not to be confused with control cost). Environmental damages may include health risks to humans and wildlife, the loss of biological diversity, the reduction of ecosystem service, etc. (Daszak et al., 2000). The social planner accounts for all economic damages and environment damages, while the individual considers only his or her economic losses.[37]

Perrings et al. (2002) notes that invasive species control is a public good which depends on the least effective individual participant, the "weakest-link." Wilen (2007)

[37] For example, Horan and Wolf (2005) show that foot and mouth disease, bovine TB (tuberculosis), and other diseases may cause (1) losses due to the death of livestock and the reduction of meat from infected livestock, etc.; (2) loss associated with the imposition of trade sanctions on the disease outbreak regions; (3) threats to human health; and (4) threats to wildlife. The social planner considers these losses as the social damages caused by TB, while an individual only includes his/her own individual economic losses, i.e. reduction of production, decrease in market value and other losses. Bicknell et al. (1999) show similar factors prevent individual livestock producers from eradicating diseases in their own herd.

suggests this externality can be internalized with chained bilateral negotiation. The farthest non-invaded parcel owner, N, may offer his/her neighbor, N-1, a payment to motivate more control and reduce the spread rate, and then the parcel owner N-1 continues to negotiate with N-2, then continue till to parcel owner 1. But the information of spread may limit in a neighborhood range. Therefore, a partial or myopic "chained bilateral negotiation" occurs within the neighborhood areas. Wilen (2007) also points out transactions costs may impede first-best negotiation. To sum up, the invasive species control with multiple participants is not addressed adequately in the literature. In this essay, a control and subsidy scheme is provided with the coordination of authority.

3. Modeling a Species Invasion

Table 4.1
Variables in theoretical model.

Variable	Definition
$x(t)$	A state variable- the invasion area at time t
$\kappa^i[x(t)]$	The percentage of land invaded in parcel i at time t
$u(t)$	A social control variable- the social control rate at time t
$u^i(t)$	Individual i's control rate at time t
$\omega(t)$	A social costate variable- the social shadow cost of an incremental increase in invasion at time t
$\omega^i(t)$	A costate variable of individualistic control- individual i's shadow cost of an incremental increase in invasion at time t
τ_{i-1}	The time of invasion reaching the west border of parcel i
τ_i	The time of invasion reaching the east border of parcel i
τ_{ss}^n	The time of reaching steady-state within parcel n under the individualistic control relay
t_{ss}	The time of reaching steady-state under social control
x_{ss}	The steady-state of invaded area under social control
x_{ss}^n	The steady-state of invaded area under the individualistic control relay

In this paper, the analysis is concentrated on the control of terrestrial invasive species. Although aquatic invasive species have biological spreading characteristics which differ from terrestrial invasive species, the basic control rule is the same as the control of terrestrial invasive species. For convenience, the definition of each variable in the model is summarized in Table 4.1.

3.1 The Invasion Spread and Control Types

Assume *I* individually owned parcels of land in units of square kilometers are adjoined in a rectangular strip area, labeled as 1 to *I* from west to east (see Figure 4.1). The width of the rectangle is normalized to one. Hereafter let "parcel" refer to the single piece of land owned by each individual owner and "region" the total area of *I* parcels. Let $A_i$represent a parcel's length (also the area) owned by owner $i = 1, 2, \dots, I$, and $A = \sum_{i=1}^{I} A_i$. The species invade from west to east along the length of the rectangle. The spread distance at $t_0 = 0$ when the invasion is first detected is x_0, and $x(t)$ is spread distance at time t.

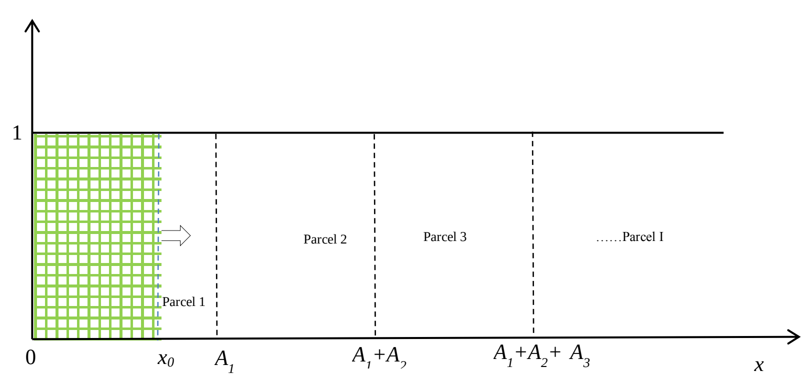

Figure 4.1. Species invasion across multiple management jurisdictions.

The status of each land parcel is described by “not invaded,” i.e., the invasion frontier has not yet reached the western border of parcel i ; “being invaded,” i.e., the invasion has reached and is spreading within parcel i ; or “fully invaded,” i.e., the invasive species has fully spread across parcel i. Assume $\kappa^i[x(t)]$ is the percentage of parcel i’s land invaded at time *t*. Therefore,

$$\kappa^i[x(t)] = \begin{cases} 0 & x(t) < \sum_{j=1}^{i-1} A_j \\ \frac{x(t)-\sum_{j=1}^{i-1} A_j}{A_i} & \sum_{j=1}^{i-1} A_j \leq x(t) < \sum_{j=1}^{i} A_j \\ 1 & x(t) \geq \sum_{j=1}^{i} A_j \end{cases} \tag{4.1}$$

The spread of an invasive species is “a process by which the species expands its range from a habitat in which it currently occupies to one in which it does not” and there are two processes: continuous spread, i.e., a local or short-range dispersal due to the growth of the population; and spread through long-distance dispersal, i.e., a long-range dispersal through human, bird, wind or other mechanisms (Liebhold and Tobin, 2008). Short-range dispersal exhibits a constant spread rate. Long-distance dispersal can result in isolated colonies, which grow and eventually merge into the main population of invasive species. The combination of the two processes (called stratified dispersal) causes spread to accelerate over time (Liebhold and Tobin, 2008). This essay assumes no new introductions and the invaded area increases exponentially which is consistent with a combination of short and long range spreading. Let $g > 0$ be the intrinsic constant spatial spread rate of the invasive species, and the invasion spread as $\frac{dx}{dt} = gx(t)$, i.e., spread occurs exponentially and uniformly across the entire region.

Assume control efforts focused in a barrier zone along the edge of the expanding population front (Sharov and Liebhold, 1998), so the owner can take control actions only when his/her land is being invaded. Thus if a parcel is fully invaded, this owner stops control and the next one initiates control. In this way, the individual control process is akin to a relay. The effective spread under control is $[g - u(t)]x(t)$, where $u(t) \geq 0$ is the spread rate reduction at time t, a control variable. Let $u(t)$ represent the social control rate, $u^i\ (t)$ the individual control rate of landowner i.

The level of control is decided by comparing the present value of flows of damage with control cost. There are three types of control, i.e., slowing, stopping, and reversing the spread of invasion (Liebhold and Tobin, 2008). If the reduction rate of invasive species is less than the natural growth rate $(0 < u(t) < g)$, control efforts slow down but not stop the spread; if the reduction rate above the natural spread rate $(u(t) > g)$ the invaded area decreases; and if $u(t) = g$, the invasion is stopped.

Table 4.2
Possible outcomes of social control.

Case Type	Description	Characteristics
Case 1	Invasion stops within the region	$x_{ss} < \sum_{i=1}^{I} A_i$
Case 2	Fully invaded region	$x_{ss} > \sum_{i=1}^{I} A_i$, stops beyond the region
		$x_{ss} = \infty$, never stopping
Case 3	Eradication	$\lim x_{ss} = 0$

Based on the results of social control, there are three cases for the terminal condition, summarized in Table 4.2. The first case is when the steady-state invaded area is smaller than the region, i.e., it is optimal to preserve a portion of the region from the social planner's perspective. The second case is the eventual complete invasion of the region. This case arises when the steady-state of invaded area is larger than the region, or when no steady-state exists. The third case corresponds to the "reversing" type where the damage of invasion is so high that eradication is the optimal strategy, the steady-state approaches the west border of the region. [38] The difference between the individual and social control path is manifested as different steady-states of invaded area and different times when that steady-state is reached. This essay focuses on the first case since both the individual and social control reaches its steady-state within the region. The other two cases can be derived directly from the first case.[39]

3.2 The Damage and Control Cost

As discussed before, invasive species' spread can cause physical damages to valuable commodities, market damages, and environmental damages. The physical damages refer to the production damage from crop death or produce decline. For example, Rice Water Weevil causes an average of 7% yield loss ($64.05 /acre) in the US (Hummel N., 2009), and about 10%-20% yield loss in the north of China (Yu et al., 2008). Market damage results from the price effect and the restricted market effects. Consumers may

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[38] It is not mathematically possible to get x equal 0, but very small values of x are possible. When x reaches a very small value at which the sustainable spread of the invasive species is not possible, we consider the invasion is eradicated.

[39] In case 2, the whole region is fully invaded regardless of the externality, and only the time when the region becomes fully invaded is different between the individual control and the social control. In this case, the social planner is able to delay the inevitable (McIntosh et al., 2010). In case 3, if it is also optimal for the individual control relay to eradicate the invasion, there is just a time difference between the individual and social control to reverse the invasion back to the west border of the region. But if it is not optimal for the individual control to eradicate the invasion, the difference will be no invasion versus partial invasion.

consider commodities from the region of invasion outbreak as damaged goods resulting in a lower the price. Product bans or quarantines will also limit markets. Due to limited information, the commodities from non-invaded parcels of the region cannot be distinguished from the invaded parcels; therefore, market damages occur to all parcels in the region.

The physical and market damages are shown in Figure 4.2. As invasion occurs, physical damages result in a decline in production captured by an upward shift in the supply curve from S to S'. The market reaction to the invasion is captured by lower demand for commodities from the invaded region and represents a downward shift of demand curve (D to D'). The physical or production effect only impacts invaded landowners, but the market effect impacts the whole region. Environmental damages refer to losses unrelated to the commodity market such as impacts to the ecosystem or human health, which are considered public losses.

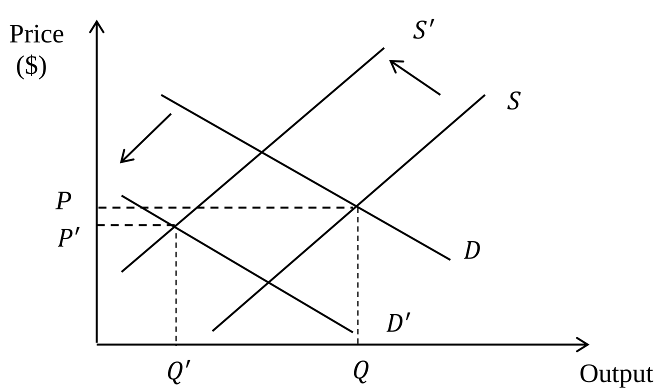

Figure 4.2. The production effect and the market effect.

The damage function captures the physical, market, and environmental damages which are all functions of the size of invasion $x(t)$. The land scales (A_i or A) considered by the individuals i and the society are important factors in individual and the social damages. Let $D[x(t), A]$ represent the social damages caused by invasive species at time t, which is the sum of each land owner's individual economic damages and additional environmental damages that accrue to society. $D^i[x(t), A_i] = D_P^i + D_m^i$ is parcel owner i's individual damage, with $\partial D^i[x(t), A_i]/\partial x > 0$ and $\partial^2 D^i[x(t), A_i]/\partial x^2 \leq 0$ and $x(t)D_{xx}^i(\cdot) + D_{xx}^i(\cdot) > 0$ at any level of invasion $x(t)$. This individual damage function captures the damages at different invasion stage of the parcel, i.e., "noninvaded," only market damage (D_m^i) occurs; "being invaded," physical (D_P^i) and market (D_m^i)damages happen, and "fully invaded," production damage is at a maximum but market damage continues to increase as the invasion spreads. $D^e[x(t)]$ represents environmental damages with $\partial D^e[x(t)]/\partial x > 0$ and $\partial^2 D^e[x(t)]/\partial x^2 \geq$ or ≤ 0. [40] In the essay, we concentrate on the case with a decreasing marginal environmental damage and assume $x(t)D_{xx}^e(\cdot) + D_{xx}^e(\cdot) > 0$ at any level of invasion $x(t)$. Therefore, the social damage is defined as

$$D[x(t), A] = \sum_{i=1}^{I} D^i[x(t), A_i] + D^e[x(t)] \tag{4.2}$$

with $\partial D[x(t), A]/\partial x > 0$ and $\partial^2 D[x(t), A]/\partial x^2 \leq 0$ and $x(t)D_{xx}(\cdot) + D_x(\cdot) > 0$ at any level of invasion $x(t)$.

The control cost is determined by the control rate in this barrier control setting. $c[u(t)]$ and $c\left[u^i(t),\right]$ are the associated social and corresponding individual i's control

[40] The marginal environmental damage may increase, or decrease, or keep constant with respect to the state variable (invading area), which depends on the characteristics of the specific spreading regions.

cost functions respectively. The marginal control cost with respect to control rate is assumed to be the same among individuals and the social planner, with $\partial c(\cdot)/\partial u(t) = \partial c(\cdot)/\partial u^i(t) > 0$, and $\partial^2 c(\cdot)/\partial u(t)^2 = \partial^2 c(\cdot)/\partial u^i(t)^2 > 0$. These cost functions represents the least cost method of control.

4. Social Optimal Control of Invasive Species Spread

4.1 The Social Optimal Control Process – the Benchmark

In case one described in the previous section, the steady-state will be reached within the region and control continues indefinitely. The region area is assumed large enough that the social optimal control process and the individual control relay both reach the steady-state within the region. The social planner's problem is to minimize the sum of social damages and control costs, $D(\cdot) + c(\cdot)$, through the choice of $u(t)$, i.e.,

$$\max_{u(t)} W = \int_0^{\infty} \{R(A) - D[x(t), A] - c[u(t), A]\} e^{-rt} dt \tag{4.3}$$

$$\text{s.t. } \frac{dx}{dt} = [g - u(t)]x(t),$$

$$x(0) = x_o > 0 \text{ given },$$

$$u_{\max} \geq u(t) \geq 0, x(t) \geq 0 .$$

where r is the social discount rate, $R(A)$ is the revenue in the entire region before invasion.

If $\lambda(t)$ is the present value costate variable for the invasion area, the present value Hamiltonian is

$$H[u(t), x(t), \lambda(t)] = e^{-rt}\{R(A) - D[x(t), A] - c[u(t), A]\}$$
$$+\lambda(t)[g - u(t)]x(t) .$$

The nonnegativity constraint on $u(t)$ is included by maximizing the Hamiltonian subject to $u(t) \geq 0$. Let $v(t)$ be the present value Lagrangian multiplier. Hence, the Kuhn-Tucker Lagrangian function is

$$L[u(t), x(t), \lambda(t), v(t)] = H[u(t), x(t), \lambda(t)] + v(t)u(t).$$

The corresponding present value necessary conditions are [41]

$$-e^{-rt}c_u(\cdot^*) - \lambda^*(t)x^*(t) \leq 0 \text{ , } u^*(t) \geq 0 \tag{4.4}$$

$$[-e^{-rt}c_u(\cdot^*) - \lambda^*(t)x^*(t)]u^*(t) = 0 \tag{4.5}$$

$$\frac{d\lambda^*(t)}{dt} = -[g - u^*(t)]\lambda^*(t) + e^{-rt}D_x(\cdot^*) \tag{4.6}$$

$$\frac{dx^*(t)}{dt} = [g - u^*(t)]x^*(t) \tag{4.7}$$

$$x(0) = x_o \tag{4.8}$$

with $v(t)u(t) = 0$ where subscripts indicate partial derivatives.

Let $\omega(t) = e^{rt}\lambda(t)$ be the current costate variable. Then, the current value necessary conditions can be written as

$$-\omega^*(t)x^*(t) - c_u(\cdot^*) \leq 0, u^*(t) \geq 0 \tag{4.4c}$$

$$[-\omega^*(t)x^*(t) - c_u(\cdot^*)]u^*(t) = 0 \tag{4.5c}$$

$$\frac{d\omega^*(t)}{dt} = \left[r - \left(g - u^*(t)\right)\right]\omega^*(t) + D_x(\cdot^*) \tag{4.6c}$$

$$\frac{dx^*(t)}{dt} = [g - u^*(t)]x^*(t) \tag{4.7c}$$

$$x(0) = x_o \tag{4.8c}$$

[41] The superscript asterisk (*) denotes optimal values.

$\omega^*(t)$ is the shadow cost of the invaded area at a given instant in time *t*. In this case, the shadow cost represents the incremental damage of an additional unit of invasion. From Equation (4.4c) and (4.5c), obtain

$$u(t) = \begin{cases} 0 & -\omega^*(t) < \frac{c_u(\cdot^*)}{x^*(t)} \\ u^*(t) & -\omega^*(t) = \frac{c_u(\cdot^*)}{x^*(t)} \\ u_{max} & -\omega^*(t) > \frac{c_u(u_{max})}{x^*(t)} \end{cases} \tag{4.9}$$

There are two extreme cases of invasive species control. If $-\omega^*(t) - \frac{c_u(\cdot^*)}{x^*(t)} < 0$, then $u^*(t) = 0$. This implies the incremental damage is lower than the marginal control cost, and no control is optimal at $x(t)$. If this condition holds at every point of invasion, the damage caused by the invasion is ignored and the invasion spreads following the natural rule through the whole region. If $-\omega^*(t) - \frac{c_u(\cdot^*)}{x^*(t)} > 0$ at any feasible control rate, $u^*(t) = u_{\max}$, where $u_{\max}$ is the maximum feasible control rate.

With an interior solution, the optimal control rate is adjusted with respect to the invasion state to satisfy the optimality condition $\frac{c_u(\cdot^*)}{x^*(t)} = -\omega^*(t)$ for $u(t) > 0$ (from Equation (4.5c)). This equation states that at every time, the marginal control cost equals the incremental damage of invasion area in order to ensure a positive optimal control rate. At steady-state, the marginal control cost at g, $\frac{c_u(g)}{x_{ss}}$, equals $D_x[x_{ss}]/r$ (Equation (4.5c) and (4.6c)), the discounted incremental damage at x_{ss} .[42]

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[42] The infinite strip case of Sharov and Liebhold (1998) can be constructed as an infinite horizon problem and solved using the same current value necessary conditions in equation (4.4c) to (4.8c). The core equation (6) of their paper corresponds to the first-order condition of positive control variable at the steady-state, i.e. $c_u(\cdot) = \frac{D_x(x_{ss})}{r} x_{ss}$. Due to their linear spread function with time, i.e., $\frac{dx}{dt}=g-u$, their discounted marginal benefit of control (or marginal damage at x_{ss}) is $\frac{D_x(x_{ss})}{r}$. It is also reasonable to conclude that the

Solving Equations (4.4c) and (4.5c) also implies when $u^*(t) > 0$

$$\omega^*(t) = -\frac{c_u(\cdot^*)}{x^*(t)} \tag{4.10}$$

Taking the time derivative of (4.10) and using Equation (4.7c) yields

$$\frac{d\omega^*(t)}{dt} = -\frac{c_{uu}(\cdot^*)\frac{du(t)}{dt} - [g - u^*(t)]c_u(\cdot^*)}{x^*(t)} \tag{4.11}$$

Substituting (4.11) into (4.6c), and using (4.7c) and (4.10)

$$\frac{du^*(t)}{dt} = \frac{rc_u(\cdot^*) - D_x(\cdot^*)x^*(t)}{c_{uu}(\cdot^*)} \tag{4.12}$$

$$= \frac{rc_u(\cdot^*) - \{\sum_{i=1}^{I} D_x^i[x^*(t), A_i] + D_x^e(x^*(t))\}x^*(t)}{c_{uu}(\cdot^*)}$$

The optimized dynamic system is described by the following coupled nonlinear system of differential equations:

$$\frac{du^*(t)}{dt} = \frac{rc_u(\cdot^*) - D_x(\cdot^*)x^*(t)}{c_{uu}(\cdot^*)} = \frac{rc_u(\cdot^*) - \{\sum_{i=1}^{I} D_x^i[x^*(t), A_i] + D_x^e(x^*(t))\}x^*(t)}{c_{uu}(\cdot^*)} \tag{4.12}$$

$$\frac{dx^*(t)}{dt} = [g - u^*(t)]x^*(t) \tag{4.7c}$$

The slope of the isocline of $\frac{du(t)}{dt} = 0$ is

$$\left.\frac{du}{dx}\right|_{\frac{du^*(t)}{dt}=0} = \frac{\overbrace{D_{xx}(\cdot^*)x^*(t) + D_x(\cdot^*)}^{+}}{\underbrace{rc_{uu}(\cdot^*)}_{+}} > 0 \tag{4.13}$$

as $x(t)D_{xx} + D_x(\cdot) > 0$ assumed before.

Figure 4.3 presents a phase diagram of this system. The $\frac{dx^*(t)}{dt} = 0$ isocline, is realized by equating the reducing rate and the invasive species natural growth rate

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discounted marginal damage, $\frac{D_x(x_{ss})}{r}$, may equal the marginal control cost at the zero spread rate, i.e. $u = g$, in some circumstances. In general, before the steady-state, the dynamic optimal rule may portray the control rate path as an increasing or decreasing process, which depends on the initial invasion. However, after the steady-state time, t_{ss}, the real spread rate will be zero.

($u^*(t) = g$). As the directional arrows indicate, around the $dx(t)/dt = 0$ isocline (the dashed line), if $u(t) > g$, $dx(t)/dt < 0$ and if $u(t) < g$ then $dx(t)/dt > 0$. Similarly, for points above the $du(t)/dt = 0$ isocline (the solid line), $rc_u(\cdot^*) > D_x(\cdot^*)x^*(t)$, implying $du(t)/dt > 0$, and for points below the isocline, $du(t)/dt < 0$. These off-equilibrium conditions result in a saddle-point stable trajectory, indicated as the dotted line.

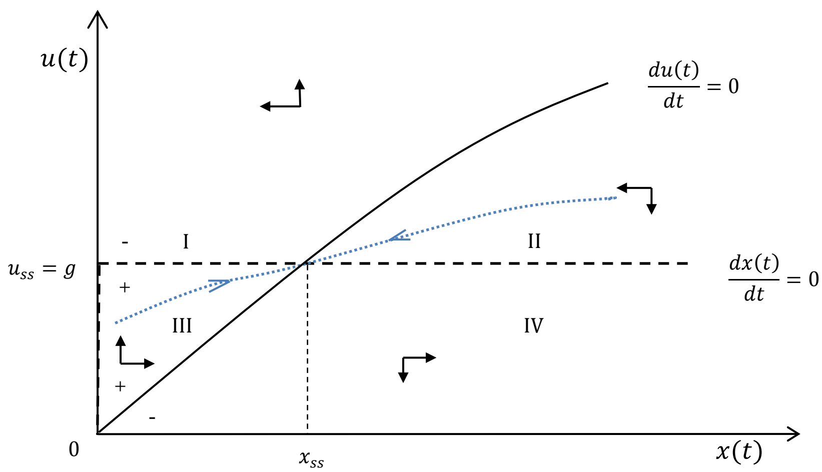

Figure 4.3. Phase plane diagram of the system: $\frac{dx(t)}{dt} = 0$ and $\frac{du(t)}{dt} = 0$.

Two isoclines divide the state space into four isosectors labeled as I to IV. Isosectors II and III are convergent while isosectors I and IV are divergent. The equilibrium (x_{ss}, u_{ss}) would be a saddle point. In isosector I, control is increased as the invasion approaches eradication. In isosector IV, decision makers give up on control as the area becomes fully invaded. Isosectors II and III each contain a trajectory (the dotted line) which converges to (x_{ss}, u_{ss}). These two separatrices in Figure 4.3 define the optimal solution trajectories for this infinite horizon problem where partial invasion is optimal. The optimal-control feedback policy for this system $u^*(t) = u^*\big(x(t)\big)$ specifies the optimal reduction rate corresponding to any given invasion level $x(t)$.

Finally, the steady-state is determined directly from Equation (4.12) and Equation (4.7c) as

$$x_{ss} = \frac{rc_u(g)}{D_x(x_{ss})} \tag{4.14}$$

As Equation (4.14) shows, the steady-state invasive species invaded area is positively related to the discount rate, r, and marginal control cost, $c_u(\cdot)$, but negatively related to marginal damage, $D_x(\cdot)$. In other words, an increase in the discount rate, which implies people care less about the future, leads to a larger steady-state x_{ss}. If marginal control cost with respect to $u(t)$ increase, less control measures are preferred which results in higher x_{ss}. On the other hand, higher marginal damages associated with invasive species induce a lower steady- state x_{ss} .

4.2 The Costate Variable in Invasive Species Control

The costate variable, $\omega^*(t)$, represents the shadow cost of an incremental increase in invasion area (or the marginal value of uninvaded land). The costate variable and the state variable play an important role in the optimal control path. Understanding the relation between them reveals the tradeoff associated with control and highlights the fundamental reasons for different invasive species control results. In this section, the relation between the costate variable and the state variable is discussed. Then, the components of the costate variable are analyzed.

From Equation (4.4c) and (4.5c), $-c_u(\cdot^*) - \omega^*(t)x^*(t) = 0$ for $u^*(t) > 0$. Using the implicit function theorem, get

$$\frac{\partial\omega^*(t)}{\partial x} = -\frac{\omega^*(t)}{x^*(t)} > 0 \tag{4.15}$$

In Zone III of Figure 4.3, the initial invasion area is small and the steady-state is reached within the region, therefore the invasion area grows with time t, $\omega^*(t)$ increases as the invasion increases, i.e., $\frac{d\omega^*(t)}{dt} > 0$ in Zone III. While in Zone II, the invasion area diminishes due to a high rate of control. Here $\omega^*(t)$ decreases as the invasion decreases, i.e., $\frac{d\omega^*(t)}{dt} < 0$. Based on the equation of motion for the costate variable, the optimal control process is interpreted in Section 4.3.

Accounting for the components of the costate variable and following Lyon (1999), start with Equation (4.6c)

$$\frac{d\omega^*(t)}{dt} = \big[r - \big(g - u^*(t)\big)\big]\omega^*(t) + D_x(\cdot^*) \tag{4.16}$$

with $\omega^*(t_{ss})$ given by the steady-state condition that

$$\omega^*(t_{ss}) \ = \frac{-D_x(x_{ss})}{r} \tag{4.17}$$

Equation (4.6c) can be written

$$\frac{d\omega^*(t)}{dt} - \big[r - \big(g - u^*(t)\big)\big]\omega^*(t) = D_x(\cdot^*) \tag{4.18}$$

Adding $-t\frac{du^*(t)}{dt}\omega^*(t)$ to both sides of Equation (4.18) and the general solution for this differential equation is

$$\begin{aligned}\omega^*(t) &= e^{[r-(g-u^*(t))]t}\left\{\int e^{-[r-(g-u^*(t))]t}\left[D_x(\cdot^*) - t\frac{du^*(t)}{dt}\omega^*(t)\right]dt + K\right\} \\ &= e^{[r-(g-u^*(t))]t}\left\{\int e^{-[r-(g-u^*(t))]t}\left[D_x(\cdot^*) + t\frac{du^*(t)}{dt}\frac{c_u(\cdot^*)}{x^*(t)}\right]dt + K\right\}\end{aligned} \tag{4.19}$$

where K is a constant of integration. Let

$$F(\mathrm{t}) = \int e^{-[r-(g-u^*(t))]t}\left[D_x(\cdot^*) + t\,\frac{du^*(t)}{dt}\frac{c_u(\cdot^*)}{x^*(t)}\right]dt \tag{4.20}$$

Then, Equation (4.19) can be simplified to

$$\omega^*(t) = e^{[r-(g-u^*(t))]t}[F(t) + K] \tag{4.21}$$

and

$$\omega^*(t_{ss}) = e^{\left[r-\left(g-u^*((t_{ss}))\right)\right](t_{ss})}\,[F(t_{ss}) + K] \tag{4.22}$$

Since at the steady-state, $u^*(t_{ss}) = g$, then

$$K = e^{-\mathrm{r}t_{ss}}\,\omega^*(t_{ss}) - F(t_{ss}) \tag{4.23}$$

Therefore,

$$\omega^*(t) = e^{[r-(g_n-u^*(t))]t}[e^{-\mathrm{r}t_{ss}}\omega^*(t_{ss}) + F(\mathrm{t}) - F(t_{ss})\,] \tag{4.24}$$

$$= \overbrace{e^{-r(t_{ss}-t)-(g-u^*(t))t}\omega^*(t_{ss})}^{\text{The instant effect}}$$

$$\underbrace{-e^{[r-(g-u^*(t))]t}\int_t^{t_{ss}} e^{-[r-(g-u^*(t))]s}\left\{D_x(\cdot^*) + s\left[\frac{rc_u(\cdot^*)}{x^*(t)} - D_x(\cdot^*)\right]\frac{c_u(\cdot^*)}{c_{uu}(\cdot^*)}\right\}ds}_{\text{The cumulative effect}}$$

The effective discount rate is a combination of the normal discount rate, the natural spread rate of the invasive species, and the control rate, i.e., $r - [g - u^*(t)]$. The effective discount rate can be positive, $r > [g - u^*(t)]$, negative, $r < [g - u^*(t)]$, and zero, $r = [g - u^*(t)]$. The value of the costate variable at t, $\omega^*(t)$, is composed of two components. One is an instant effect of invasion, i.e, the present value of uninvaded land after the invasion has been stopped (costate variable at the steady-state), and the other is a cumulative effect of damage and control cost, i.e., the discounted value of damage and control cost flow for an incremental increase in invaded area from t to t_{ss}.

The first component, $e^{-r(t_{ss}-t)-(g-u^*(t))t}\omega^*(t_{ss})$, integrates the normal discounting of time, $e^{-r(t_{ss}-t)}$, and the biological discount rate $e^{-(g-u^*(t))t}$. Similar to "the Scarcity Effect" in the optimal control problem of exhaustible resources (Lyon, 1999), this first component captures the scarcity value of uninvaded land - an exhaustible resource. The instant effect of invasion only includes the current time's damage, no future effect, which therefore is called an instant damage effect. The absolute value of the instant effect component increases with time and it approaches the steady-state value of $\frac{-D_x(x_{ss})}{r}$ as t approaches t_{ss}.[43] The diminishing instant effect induces less control in early periods.

The other component of the costate variable represents the cumulative effect of a current incremental invasion at t on damage and control cost from t to t_{ss}, i.e., $-e^{[r-(g-u^*(t))]t}\int_t^{t_{ss}} e^{-[r-(g-u^*(t))]s}\left\{D_x(\cdot^*) + s\left[\frac{rc_u(\cdot^*)}{x^*(t)} - D_x(\cdot^*)\right]\frac{c_u(\cdot^*)}{c_{uu}(\cdot^*)}\right\}ds$. It corresponds "the Cost Effect" in the natural resource optimal control problem (Lyon, 1999). This cumulative effect is becoming less as t approaches t_{ss}, i.e., due to the negativity of this component, the value of this component is increasing to zero, and the absolute value is decreasing. Therefore, the cumulative effect gives more weight to damages early in the invasion and induces high early control rate. The instant effect provides more weight on later control, while the cumulative effect causes more attention on earlier control. These two opposing flows interact together to decide the optimal control path.

[43] Because $\omega^*(t) < 0$, a decreasing costate variable implies an increasing $\omega^*(t)$ in absolute value.

4.3 Invasive Species Control and the Change of Costate Variable

The motion of the optimal control rate, $u(t)$, is related with the state variable, $x(t)$, and the costate variable, $\omega^*(t)$. From Equations (4.4c) and (4.5c), $-c_u(\cdot^*) - \omega^*(t)x^*(t) = 0$ when $u^*(t) > 0$. Taking $\omega^*(t) \leq 0,\ x^*(t) \geq 0,$ and $c_{uu}(\cdot) > 0$, then using the implicit function theorem, get

$$\frac{\partial u^*(t)}{\partial \omega^*(t)} = -\frac{x^*(t)}{c_{uu}(\cdot)} < 0 \tag{4.25}$$

and

$$\frac{\partial u^*(t)}{\partial x^*(t)} = -\frac{\omega^*(t)}{c_{uu}(\cdot)} > 0 \tag{4.26}$$

Also from Equations (4.4c) and (4.5c), when $u^*(t) > 0$,

$$u^*(t) = c_u^{-1}\big(-\omega^*(t)x^*(t)\big) \tag{4.27}$$

Totally differentiate Equation (4.27),

$$du^*(t) = -c_{uu}^{-1}(\cdot)x^*(t)d\omega^* - c_{uu}^{-1}(\cdot)\omega^*(t)dx^* \tag{4.28}$$

Therefore, the motion of control rate is determined by the combined effect of costate variable and state variable. Equation (4.25) implies if at a given invasion point the decision maker values the future damages of the incremental invasion less, the control will be less, i.e., as the costate variable increases, the control rate decreases ceteris paribus.[44] But the invasion's spread has an increasing effect on the control rate, shown in Equation (4.26). As discussed above, the optimal costate variable may increase as the invasion expands. However, the control rate increases, when $-c_{uu}^{-1}(\cdot)x^*(t)d\omega^* - c_{uu}^{-1}(\cdot)\omega^*(t)dx^* > 0$, Equation (4.28). That implies

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[44] Since the costate variable is negative, an increase in the costate variable implies the absolute value is decreasing.

$$d\omega^* < -\frac{\omega^*(t)}{x^*(t)}dx^* \tag{4.29}$$

In case one (the steady-state reached within the region), when the initial invasion area is small ($x_0 < x_{ss}$), the optimal control process implies $dx^* > 0$, then $-\frac{\omega^*(t)}{x^*(t)}dx^* > 0$. As long as $d\omega^* < -\frac{\omega^*(t)}{x^*(t)}dx^*$, the control rate is increasing. When the initial invasion area is above the steady-state, the optimal control process implies $dx^* < 0$, then $-\frac{\omega^*(t)}{x^*(t)}dx^* < 0$. As long as $d\omega^* > -\frac{\omega^*(t)}{x^*(t)}dx^*$, the control rate is decreasing.

From Equation (4.11) and using Equation (4.10) gets

$$\frac{du(t)}{dt} = -\frac{\frac{d\omega^*(t)}{dt}x^*(t) - [g - u^*(t)]c_u(\cdot^*)}{c_{uu}(\cdot^*)}$$

$$= -\frac{x^*(t)\left\{\frac{d\omega^*(t)}{dt} + [g - u^*(t)]\omega^*(t)\right\}}{c_{uu}(\cdot^*)} \tag{4.30}$$

If the control rate is increasing over time, i.e., $\frac{du(t)}{dt} > 0$, it must be true that $\frac{d\omega^*(t)}{dt} + [g - u^*(t)]\omega^*(t) < 0$. Substituting equation (4.6c), yields the following condition for the costate variable

$$r\omega^*(t) + D_x(\cdot^*) < 0 \tag{4.31}$$

That implies

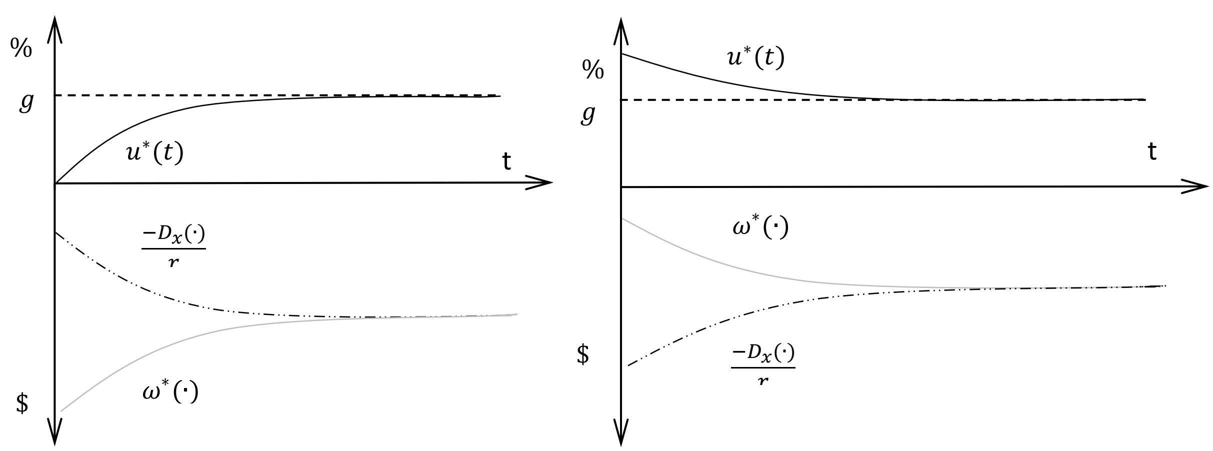
$$\omega^*(t) < \frac{-D_x(\cdot^*)}{r} \tag{4.32}$$

In contrast, if the control rate is decreasing over time, i.e., $\frac{du(t)}{dt} < 0$, the costate variable must be

$$\omega^*(t) > \frac{-D_x(\cdot^*)}{r} \tag{4.33}$$

In Figure 4.4, the controls of invasive species spread are shown as two different converging paths, a small initial invasion area ($x_0 < x_{ss}$), and a large initial invasion area ($x_0 > x_{ss}$). The changing control rate and the costate variable in Figure 4.4a corresponds to the optimal control process of Zone III of Figure 4.3, i.e., a small initial invasion. In that isosector, $\frac{du^*(t)}{dt} > 0$ only when $\omega^*(t) < \frac{-D_x(\cdot^*)}{r}$ and $d\omega^* < -\frac{\omega^*(t)}{x^*(t)}dx^*$, the control follows the trajectory (the dotted line of Figure 4.3) which converges to (x_{ss}, u_{ss}). If $\omega^*(t) > \frac{-D_x(\cdot^*)}{r}$, the control deviates from Zone III to Zone IV.

If the initial invasion area is above the steady-state, the optimal control process is in Zone II of Figure 4.3, which corresponds to Figure 4. 4b. Following the same logic, if $\omega^*(t) > \frac{-D_x(\cdot^*)}{r}$ the control rate is decreasing with respect to t, and the steady-state is reached. If $\omega^*(t) < \frac{-D_x(\cdot^*)}{r}$, the control deviates from Zone II to Zone I in Figure 4.3.



(a) A Small initial invasion area (b) A large initial invasion area
Figure 4.4. The trajectory of optimal control rate and costate variable of case one.

5. Dynamic Control of Invasive Species under Individual Land Ownership

Without regulatory intervention, the individual land owner will take control actions only with respect to his/her own interest. This individual level of control will be less than the social optimal control. The deficiency of individual control results from the nature of invasive species control - individual cost but partially public benefit. When the invasion is found within parcel i, the land owner chooses a level of control at each point of time to minimize the present value of his/her own individual damage and control cost flow from now to the future. If owner i's steady-state invaded area is larger than parcel i, he/she stops any control once parcel i becomes fully invaded but continues suffering the damage from full invasion. Assume τ_0 ($\tau_0 = 0$) is the time the invasive species is first discovered on parcel 1 and the individualistic control relay starts. For $i > 1$, τ_{i-1} is the time at which parcel i-1 becomes fully invaded and its owner stops any controls beyond the border. At this point (τ_{i-1}), the invasion initially occurs at parcel i and the individual control relay transfers to owner i,

$$x(\tau_{i-1}) = \begin{cases} x_0 & i = 1 \\ \sum_{j=1}^{i-1} A_j & i > 1 \end{cases} \tag{4.34}$$

where x_0 is given.

Since the individual can only control the spread of invasive species within his/her parcel, the control starts at the west border and ends at the east border. Because the market damage occurs on all parcels (noninvaded and invaded) in an invaded region, individuals initially suffer market damage before the parcel is invaded. For example, the decreasing price of output from an invaded region causes an economic loss to all parcel owners in the invaded region. But when invasion spreads onto the parcel this owner also starts to incur physical damage which reaches a maximum when fully invaded. Following complete invasion, market damage continues to increase as invasion spreads in the region and physical damage remains constant.

Following this individual control process, each parcel owner's individual control is one turn of an individual spatial control relay. Assume individuals are rational with perfect information, they can calculate the time they start and stop the control.[45] Each parcel owner's control starts at τ_{i-1}, which is decided by the previous controls. However, these previous controls do not change the following individual's control path as a given initial condition. Nevertheless, the controls of the following parcel owners determine individual *i*'s terminal time τ_i, being regarded as a transversality condition through an anticipated future damage.

The private optimum control strategy is solved as a chain of individual optimal control problems. Links between individual control problems are handled through initial conditions and terminal salvage values. An individual's initial condition reflects the control decision of all previously invaded individuals. The salvage value represents an individual's anticipation of future damages given all subsequent individuals behave optimally. Individual control over the course of the invasion is found through backward induction where the optimal control path of the individual that stops spread (the steady-state individual) determines the terminal salvage value of the preceding individual's control problem. This procedure is repeated to find all the control decisions from the steady-state individual to the initially invaded individual.

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[45] In this study, the individuals are assumed to be rational, i.e., all individuals minimize his/her own control cost and damage.

5.1 The Control of an Individual Owner Reaching the Steady-State

Assume the steady-state is reached within parcel *n*, $n \in [1, I]$. Parcel *n* is facing an infinite horizon optimal control problem since control must be exerted indefinitely to keep invaded area at steady-state. In contrast, the land parcels before this steady-state parcel, denoted as $q \in [1, n-1]$, are characterized by a fixed terminal state, $x(\tau_q) = \sum_{j=1}^{q} A_j$, and free terminal time optimal control problem. Let the analysis work backward starting with the control decision on parcel n, whose initial condition is described by the present value of damages occur before invasion on parcel *n* as

$$s_0^n[x(\tau_{n-1})] = \sum_{j=1}^{n-1} \int_{\tau_{j-1}}^{\tau_j} \{-D^n[x(t), A_n]\} e^{-rt} dt$$

$$= \int_{\tau_0}^{\tau_{n-1}} \{-D^n[x(t), A_n]\} e^{-rt} dt \tag{4.35}$$

When the invasion reaches the west border of parcel *n*, parcel *n*'s owner solves the problem,

$$\max_{u^n(t)} W^n = \int_{\tau_{n-1}}^{\infty} \{R(A_n) - D^n[x(t), A_n] - c[u^n(t)]\} e^{-rt} dt + s_0^n[x(\tau_{n-1})] \tag{4.36}$$

$$\text{s.t. } \frac{dx}{dt} = [g - u^n(t)]x(t) \ ,$$

$$x(\tau_{n-1}) = \begin{cases} x_o & n = 1 \\ \sum_{j=1}^{n-1} A_j & n > 1 \end{cases},$$

$$u_{\max}^n \geq u^n(t) \geq 0 \ , x(t) \geq 0.$$

If $\omega^n(t)$ is the current value costate variable and $\nu^n(t)$ is the Lagrangian multiplier, the current value Kuhn-Tucker Lagrangian function is

$$L^{nc}[u^n(t), x(t), \omega^n(t), \nu^n(t)] = H^n[u^n(t), x(t), \omega^n(t)] + \nu^n(t) u^n(t)$$

where

$$H^n[u^n(t), x(t), \omega^n(t)] = \{R(A_n) - D^n[x(t), A_n] - c[u^n(t)]\}$$
$$+\omega^n(t)[g - u^n(t)]x(t)$$

is the current value Hamiltonian. The corresponding current value necessary conditions can be written as

$$-c_{u^n}(\cdot^*) - \omega^{n*}(t)x^*(t) \leq 0,\ u^{n*}(t) \geq 0 \tag{4.37}$$

$$[-c_{u^n}(\cdot^*) - \omega^{n*}(t)x^*(t)]u^{n*}(t) = 0 \tag{4.38}$$

$$\frac{d\omega^{n*}(t)}{dt} = \left[r - \left(g - u^{n*}(t)\right)\right]\omega^{n*}(t) + D_x^n(\cdot^*) \tag{4.39}$$

$$\frac{dx^*(t)}{dt} = [g - u^{n*}(t)]x^*(t) \tag{4.40}$$

$$x(\tau_{n-1}) = \begin{cases} x_o & n = 1 \\ \sum_{j=1}^{n-1} A_j & n > 1 \end{cases} \tag{4.41}$$

For $u^{n*}(t) \geq 0$, Equation (4.38) implies

$$c_{u^n}(\cdot^*) = -\omega^{n*}(t)x^*(t) \tag{4.42}$$

and then

$$\omega^{n*}(t) = -\frac{c_{u^n}(\cdot^*)}{x^*(t)} \tag{4.43}$$

Taking the time derivative of (4.43) and using (4.40) yields

$$\frac{d\omega^{n*}(t)}{dt} = -\frac{c_{u^n u^n}(\cdot^*)x^*(t)\frac{du^n(t)}{dt} - \frac{dx^*(t)}{dt}c_{u^n}(\cdot^*)}{(x^*(t))^2}$$

$$= -\frac{c_{u^n u^n}(\cdot^*)\frac{du^n(t)}{dt} - [g - u^{n*}(t)]c_{u^n}(\cdot^*)}{x^*(t)} \tag{4.44}$$

Substituting Equation (4.44) into Equation (4.39), and using Equation (4.43), obtain

$$\frac{du^{n*}(t)}{dt} = \frac{rc_{u^n}(\cdot^*) - D_x^n(\cdot^*)x^*(t)}{c_{u^n u^n}(\cdot^*)} \tag{4.45}$$

Individual n's optimal dynamic control is described by the following coupled nonlinear system of differential equations

$$\frac{du^{n*}(t)}{dt} = \frac{rc_{u^n}(\cdot^*) - D_x^n(\cdot^*)x^*(t)}{c_{u^n u^n}(\cdot^*)} \tag{4.45}$$

$$\frac{dx^*(t)}{dt} = [g - u^{n*}(t)]x^*(t) \tag{4.40}$$

This system of differential Equation is the same as the social one except for $D_x^n(\cdot^*) < D_x(\cdot^*)$. As in the social optimal control path, it can be shown that the slope of the $du^n(t)/dt = 0$ isocline is positive,

$$\left.\frac{du^n}{dx}\right|_{\frac{du^{n*}(t)}{dt}=0} = \frac{\overbrace{D_{xx}^n(\cdot^*)x^*(t) + D_x^n(\cdot^*)}^{+}}{\underbrace{rc_{u^n u^n}(\cdot^*)}_{+}} > 0 \tag{4.46}$$

For the $\frac{dx^*(t)}{dt} = 0$ isoclines, the reducing rate equals the invasive species' natural spread rate, i.e, $u^{n*}(t) = g$. This isoline , $\frac{dx^*(t)}{dt} = 0$, is a horizontal line with $\left.\frac{du^n}{dx}\right|_{\frac{dx^*(t)}{dt}=0} = 0$.

τ_{ss}^n corresponds to the time at which the individual control process reaches the steady-state within the land parcel n, x_{ss}^n, following the individual control relay of the land owners from *1* to n. Finally, the steady-state is determined directly from Equations (4.45) and (4.40) as

$$x_{ss}^n = \frac{rc_{u^n}(g)}{D_x^n(\cdot^*)} \tag{4.47}$$

Due to the characteristics of damage function and control cost function, $D_x^n(\cdot^*) < D_x(\cdot^*)$ and $x_{ss}^n > x_{ss}$. This will be shown formally in section 5.3 (see Lemma 4.1).

5.2 The Control of the Individual Owners before the Steady-State

Let $s_0^q\left[x\left(\tau_{q-1}\right)\right]$ and $s_1^q\left[x\left(\tau_q\right)\right]$be the damages suffered by land owner q before being invaded (τ_0 to τ_{q-1}) and after being fully invaded (τ_q to ∞)

$$s_0^q\left(x\left(\tau_{q-1}\right)\right) = \int_0^{\tau_{q-1}}\left\{-D^q\left[x(t), A_q\right]\right\}e^{-rt}dt \tag{4.48}$$

$$s_1^q\left(x\left(\tau_q\right)\right) = \int_{\tau_q}^{\tau_{ss}^n}\left\{-D^q\left(x(t), A_q\right)\right\}e^{-r\left(t-\tau_q\right)}d + \int_{\tau_{ss}^n}^{\infty}\left[-D^q\left(x_{ss}^n, A_q\right)\right]e^{-r\left(t-\tau_q\right)}dt$$

$$= \int_0^{\tau_{ss}^q}\left\{-D^q\left(x(t), A_q\right)\right\}e^{-rt}dt + \frac{\left[-D^q\left(x_{ss}^n, A_q\right)\right]e^{-r\tau_{ss}^q}}{r} \tag{4.49}$$

where τ_{ss}^q represents the time between individual q becoming fully invaded and the individual control relay reaching the steady-state: $\tau_{ss}^n = \tau_q + \tau_{ss}^q$.

The salvage damage, $s_1^q\left(x\left(\tau_q\right)\right)$, consists of two time periods. The first time period is from parcel q being fully invaded to the time the individual control steady-state is reached, τ_q to τ_{ss}^n ; and during this period the market damage still increases but the production damage stays fixed. The other period extends from the time steady-state is reached to infinity, τ_{ss}^n to ∞ ; and during this period, a constant flow of physical and market damages accrue to infinity. Individual q takes the control decisions of other parcel owners as given, and makes the optimal control decision to solve

$$\max_{u^q(t)} W^q = \int_{\tau_{q-1}}^{\tau_q}\left\{R(A_q) - D^q\left[x(t), A_q\right] - c\left[u^q(t)\right]\right\}e^{-rt}dt$$

$$+s_0^q\left[x\left(\tau_{q-1}\right)\right] + e^{-r\tau_q}s_1^q\left[x\left(\tau_q\right)\right] \tag{4.50}$$

$$\text{s.t.}\ \frac{dx}{dt} = \left[g - u^q(t)\right]x(t),$$

$$x\left(\tau_{q-1}\right) = \begin{cases} x_o & q = 1 \\ \sum_{j=1}^{q-1} A_j & q > 1 \end{cases},$$

$$u_{\max}^{q} \geq u^{q}(t) \geq 0,\ x(t) \geq 0,\ x(\tau_q) = \sum_{j=1}^{q} A_j \text{ , } \tau_q \text{ is free.}$$

The Hamiltonian and Kuhn-Tucker current Lagrangian function are similar to individual n. From (4.50), the current value necessary conditions can be written as

$$-c_{u^q}(\cdot^*) - \omega^{q*}(t)x^*(t) \leq 0,\ u^{q*}(t) \geq 0 \tag{4.51}$$

$$[-c_{u^q}(\cdot^*) - \omega^{q*}(t)x^*(t)]u^{q*}(t) = 0 \tag{4.52}$$

$$\frac{d\omega^{q*}(t)}{dt} = \left[r - \left(g - u^{q*}(t)\right)\right]\omega^{q*}(t) + D_x^q(\cdot^*) \tag{4.53}$$

$$\frac{dx^*(t)}{dt} = [g - u^{q*}(t)]x^*(t) \tag{4.54}$$

$$x(\tau_{q-1}) = \begin{cases} x_o & q = 1 \\ \sum_{j=1}^{q-1} A_j & q > 1 \end{cases} \tag{4.55}$$

Individual q's control problem differs from individual n in that individual q has the additional choice variable τ_q. This requires the following current value transversality condition

$$R(A_q) - D^q\left[x^*(\tau_q), A_q\right] - c\left[u^{q*}(\tau_q)\right] + \omega^{q*}(\tau_q)\left[g - u^{q*}(\tau_q)\right]x^*(\tau_q)$$
$$-rs_1^q\left[x(\tau_q)\right] = 0 \tag{4.56}$$

This transversality condition provides the requirement for the individual to decide the optimal time to his/her stop control and suffer a fully invasion

For $u^{q*}(t) \geq 0$, Equation (4.52) implies

$$\omega^{q*}(t) = -\frac{c_{u^q}(\cdot^*)}{x^*(t)} \tag{4.57}$$

Taking the time derivative of (4.57) and using (4.54) yields

$$\frac{d\omega^{q*}(t)}{dt} = -\frac{c_{u^q u^q}(\cdot^*)\frac{du^q(t)}{dt} - [g - u^{q*}(t)]c_{u^q}(\cdot^*)}{x^*(t)} \tag{4.58}$$

Substituting (4.58) into (4.53), and using (4.57), obtains

$$\frac{du^{q*}(t)}{dt} = \frac{rc_{u^q}(\cdot^*) - D_x^q(\cdot^*)x^*(t)}{c_{u^q u^q}(\cdot^*)} \tag{4.59}$$

Therefore the optimaized system is described by the coupled nonlinear system of differential equations,

$$\frac{du^{q*}(t)}{dt} = \frac{rc_{u^q}(\cdot^*) - D_x^q(\cdot^*)x^*(t)}{c_{u^q u^q}(\cdot^*)} \tag{4.59}$$

$$\frac{dx^*(t)}{dt} = [g - u^{q*}(t)]x^*(t) \tag{4.54}$$

and the transversality condition in equation (4.56).

It can be shown that the slope of the isocline of $du^q(t)/dt = 0$ is positive,

$$\left.\frac{du^q}{dx}\right|_{\frac{du^{q*}(t)}{dt}=0} = \frac{\overbrace{D_{xx}^q(\cdot^*)x^*(t) + D_x^q(\cdot^*)}^{+}}{\underbrace{rc_{u^q u^q}(\cdot^*)}_{+}} > 0 \tag{4.60}$$

$\omega^{q*}(t)$ $\left(\text{or } \omega^{n*}(t)\right)$ is the shadow price of invasion area for parcel $q(n)$. It is different from $\omega^*(t)$ of the social control process. $\omega^{q*}(t)$ $\left(\text{or } \omega^{n*}(t)\right)$ represents only parcel q's (or n's) valuation of the incremental damage of his/her own parcel, while $\omega^*(t)$ values the incremental damage of the whole region- the scope difference. From the perspective of an individual parcel owner, at every instant time where there is positive control, the marginal control cost should equal the shadow price of invasion area only for parcel q or n. Therefore, the individual control relay is different from the social control. Later it will be shown that the control trajectory of the individual control relay is lower at the same point in the invasion and the invasion state variable trajectory is larger at the same point in time.

5.3 The Comparison of the Individual Control and Social Optimal Control

Compared to the social optimal control scheme, the individual isocline $du^i(t)/dt = 0\,(i = 1, \cdots, I)$ is underneath the social isocline $du(t)/dt = 0$. That leads to the Lemma 4.1.

Lemma 4.1 The individual control scheme, in which the landowner only considers damages that accrue on his/her parcel when making control decisions, leads to a larger invaded area.[46]

As shown in equation (4.14) and (4.47), the social steady-state is reached at the point where the marginal control cost equals $-\frac{xD_x(\cdot)}{r}$; the individual's damage is a part of the social one, i.e., $-\frac{xD_x^n(\cdot)}{r}$ is smaller than $-\frac{xD_x(\cdot)}{r}$ at any given x in absolute value, and therefore the steady-state of invasion area under the individual control relay is always larger than the social one (see figure 4.5).

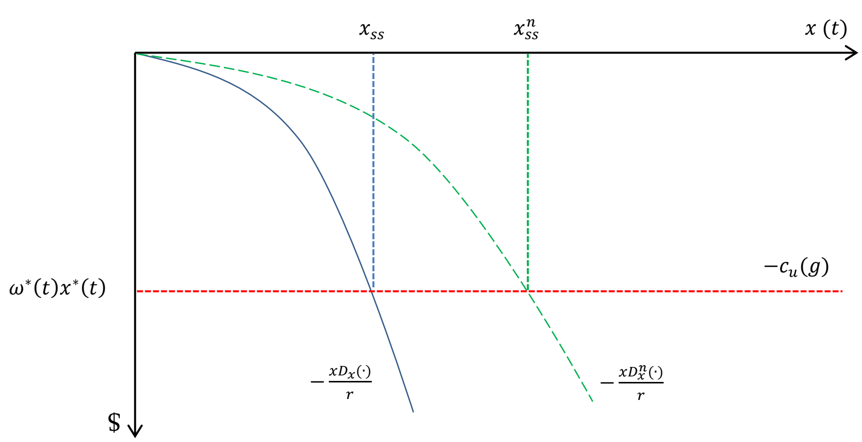

Figure 4.5. Social steady-state versus individual steady-state.

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[46] See the Appendix C for a detailed proof of this result.

To illustrate these findings consider the hypothetical scenario in Fig. 4.6. A steady-state invaded area is shown to be reached within the region (case one). Specifically the social steady-state of invasion area (x_{ss}) is just above A_1 but within A_2. The individual isoclines $du^1(t)/dt = 0$ and $du^2(t)/dt = 0$ are always under the social isocline $du(t)/dt = 0$, the individual control rate at a given invasion area is smaller than the social one, $u^{1*}(x) \leq u^*(x)$ and $u^{2*}(x) \leq u^*(x)$.

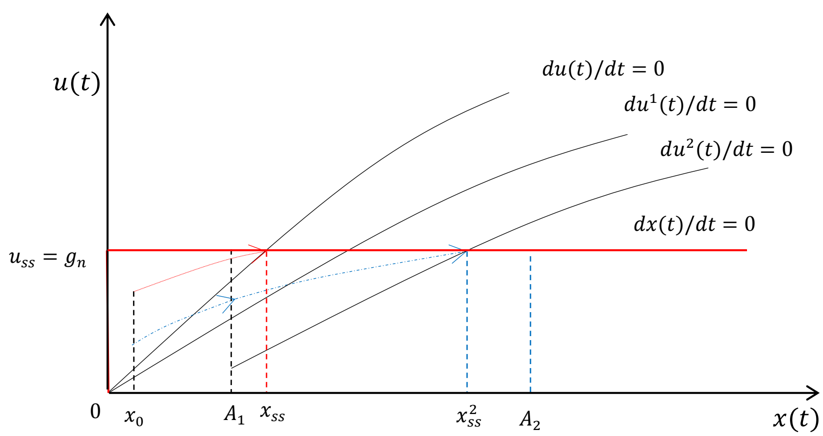

Figure 4.6. Social steady-state versus individual steady-state of case one with $A_1 + A_2 > x_{ss}^2 > x_{ss} > A_1$.

Paths of invasion area implied by social and individualistic control processes are shown in Figure 4.7. The dashed and the solid lines describe how the state variable, $x(t)$, changes with time under the individual control relay and the social control. Both lines start at the same beginning point x_0 at time $t_0 = 0$. Since the individual optimal control rate is lower than the social one $\left(u^{i*} < u^*\right)$, the invasion area is increasing faster under the individual control than under the social control. At time τ_1, parcel 1 is fully invaded, then the owner of parcel 2 starts his/her control and reaches the steady-state x_{ss}^2 at time τ_{ss}^2. The steady-state of invasion area under social optimal control is smaller and reached sooner at time t_{ss}.

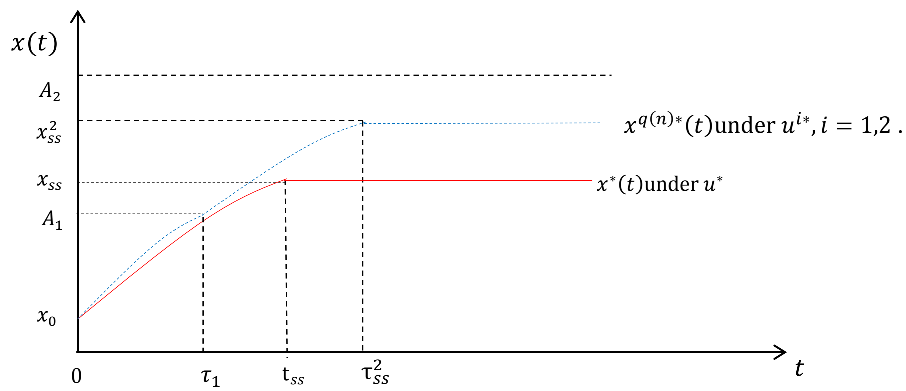

Figure 4.7. Invasion areas under social and individual controls of case one with $A_1 + A_2 > x_{ss}^2 > x_{ss} > A_1$.

6. Subsidy Scheme

The deficiency of individual control is due to the limit of individual interest compared to the social interest. The smaller the individual parcels, the more serious the externality is.[47] As assumed before, the social damage of invasion consists of two components: the sum of individual land owner's economic damages and the environmental damages. An individual's pecuniary damage consists of decreases in production and reduced quality of the commodity which triggers a reduction in the

[47] This is similar to Hansen and Libecap (2004) who show that the abundance of small farms in the 1930s and the potential for uncompensated benefits of erosion control exacerbated wind erosion leading to the Dust Bowl.

market price. Environmental damages represent the loss in social welfare from an invaded ecosystem that accrues to the society other than the parcel owners.[48] However, the parcel owner is only concerned with his/her individual economic losses, thus excluding the other land parcels' losses and the environmental damages from his/her optimal control decision making. As discussed in section 5, due to the limitation of individual interest, individual landowners enact lower control efforts. Specifically the management authority has to create incentives to encourage the "being invaded" parcel's owner to enact more control efforts to reach the social optimum. [49]

A tax or subsidy can be used to motivate an individual to take more control. Because individual control efforts create benefits to society (positive externality), a subsidy system can be a more reasonable incentive policy approach within an individual's border. Also, the implementation of a tax aggravates the individual's control burden, which may impede the management of invasive species. Therefore, subsidy is considered the main measure to internalize the spatial externality in this essay. [50]

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[48] For example, Foot-and-Mouth disease (FMD) is a viral disease in cloven-hoofed animals. This disease can decrease the production of milk and meat, and cause high mortality of young animals. Even more, the animal product from an FMD outbreak area will be banned to other FMD-free regions or sold at a 10-50% lower price compared to FMD-free regions (Rich et al., 2005). FMD can also cause environmental damages, such as threatening the health of wild animals. Mad-cow disease, bovine spongiform encephalopathy (BSE), is another fatal disease of cattle. To eradicate BSE, millions of cattle were slaughtered (Brown, 2000). This disease has also killed more than 200 people around the world by October 2009 (The National Creutzfeldt-Jakob Disease Surveillance Unit (NCJDSU), University of Edinburgh, 2009). Beef exports from BSE outbreak countries have been also banned. Among the damage caused by EAB (Emerald Ash Borer), market damage includes: 1) opportunity costs as ash trees are not permitted to be traded from quarantined areas, and 2) other products from infested areas receiving a lower price than from uninvaded areas. These examples illustrate the cumulative nature of productivity loss and market damage, as well as environmental loss.

[49] At time t, only the "being invaded" parcel is making control efforts to slow the spread, while the "fully invaded" parcels have stopped control activities and the "not invaded" parcels have not yet start control activities.

[50] Segerson (1988)'s linear ambient tax gives the correct incentive for polluters to control nonpoint source pollution for single or multiple polluters. Here a subsidy is based on the same purpose.

6.1 Subsidy on Invaded Land Avoided Index

The subsidy is temporarily offered to the owner of the parcel located at the invasion frontier where control activities are being implemented. The subsidy is composed of two parts. The first part is incentive compatible component, $IC^i(t)$, provided at a uniform rate of $h^i(t)$ per invaded area avoided, $[x'(t) - x(t)]$, where $x'(t)$ represents the path of invasion under the individual control relay.This part subsidy internalizes the externality and induces the individual to choose the optimal social control path. The second part is to ensure each individual to voluntarily participate the social control scheme, which is called the participation compatible component. This subsidy, $PC^i(t)$, results in no individual worse off to participate the social control path than under the individualistic control relay, which is lump sum subsidy at each time.

Let $u^{qs}(t)$ and $u^{ns}(t)$ represent the individual q and n' s reduction rate under the subsidy scheme respectively. First, for the steady-state parcel n, the owner solves

$$\max_{u^{ns}(t)} W^n = \int_{\tau_{n-1}}^{\infty} \begin{Bmatrix} R(A_n) - D^n[x(t), A_n] - c[u^{ns}(t)] \\ +h^n(t)[x'(t) - x(t)] + PC^n(t) \end{Bmatrix} e^{-rt} dt$$

$$+s_0^n[x(\tau_{n-1})] \tag{4.61}$$

$$\text{s.t. } \frac{dx}{dt} = [g - u^{ns}(t)]x(t),$$

$$x(\tau_{n-1}) = \begin{cases} x_o & n = 1 \\ \sum_{j=1}^{n-1} A_j & n > 1 \end{cases},$$

$$u_{\max}^n \geq u^{ns}(t) \geq 0,\ 0 \leq x(t) \leq \sum_{j=1}^{n} A_j ,$$

where $s_0^n[x(\tau_{n-1})] = \int_{\tau_0}^{\tau_{n-1}} \left\{-D^n\left[x(t), A_q\right] - F^{n\to -n}(t)\right\} e^{-rt} dt,$

and $F^{n\rightarrow -n}(t)$ is the compensation paid by individual n to other landowners doing control. Let $\omega^{ns}(t) = e^{rt}\lambda^{ns}(t)$ be the current value costate variable for the invaded area under the subsidy scheme. The current value necessary conditions are

$$-c_{u^{ns}}(\cdot^{*}) - \omega^{ns*}(t)x^{*}(t) \leq 0,\ u^{ns*}(t) \geq 0 \tag{4.62}$$

$$[-c_{u^{ns}}(\cdot^{*}) - \omega^{ns*}(t)x^{*}(t)]u^{ns*}(t) = 0 \tag{4.63}$$

$$\frac{d\omega^{ns*}(t)}{dt} = \left[r - \left(g - u^{ns*}(t)\right)\right]\omega^{ns*}(t) + D_x^n(\cdot^{*}) + h^n(t) \tag{4.64}$$

$$\frac{dx^{*}(t)}{dt} = [g - u^{ns*}(t)]x^{*}(t) \tag{4.65}$$

$$x(\tau_{n-1}) = \begin{cases} x_o & n = 1 \\ \sum_{j=1}^{n-1} A_j & n > 1 \end{cases} \tag{4.66}$$

The owner of parcel q, $q \in [1, n-1]$, the land parcels before the steady-state, solves

$$\max_{u^{qs}(t)} W^q = \int_{\tau_{q-1}}^{\tau_q} \begin{Bmatrix} R(A_q) - D^q[x(t), A_q] - c[u^{qs}(t)] \\ +h^q(t)[x'(t) - x(t)] + PC^q(t) \end{Bmatrix} e^{-rt}dt$$

$$+s_0^q\left[x\left(\tau_{q-1}\right)\right] + e^{-r\tau_q}s_1^q\left[x\left(\tau_q\right)\right] \tag{4.67}$$

$$\text{s.t. } \frac{dx}{dt} = [g - u^{qs}(t)]x(t),$$

$$x\left(\tau_{q-1}\right) = \begin{cases} x_o & q = 1 \\ \sum_{j=1}^{q-1} A_j & q > 1 \end{cases},$$

$$u_{\max}^q \geq u^{qs}(t) \geq 0,\ x(t) \geq 0,\ x\left(\tau_q\right) = \sum_{j=1}^{q} A_j\ ,$$

τ_q is free.

where $s_0^q\left(x\left(\tau_{q-1}\right)\right) = \int_{\tau_0}^{\tau_{q-1}}\left\{-D^q\left[x(t), A_q\right] - F^{q\rightarrow -q}(t)\right\}e^{-rt}dt$,

and $s_1^q\left(x\left(\tau_q\right)\right) = \int_{\tau_q}^{\tau_m}\left\{-D^q\left[x(t), A_q\right] - F^{q\rightarrow -q}(t)\right\}e^{-r(t-\tau_q)}dt$

$$+\int_{\tau_{ss}^{n}}^{\infty}\left[-D^{q}(x_{ss}^{n},A_{q})-F^{q\to n}(\tau_{ss}^{n})\right]e^{-r(t-\tau_{q})}dt$$

$$=\int_{0}^{\tau_{ss}^{q}}\left\{-D^{q}\left[x(t),A_{q}\right]-F^{q\to -q}(t)\right\}e^{-rt}dt$$

$$+\frac{\left[-D^{q}(x_{ss}^{n},A_{q})-F^{q\to n}(\tau_{ss}^{n})\right]e^{-r\tau_{ss}^{q}}}{r},$$

where $F^{q\to -q}(t)$ is the compensation paid by individual q to other landowners doing control.

Let $\omega^{qs}(t)=e^{rt}\lambda^{qs}(t)$ be the current value costate variable under the subsidy scheme. Then, the current value necessary conditions can be written as

$$-c_{u^{qs}}(\cdot^{*})-\omega^{qs*}(t)x^{*}(t)\le 0,\ u^{qs*}(t)\ge 0 \tag{4.68}$$

$$[-c_{u^{qs}}(\cdot^{*})-\omega^{qs*}(t)x^{*}(t)]u^{qs*}(t)=0 \tag{4.69}$$

$$\frac{d\omega^{qs*}(t)}{dt}=\left[r-\left(g-u^{qs*}(t)\right)\right]\omega^{qs*}(t)+D_{x}^{q}(\cdot^{*})+h^{q}(t) \tag{4.70}$$

$$\frac{dx^{*}(t)}{dt}=[g-u^{qs*}(t)]x^{*}(t) \tag{4.71}$$

$$x(\tau_{q-1})=\begin{cases}x_{o} & q=1\\ \sum_{j=1}^{q-1}A_{j} & q>1\end{cases} \tag{4.72}$$

And the current value transversality conditions are

$$R(A_{q})-D^{qs}\left[x^{*}(\tau_{q}),A_{q}\right]-c\left[u^{qs*}(\tau_{q})\right]$$

$$+\omega^{qs*}(\tau_{q})\left[g-u^{qs*}(\tau_{q})\right]x^{*}(\tau_{q})-rs_{1}^{qs}\left[x(\tau_{q})\right]=0 \tag{4.73}$$

$$x^{*}(\tau_{q})=\sum_{i=1}^{q}A_{i} \tag{4.74}$$

Comparing the subsidized individual optimal paths of the control variable, the state variable, and the costate variable with the optimal social ones, the only difference exists in the costate variable motion rule, i.e., the individual motion rule of the costate variable fails to include the other individuals’ and environmental marginal damages with respect to invaded area $(x(t))$. Therefore, the social planner can set the subsidy so as to compensate the individual owner for the spill-over benefit of his/her control actions which will increase the reduction rate of the spread to coincide with the social optimal control path. The subsidy rate that internalizes the externality is

$$h^i(t) = \sum_{\substack{j=1 \\ j\neq i}}^{I} D_x^j\left[x^*(t), A_j\right] + D_x^e(x^*(t)) \quad \text{for} \quad u^{is*}(t) > 0 \ \ (i = q \ or \ n) \tag{4.75}$$

when the owner of parcel q or n is performing the control activities. The subsidy rate captures the damages not included in the individual's control decision. As the invasion spreads, other land owner's damages and the environmental damages are increasing but not at an increasing rate. And the multiplier $\left[x'(t) - x(t)\right]$ may increase as the further difference between an individualistic control and social control results.

The individual costate variable changing function following the subsidy payment is

$$\frac{d\omega^{q*}(t)}{dt} = \left[r - \left(g - u^{qs*}(t)\right)\right]\omega^{qs*}(t) + D_x^q(\cdot^*) +$$

$$+ \sum_{\substack{j=1 \\ j\neq q}}^{I} D_x^j\left[x^*(t), A_j\right] + D_x^e(x^*(t)), \text{ i.e.,}$$

$$\frac{d\omega^{q*}(t)}{dt} = \left[r - \left(g - u^{q*}(t)\right)\right]\omega^{q*}(t) + D_x(\cdot^*) \tag{4.76}$$

then

$$\frac{d\omega^{n*}(t)}{dt} = \left[r - \left(g - u^{ns*}(t)\right)\right]\omega^{ns*}(t) + D_x^n(\cdot^*) +$$

$$+ \sum_{\substack{j=1 \\ j\neq n}}^{I} D_x^j\left[x^*(t), A_j\right] + D_x^e(x^*(t)),$$

i.e.,

$$\frac{d\omega^{n*}(t)}{dt} = \left[r - \left(g - u^{n*}(t)\right)\right]\omega^{n*}(t) + D_x(\cdot^*) \tag{4.77}$$

Note that equations (4.76) and (4.77) are the same as Equation (4.6c) which ensures the externality has been internalized. The subsidy is only offered to the land which is being invaded and taking control efforts. Otherwise, when a parcel is totally invaded or not invaded, there are no control efforts, and no subsidy:

$$h^i(t) = \begin{cases} \sum_{\substack{j=1 \\ j\neq i}}^{I} D_x^j\left[x^*(t), A_j\right] + D_x^e(x^*(t)) & u^{i*}(t) > 0 \\ 0 & u^{i*}(t) = 0 \end{cases} \quad i = 1, \cdots I \tag{4.78}$$

The participation compatibility component of subsidy is to ensure each individual at least as well off as they are under the individualistic control relay. This subsidy represents the physical damage and control cost avoided by some individuals due to social high control level and low invasion state (x^*). These individuals gain benefit from the social control from the physical damage and control costs otherwise occur under individualistic control relay. Therefore, this part of subsidy is:

$$PC_i\,(t) = \begin{cases} 0 & if\ x' < \sum_{j=1}^{i} A_j \\ \sum_{k=i+1}^{n} \begin{Bmatrix} \left[D_p^k(x', A_k) + \mathrm{c}\left[u^{k'}\right]\right] \\ -\left[D_p^k(x^*, A_k) + \mathrm{c}\left[u^{k*}\right]\right] \end{Bmatrix} & if\ x' \geq \sum_{j=1}^{i} A_j \end{cases} \tag{4.79}$$

where k is the set of individuals who will benefit from a delay in invasion as the result of additional control by individual i.

The subsidy at time t , paid by individuals $-i$ to individual i who is controlling the spread of invasion, is

$$F^{-i\to i}(t) = [x'(t) - x(t)]\left[\sum_{\substack{j=1 \\ j\neq i}}^{I} D_x^j\left[x^*(t), A_j\right] + D_x^e(x^*(t))\right] + PC_{-i\to i}(t) \tag{4.80}$$

where $PC_{-i\to i}\,(t) = \begin{cases} 0 & if\ x' < \sum_{j=1}^{i} A_j \\ \sum_{k=i+1}^{n}\left\{\left[D_P^k(x', A_k) + \mathrm{c}[u_k']\right] - \left[D_P^k(x^*, A_k) + \mathrm{c}[u_k^*]\right]\right\} & if\ x' \geq \sum_{j=1}^{i} A_j \end{cases}.$

6.2 Sources of Subsidy

As discussed before, the subsidy is a compensation scheme organized by the social planner to compensate the individual owner for the spill-over benefit from individualistic control actions in order to increase the reduction in the spread rate. If the frontier land owner can slow the invasion, society and all land parcel owners benefit from his/her control efforts by delaying the pace of the invasion. Since the externality affects other parcel owners and society as a whole, the subsidy can come from two main sources. One is from the owners of individual parcels which are already or not yet invaded. The other is from the government. Each parcel owner, who is not controlling the invasion, has an incentive to decrease the spread rate of invasion. Society also has an additional incentive to decrease the environmental damage (D^e) due to the invasive species. The social planner may calculate the total damage and the spill-over benefit of the control activities on each parcel and organize the individual owners to implement the subsidy scheme.

The total spill-over from control by owner q to each of the other land owners i is

$$B^i = \int_{\tau_{q-1}}^{\tau_q} \left\{ D^i\left[e^{gt} \sum_{j=1}^{q-1} A_j\right] - D^i\left[e^{(g-u^q)t} \sum_{j=1}^{q-1} A_j\right]\right\} dt \quad i = 1, \cdots, I; i \neq q.$$

Without control on parcel q, the spread rate is g, and all other parcel owners experience increasing damage as the invaded area grows, i.e., $\int_{\tau_{q-1}}^{\tau_q} D^i\left[e^{gt} \sum_{j=1}^{q-1} A_j\right] dt$, $i = 1, \cdots, I$ and $i \neq q$. Under parcel q's control, the slower spread rate lessens the other parcels' damage from time τ_{q-1} through τ_q to be $\int_{\tau_{q-1}}^{\tau_q} D^i\left[e^{(g-u^q)t} \sum_{j=1}^{q-1} A_j\right] dt$ $i = 1, \cdots, I$ and $i \neq q$. This difference is the spillover benefit to parcel owner i from control on parcel q .

The government also has an incentive to encourage the individual parcel owner to do more to slow the spread of invasion. An additional subsidy is needed to motivate the controlling parcel owner to include the environmental damage and do even more control. The government only provides the part of the subsidy which compensates the individual for the effect of their control on the environment. The total spill-over on the environment (B^e) is $\int_{\tau_{q-1}}^{\tau_q}\left\{D^e\left[e^{gt}\sum_{j=1}^{q-1}A_j\right]-D^e\left[e^{(g-u^q)t}\sum_{j=1}^{q-1}A_j\right]\right\}dt,$ which is due to the individual control of parcel land owner q. Without the control by owner q, the spread rate is g, and the environmental damage from time τ_{q-1}through τ_q is $\int_{\tau_{q-1}}^{\tau_q}D^e\left[e^{gt}\sum_{j=1}^{q-1}A_j\right]dt$. But under parcel owner q's control, the lower spread rate lessens the environmental damage from time τ_{q-1}through τ_q to be $\int_{\tau_{q-1}}^{\tau_q}D^e\left[e^{(g-u^q)t}\sum_{j=1}^{q-1}A_j\right]dt$.

Regarding to the subsidy, the authority may calculate the benefit from q' s control as the participants' valuation about the uninvaded land instead. For individual i, at time t his/her valuation is estimated as

$$B^i = D_x^i\left(x(t)\right)\left(x'(t)-x(t)\right) i = 1,\cdots,I \text{ and } i \neq q \text{[51]} \tag{4.81}$$

The part for environment is estimated as

$$B^e = D_x^e\left(x(t)\right)\left(x'(t)-x(t)\right) \tag{4.82}$$

And the authority can persuade individual i to provide subsidy to the individual q who is controlling the spread of invasion,

$$F^{i\to q}(t) = D_x^i\left(x(t)\right)\left(x'(t)-x(t)\right) + PC_{-i\to i}(t)$$

[51] This equation estimates the difference of damage between an invaded land area under individualistic control and an invasion level under control with subsidy, i.e., $D^i\left(x'(t)\right)-D^i\left(x(t)\right)\approx D_x^i\left(x(t)\right)\left(x'(t)-x(t)\right)$. The same is as equation (4.84).

$$i = 1, \cdots, I, \text{and } u^i(t) = 0 \tag{4.83}$$

where

$$PC_{i \to q}(t) = \begin{cases} 0 & if i < q \; or \; i > n \\ \left[D_P^i(x', A_i) + \mathrm{c}\left[u^{i\prime}\right]\right] - \left[D_P^i(x^*, A_k) + \mathrm{c}\left[u^{i*}\right]\right] & if \; q < i \leq n \end{cases} \tag{4.84}$$

and the government to provide

$$F^{g \to i}(t) = D_x^e\left(x(t)\right)\left(x'(t) - x(t)\right) \tag{4.85}$$

This subsidy may differ from the real benefit at each time, but the sum of subsidy approximately represents the spill-over benefit effect. This subsidy scheme reduces the stress on the public budget by raising funds from other individual parcel owners and the management authority. The subsidy scheme can also be designed to internalize the externality on different indexes, such as an individual's control rate. To sum up, the multisource subsidy scheme should compensate individuals for the spill-over benefits of their invasive species control (the "partial public" good supplied by the individuals).

7. Numerical Simulation

To illustrate the model's main findings, consider the following hypothetical example. A single commodity is produced in the region and sold in a perfectly competitive market. For exposition two simplifying assumptions are made. First, the region is a small player in the commodity market. The output of this region counts for such a small proportion of the market that the reduction of output due to the invasion does not affect the price. Second, the supply of the commodity in this region is inelastic which is consistent with parcels that are unsuitable to produce other commodities and also are prohibited from other utilizations.[52]

Assume the invasion causes a constant percentage (α) decrease in output in the invaded area.[53] Before being invaded parcel i produces $Q(A_i)$ and after being invaded the output decreases to be $\{1 - \alpha\kappa^i[x(t)]\}Q(A_i)$ at time t. $\kappa^i[x(t)]$ is still the percentage of invasion of parcel i , as defined in Equation (4.1) of section 3. As invasion expands, $\kappa^i[x(t)]$ increases and reaches 1 once A_i is fully invaded and produces the lowest output level. Assume P is the given price of this product with high quality before the invasion. Thus, individual i incurs production damage $[PQ(A_i)]\alpha\kappa^i(x(t))$ before being fully invaded, the maximum ($[PQ(A_i)]\alpha$) at τ_i (fully invaded), and then the constant maximum production damage as the invasion spreads beyond the parcel. The market damage is another damage resulting from lower prices for commodities from invaded regions. Let $D_m[x(t)]$ be the total market damage of the region, and $D_m^i[x(t)]$ represent the market damage on parcel i, which is proportional to the total market damage weighted by some index, such as land shares and output levels.

The production damage and the market damage of the land parcel i at time t are shown in Figure 4. 8. The perpendicular line represents the inelastic supply and the horizontal line describes the perfectly competitive market, i.e. a special case of Figure 4.2. At time t the region is found to be invaded and the market price of product from the

[52] Adaptation, such as planting more resistant crop varieties or removing land from cultivation in response to the establishment of pests can be a constructive means of decreasing the damage caused by the spread of the invasion. Therefore, control and adaptation can be combined in the management of invasive species. But in this example, the land owners are excluded from using any adaptation in order to concentrate on the externality analysis. In short, the numerical simulation considers intensive margin effects but not extensive margin effects.

[53] It is straightforward to allow the rate of commodity depreciation to increase as invaded area expands.

region drops from P to P_t. If parcel i is not invaded yet, only market damage occurs and the damage is area I+II. Once invaded, the production level decreases from $Q(A_i)$ to $\{1-\kappa^i[x(t)]\alpha\}Q(A_i)$ and both market and production damages occur given by areas I+II +III. Once fully invaded, the production damage reaches its apex, but the market damage continues to increase as the invaded area expands beyond the parcel. That market damage is the reason why "fully" and "non-invaded" land owner have incentive to control the spread of invasive species at each point in time.

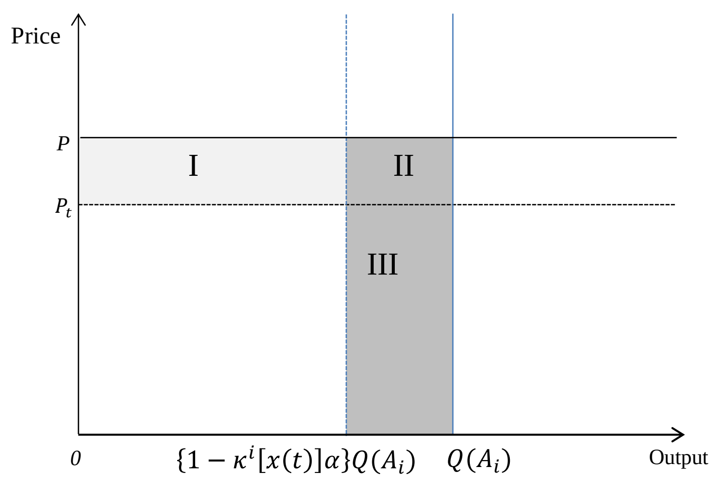


Figure 4.8. The damage of the land parcel i.

The market damage is assumed to be a linear function:

$$D_m[x(t)] = zx(t) \tag{4.86}$$

And the environmental damage is omitted here to simplify the simulation. This omission will not affect the analysis result. The quantity of output is normalized such that one km^2 of area yields one unit of output, $Q(A_i) = A_i$. Therefore, the social damage is

$$D[x(t), A] = P\alpha x(t) + zx(t) \tag{4.87}$$

Market damage is dispersed among land owners according to land share, i.e, the weight coefficient of each individual is the land share, $\frac{A_i}{A}, A = \sum_{i=1}^{I} A_i$. Therefore, parcel i's damage is

$$D^i[x(t), A_i] = \begin{cases} zx(t)\ \frac{A_i}{A} & \kappa^i[x(t)] = 0 \\ PA_i\alpha\kappa^i[x(t)] + zx(t)\ \frac{A_i}{A} & 0 < \kappa^i[x(t)] < 1 \\ PA_i\alpha + zx(t)\ \frac{A_i}{A} & x(t) \geq \sum_{j=1}^{i} A_j \end{cases} \tag{4.88}$$

The social and individual control cost functions are assumed to be the same as

$$c(u, A) = \eta[u(t)]^3 \tag{4.89}$$

We assume a barrier zone control along the expanding front, and the control cost directly relates with the control rate with an increasing marginal control cost. The net revenue before invasion ($R(A)$) is assume to be 40% of revenue, i.e., ($P \times A \times 0.4$).

Table 4.3

The parameters in simulation.

parameter	Definition	value
r	Discount rate	5%
g	Natural spreading rate of invasive species	10%
A_i	Parcel i's area	7.5km^2
P	Price of commodity before invasion	\$20
α	Percent reduction in yield due to invasion	15%
z	A parameter of market damage function	4
η	A parameter of control cost	22,000

For convenience, the definition and values of each parameter in the simulations are summarized in Table 4.3. Assume there are three parcels in this region, i.e., $A_1 = A_2 =$

$A_3 = 7.5$ km^2. Later the number, order, and sizes of parcels are varied in the simulation of the individualistic control relay. Two initial invaded areas are considered to illustrate the effect of species detection on the control decision. The small initial invasion area is 2 km^2 and the large initial invasion area is 12 km^2. The control path is simulated by using GAMS (23.9.2) solvers PATH and CONOPT.

7.1 Simulation of the Social Optimal Control

With these definitions, the social planner maximizes minus sum of damages and control costs, i.e.,

$$\max_{u(t)} W = \int_0^{\infty} \{R(A) - P\alpha x(t) - zx(t) - \eta[u(t)]^3\} e^{-rt} dt \tag{4.90}$$

$$\text{s.t. } \frac{dx}{dt} = [g - u(t)]x(t),$$

$$x(0) = x_o > 0 \text{ given },$$

$$u_{max} \geq u(t) \geq 0 \text{ , } x(t) \geq 0 \text{ .}$$

And the current value Hamiltonian is

$$H(\cdot) = R(A) - P\alpha x(t) - -zx(t) - \eta[u(t)]^2 + \omega(t)[g - u(t)]x(t) \tag{4.91}$$

The equations to be solved to find the social optimal path are:

$$-3\eta[u(t)]^2 - \omega^*(t)x^*(t) \leq 0, u(t) \geq 0 \tag{4.92}$$

$$[-3\eta[u(t)]^2 - \omega^*(t)x^*(t)]u(t) = 0 \tag{4.93}$$

$$\frac{d\omega^*(t)}{dt} = \left[r - \left(g - u^*(t)\right)\right]\omega^*(t) + P\alpha + z \tag{4.94}$$

$$\frac{dx^*(t)}{dt} = [g - u^*(t)]x^*(t) \tag{4.95}$$

$$x(0) = x_0 \tag{4.96}$$

The results of social optimal control, small initial invasion area case vs. large one, for the state variable (invasion area), the control variable (reduction rate) and the costate variable (shadow cost) are shown in Figures 4.9. In the small initial invasion case, the control rate is increasing from about 8% to 10%, and the invasion spreads from 2 km^2 and eventually stops at the steady-state, 4.714 km^2. The costate variable is increasing from -195.225 as the invasion continues and reaches - 140 at the steady-state. In the case of large initial invasion, the control rate declines from 13% to 10%, and the invasion is reversed from 12 km^2 to 4.714 km^2. The costate variable decrease as the invasion shrinks from -98.546 to -140. In both small and large initial invasion cases, the same robust steady-state is reached.

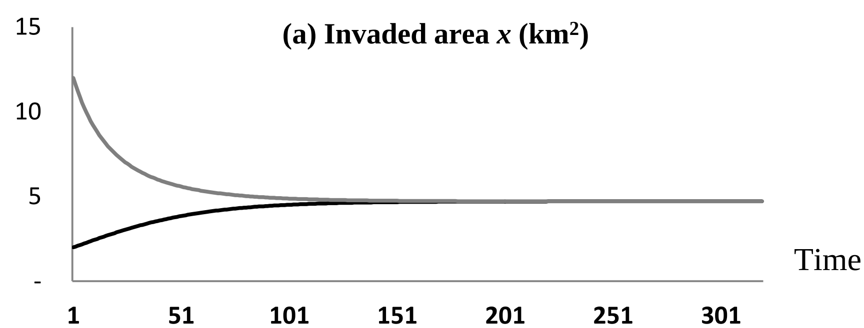
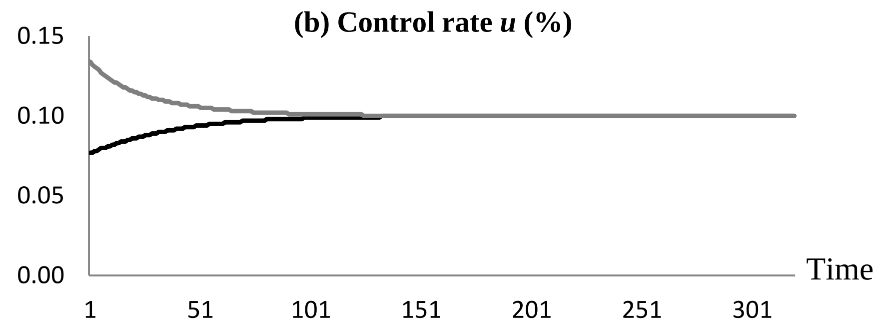


Figure 4.9. Simulation results for social control of invasion.



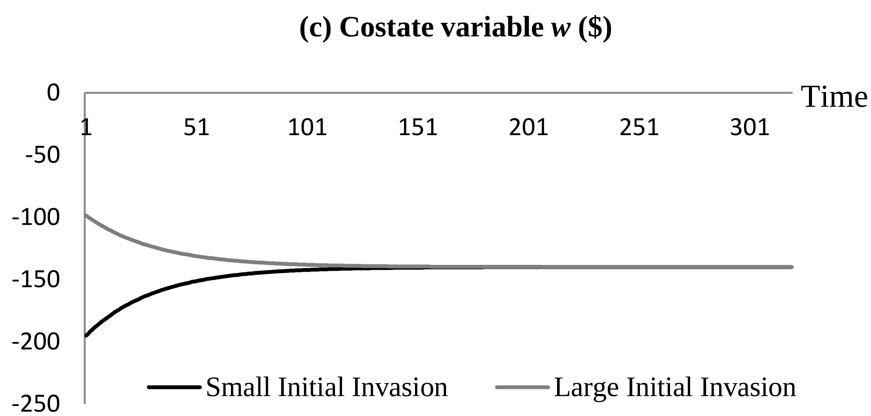


Figure 4.9. (Continual).

7.2 Simulation of the Individual Control Relay

As in the theoretical analysis, individual control experiences a control relay. Assume the individual steady-state is reached within parcel n. Individual 1 to individual $n-1$follow their own dynamic optimal control path represented by a fixed terminal state and a free terminal time. Individual n's infinite horizon dynamic optimal control follows. The simulation exercise of individualistic control relay is performed backward. When the control relay reaches to the west border of parcel n, the individual owner n is to solve the problem,

$$\max_{u^n(t)} W = \int_{\tau_{n-1}}^{\infty} \left\{R(A_n) - PA_n\alpha\kappa^n[x(t)] - zx(t)\,\frac{A_n}{A} - \eta[u^n(t)]^3\right\} e^{-rt}\,dt$$

$$+s_0^n[x(\tau_{n-1})] \tag{4.97}$$

$$\text{s.t.}\ \frac{dx}{dt} = [g - u^n(t)]x(t)\ ,$$

$$x(\tau_{n-1}) = \begin{cases} x_o & n = 1 \\ \sum_{j=1}^{n-1} A_j & n > 1\text{'} \end{cases}$$

$$u^n(t) \geq 0\ ,$$

$$x(t) \geq 0,$$

where $s_0^n[x(\tau_{m-1})] = \int_{\tau_0}^{\tau_{n-1}} \left\{-zx(t)\,\frac{A_n}{A}\right\} e^{-rt}dt,$

$$\kappa^n[x(t)] = \begin{cases} 0 & x(t) \leq \sum_{j=1}^{n-1} A_j \\ \frac{x(t) - \sum_{j=1}^{n-1} A_j}{A_n} & \sum_{j=1}^{n-1} A_j < x(t) < \sum_{j=1}^{n} A_j \\ 1 & x(t) \geq \sum_{j=1}^{n} A_j \end{cases}.$$

The current value Hamiltonian is

$$H\,(\cdot) = R(A_n) - PA_n\alpha\kappa^n[x(t)] - zx(t)\frac{A_n}{A} - \eta[u^n(t)]^3$$

$$+\omega^n(t)[g - u^n(t)]x(t) \tag{4.98}$$

The equations are to be solved to find the parcel owner *m*'s optimal path:

$$-3\eta[u^n(t)]^2 - \omega^{n*}(t)x^*(t) \leq 0, u^n(t) \geq 0 \tag{4.99}$$

$$[-3\eta[u^n(t)]^2 - \omega^{n*}(t)x^*(t)]u^n(t) = 0 \tag{4.100}$$

$$\frac{d\omega^{n*}(t)}{dt} = \left[r - \left(g - u^{n*}(t)\right)\right]\omega^{n*}(t) + P\alpha + z\,\frac{A_n}{A} \tag{4.101}$$

$$\frac{dx^*(t)}{dt} = [g - u^{n*}(t)]x^*(t) \tag{4.102}$$

$$x(\tau_{n-1}) = \begin{cases} x_o & n = 1 \\ \sum_{j=1}^{n-1} A_j & n > 1 \end{cases} \tag{4.103}$$

As before, τ_{ss}^{n} is the time at which the individualistic control relay reaches the steady-state. Though individual q can change his/her terminal control time, he/she cannot change the other individuals' control process. Individual q takes these optimal control times as a given when making his/her decision. Also as before, τ_{ss}^{q} represents the time period between individual q's terminal time and the individual control relay reaching the steady-state: $\tau_{ss}^{\mathrm{n}} = \tau_q + \tau_{ss}^{q}$.

Individual parcel q's owner solves the following problem, $q \in [1, m-1]$,

$$\max_{u^q(t)} W = \int_{\tau_{q-1}}^{\tau_q} \left\{ R(A_q) - PA_q \alpha \kappa^q [x(t)] - zx(t)\ \frac{A_q}{A} - \eta [u^q(t)]^3 \right\} e^{-rt} dt$$

$$+ s_0^q \left[x\left(\tau_{q-1}\right) \right] + \ s_1^q \left[x\left(\tau_q\right) \right] e^{-r\tau_q} \tag{4.104}$$

$$\text{s.t. } \frac{dx}{dt} = [g - u^q(t)] x(t),$$

$$x\left(\tau_{q-1}\right) = \begin{cases} x_o & q = 1 \\ \sum_{j=1}^{q-1} A_j & q > 1 \end{cases},$$

$$u^q(t) \geq 0,\ x(t) \geq 0,\ x\left(\tau_q\right) = \sum_{j=1}^{q} A_j\ ,$$

$$\tau_q \text{ is free },$$

Where $s_0^q \left(x\left(\tau_{q-1}\right) \right) = \int_{\tau_0}^{\tau_{q-1}} \left\{ -zx(t)\ \frac{A_q}{A} \right\} e^{-rt} dt$,

$$s_1^q \left(x\left(\tau_q\right) \right) = \int_{\tau_q}^{\tau_{ss}^m} \left[-PA_q \alpha - zx(t)\ \frac{A_q}{A} \right] e^{-r(t-\tau_q)} dt + \int_{\tau_{ss}^n}^{\infty} \left[-PA_q \alpha - zx(t)\ \frac{A_q}{A} \right] e^{-r(t-\tau_q)} dt$$

$$= \int_0^{\tau_{ss}^q} \left[-PA_q \alpha - zx(t)\ \frac{A_q}{A} \right] e^{-rt} dt + \frac{\left[-PA_q - zx_{ss}^n \frac{A_q}{A} \right] e^{-r\tau_{ss}^q}}{r}\ ,$$

$$\kappa^q[x(t)] = \begin{cases} 0 & x(t) \le \sum_{j=1}^{q-1} A_j \\ \frac{x(t)-\sum_{j=1}^{q-1} A_j}{A_q} & \sum_{j=1}^{q-1} A_j < x(t) < \sum_{j=1}^{q} A_j. \\ 1 & x(t) \ge \sum_{j=1}^{q} A_j \end{cases}$$

The current value Hamiltonian equation is

$$H(\cdot) = R(A_q) - PA_q\alpha\kappa^q[x(t)] - zx(t)\frac{A_q}{A} - \eta[u^q(t)]^3$$

$$+\omega^q(t)[g - u^q(t)]x(t) \qquad (4.105)$$

The equations are to be solved to find the parcel owner q's optimal path:

$$-3\eta[u^q(t)]^2 - \omega^{q*}(t)x^*(t) \le 0,\ u^q(t) \ge 0 \qquad (4.106)$$

$$[3\eta[u^q(t)]^2 - \omega^{q*}(t)x^*(t)]u^q(t) = 0 \qquad (4.107)$$

$$\frac{d\omega^{q*}(t)}{dt} = \left[r - \left(g - u^{q*}(t)\right)\right]\omega^{q*}(t) + P\alpha + z\,\frac{A_q}{A} \qquad (4.108)$$

$$\frac{dx^*(t)}{dt} = [g - u^{q*}(t)]x^*(t) \qquad (4.109)$$

$$x(\tau_{q-1}) = \begin{cases} x_o & q = 1 \\ \sum_{j=1}^{q-1} A_j & q > 1 \end{cases} \qquad (4.110)$$

And the current value transversality condition is

$$R(A_q) - PA_q\alpha\kappa^q\left[x(\tau_q)\right] - zx(\tau_q)\frac{A_q}{A} - \eta\left[u^q * (\tau_q)\right]^3$$

$$+\omega^{q*}(\tau_q)\left[g - u^{q*}(\tau_q)\right]x^*(\tau_q) - rs_1^q\left[x(\tau_q)\right] = 0 \qquad (4.111)$$

$$x(\tau_q) = \sum_{i=1}^{q} A_i \qquad (4.112)$$

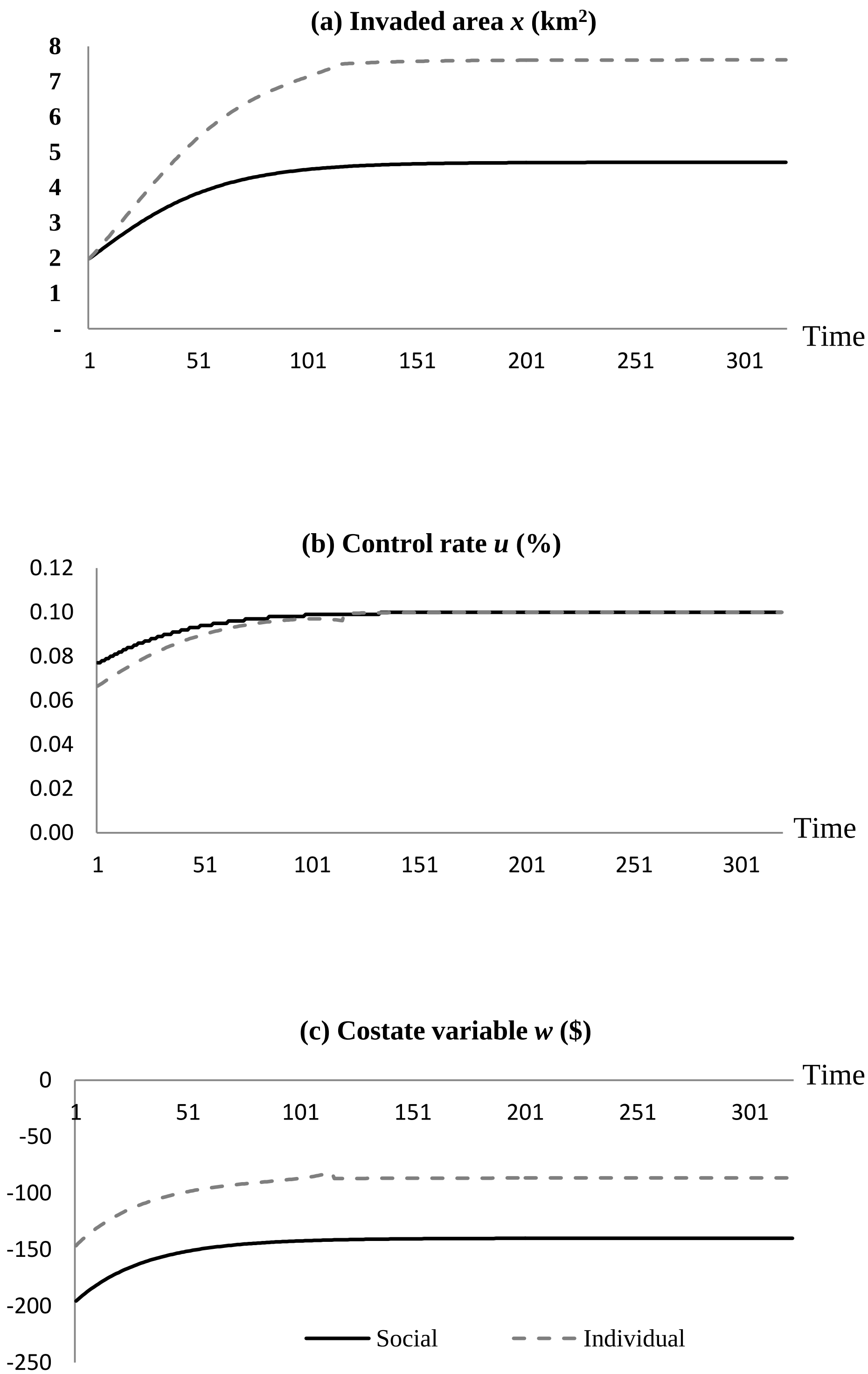


Figure 4.10 Simulation results for social optimal control and individual control relay

The simulation exercise of individuals before steady-state is applied by a backward algorithm design.[54] A comparison of the individualistic and socially optimal path for the invasion area, the reduction rate, and the shadow cost are shown in Figure 4.10. With a small initial invasion, the individual control relay reaches the steady-state invasion area at 7.615 km^2, larger than the social one (4.714 km^2). The absolute value of individualistic control relay's costate variable is smaller than the social one, revealing the insufficient individualistic interest in controlling invasive species spread. Consequently, the limited interest of the individual parcel owner results in a lower control path.

Table 4.4
Alternative land ownership scenarios.

Type	Notation	number of producers	Individual parcel	Total area
Benchmark	A(7.5×3)	3	A_1=7.5 A_2=7.5 A_3=7.5	22.5
Scenario 1: Increased producers	A(5.625 × 4)	4	A_1=5.625 A_2=5.625 A_3=5.625 A_4=5.625	22.5
Scenario 2: Heterogeneous producers, largest initially impacted	A(9, 7, 6.5)	3	A_1=9.0 A_2=7.0 A_3=6.5	22.5
Scenario 3: Heterogeneous producers, smallest initially impacted	A(6.5, 7, 9)	3	A_1=6.5 A_2=7.0 A_3=9.0	22.5

[54] See the Appendix D for a detailed backward algorithm.

The insufficiency of privately supplied invasive species control will fluctuate with changes in the number of individual owners, the size of individual parcels, and the order of small and large parcels. Now four different scenarios are summarized in Table 4.4, with simulations of the state variable, the control variable, and the costate variable in Figure 4.11. Given a fixed size of suitable habitat, increasing the number of individual owners aggravates the effect of the uncompensated externality and causes the individualistic control relay to deviate farther away from the social one and results in a larger steady-state invasion area. When landowners are heterogeneous in size, the order of parcels also impacts the individualistic control result, e.g., 8.25 km^2 of the steady-state of invasion area at Scenario 1 compares to 7.775 km^2 at Scenario 3.

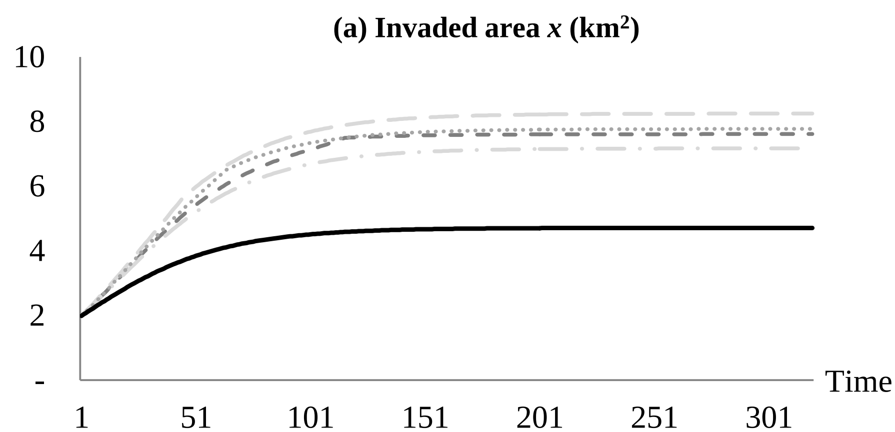
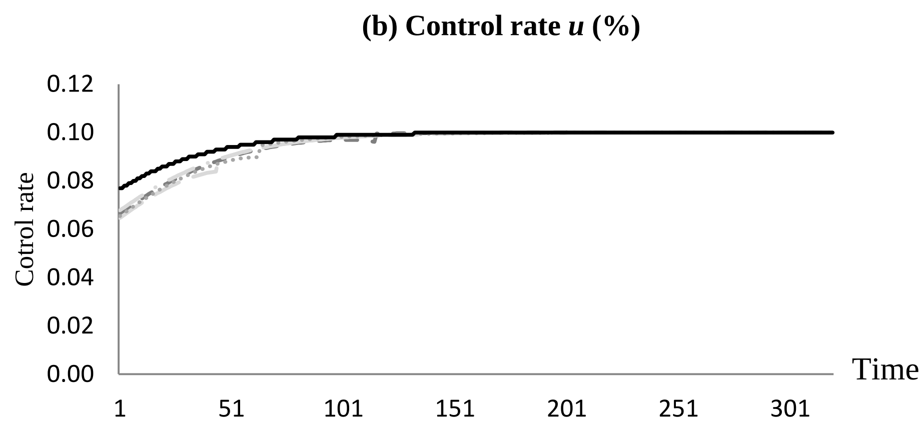


Figure 4.11. Simulation results under various ownership scenarios.



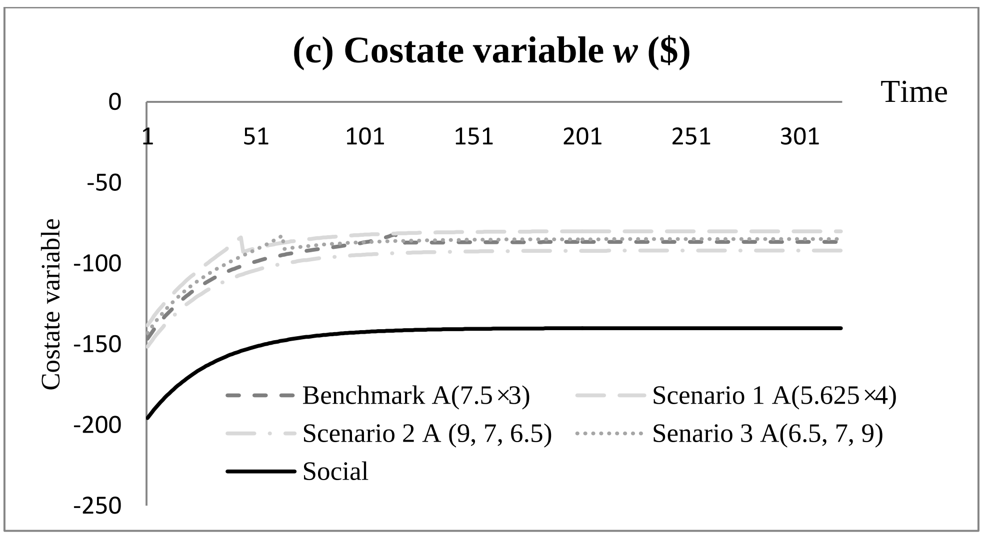


Figure 4.11. (Continual).

7.3 Simulation of Individual Control under a Subsidy

Now following the above assumptions, the subsidy rate is set as

$$h^q(t) = \begin{cases} \sum_{\substack{j=1 \\ j\neq q}}^{I} z\,\frac{A_j}{A} & u^{q*}(t) > 0 \\ 0 & u^{q*}(t) = 0 \end{cases} \tag{4.113}$$

The subsidy for the individual q at time t , $F^{-q\to q}(t)$, is

$$F^{-q\to q}(t) = \begin{cases} [x^{'}(t) - x(t)] \sum_{\substack{j=1 \\ j\neq q}}^{I} z \frac{A_j}{A} + PC_{-q\to q}(t) & u^{q*}(t) > 0 \\ 0 & u^{q*}(t) = 0 \end{cases} \tag{4.114}$$

Where

$$PC_{-q\to q}(t) = \begin{cases} 0 & if\ x' < \sum_{j=1}^{q} A_j \\ \sum_{k=q+1}^{n} \left\{ \left[D_P^k(x', A_k) + \mathrm{c}[u^{k\prime}] \right] - \left[D_P^k(x^*, A_k) + \mathrm{c}[u^{k*}] \right] \right\} & if\ x' \geq \sum_{j=1}^{q} A_j \end{cases}.$$

Assume that individual n reaches the steady-state. With the subsidy individual n solves

$$\max_{u^{ns}(t)} W = \int_{\tau_{n-1}}^{\infty} \left\{ \begin{matrix} R(A_n) - PA_n\alpha\kappa^n[x(t)] - zx(t)\frac{A_n}{A} - \eta[u^{ns}(t)]^3 \\ +h^n(t)[x'(t) - x(t) + PC_{-n\to n}(t)] \end{matrix} \right\} e^{-rt}\, dt$$

$$+s_0^n[x(\tau_{n-1})] \tag{4.115}$$

$$\text{s.t. } \frac{dx}{dt} = [g - u^{ns}(t)]x(t) \ ,$$

$$x(\tau_{n-1}) = \begin{cases} x_o & n = 1 \\ \sum_{j=1}^{n-1} A_j & n > 1 \end{cases},$$

$$u_{max} \geq u^{ns}(t) \geq 0, \quad x(t) \geq 0,$$

where $s_0^n[x(\tau_{n-1})] = \int_{\tau_0}^{\tau_{n-1}} \left\{ -zx(t)\frac{A_n}{A} - F^{n\to -n}(t) \right\} e^{-rt} dt,$

$$\kappa^n[x(t)] = \begin{cases} 0 & x(t) \leq \sum_{j=1}^{n-1} A_j \\ \frac{x(t) - \sum_{j=1}^{n-1} A_j}{A_n} & \sum_{j=1}^{n-1} A_j < x(t) < \sum_{j=1}^{n} A_j \\ 1 & x(t) \geq \sum_{j=1}^{n} A_j \end{cases}.$$

The current value Hamiltonian is

$$H(\cdot) = R(A_n) - PA_n\alpha\kappa^n[x(t)] - zx(t)\frac{A_n}{A} - \eta[u^{ns}(t)]^3$$

$$+h^n(t)[x'(t) - x(t)] + PC_{-n\to n}(t) + \omega^{ns}(t)[g - u^{ns}(t)]x(t) \tag{4.116}$$

The equations are to be solved to find the parcel owner n's optimal path:

$$-3\eta[u^{ns}(t)]^2 - \omega^{ns*}(t)x^*(t) \leq 0, u^{ns}(t) \geq 0 \tag{4.117}$$

$$[-3\eta[u^{ns}(t)]^2 - \omega^{ns*}(t)x^*(t)]u^{ns}(t) = 0 \tag{4.118}$$

$$\frac{d\omega^{ns*}(t)}{dt} = \left[r - \left(g - u^{ns*}(t)\right)\right]\omega^{ns*}(t) + P\alpha + z\,\frac{A_n}{A} + h^n(t) \tag{4.119}$$

$$\frac{dx^*(t)}{dt} = [g - u^{ns*}(t)]x^*(t) \tag{4.120}$$

$$x(\tau_{n-1}) = \begin{cases} x_o & n = 1 \\ \sum_{j=1}^{n-1} A_j & n > 1 \end{cases} \tag{4.121}$$

For the individuals q , $q \in [1, n-1]$, they solve

$$\max_{u^{qs}(t)} W = \int_{\tau_{q-1}}^{\tau_q} \begin{Bmatrix} R(A_q) - PA_q\alpha\kappa^q[x(t)] - zx(t)\frac{A_q}{A} - \eta[u^{qs}(t)]^3 \\ +h^q(t)[x'(t) - x(t)] + PC_{-q\to q}(t) \end{Bmatrix} e^{-rt}dt$$

$$+s_0^q\left[x\left(\tau_{q-1}\right)\right] + s_1^q\left[x\left(\tau_q\right)\right]e^{-r\tau_q} \tag{4.122}$$

s.t. $\frac{dx}{dt} = [g - u^{qs}(t)]x(t)$,

$$x\left(\tau_{q-1}\right) = \begin{cases} x_o & q = 1 \\ \sum_{j=1}^{q-1} A_j & q > 1 \end{cases},$$

$u^{qs}(t) \geq 0,\ x(t) \geq 0,\ x\left(\tau_q\right) = \sum_{j=1}^{q} A_j$,

τ_q is free ,

where $s_0^q\left(x\left(\tau_{q-1}\right)\right) = \int_{\tau_0}^{\tau_{q-1}} \left\{-zx(t)\,\frac{A_q}{A} - F^{q\to -q}(t)\right\} e^{-rt}dt$,

$$s_1^q\left(x\left(\tau_q\right)\right) = \int_{\tau_q}^{\tau_{ss}^n} \left[-PA_q - zx(t)\,\frac{A_q}{A} - F^{q\to -q}(t)\right] e^{-r(t-\tau_q)}dt$$

$$+\int_{\tau_{ss}^n}^{\infty} \left[-PA_q\alpha - zx(t)\,\frac{A_q}{A} - F^{q\to n}(t)\right] e^{-r(t-\tau_q)}dt$$

$$= \int_0^{\tau_{ss}^q} \left[-PA_q\alpha - zx(t)\,\frac{A_q}{A} - F^{q\to -q}(t)\right] e^{-rt}dt$$

$$+\frac{\left[-PA_q\alpha - zx_{ss}^n\frac{A_q}{A} - F^{q\to n}(t_{ss}^n)\right]e^{-r\tau_{ss}^q}}{r},$$

$$\kappa^q[x(t)] = \begin{cases} 0 & x(t) \le \sum_{j=1}^{q-1} A_j \\ \frac{x(t)-\sum_{j=1}^{q-1} A_j}{A_q} & \sum_{j=1}^{q-1} A_j < x(t) < \sum_{j=1}^{q} A_j. \\ 1 & x(t) \ge \sum_{j=1}^{q} A_j \end{cases}$$

The current value Hamiltonian equation is

$$H(\cdot) = R(A_q) - PA_q\alpha\kappa^q[x(t)] - zx(t)\frac{A_q}{A} - \eta[u^{qs}(t)]^3$$

$$+h^q(t)[x'(t) - x(t)] + PC_{-q\to q}(t) + \omega^{qs}(t)[g - u^q(t)]x(t) \quad (4.123)$$

The equations are to be solved to find the parcel owner q's optimal path:

$$-3\eta[u^{qs}(t)]^2 - \omega^{qs*}(t)x^*(t) \le 0,\ u^{qs}(t) \ge 0 \quad (4.124)$$

$$[-3\eta[u^{qs}(t)]^2 - \omega^{qs*}(t)x^*(t)]u^{qs}(t) = 0 \quad (4.125)$$

$$\frac{d\omega^{qs*}(t)}{dt} = \left[r - \left(g - u^{qs*}(t)\right)\right]\omega^{qs*}(t) + P\alpha + z\,\frac{A_q}{A} + h^q(t) \quad (4.126)$$

$$\frac{dx^*(t)}{dt} = [g - u^{qs*}(t)]x^*(t) \quad (4.127)$$

$$x(\tau_{q-1}) = \begin{cases} x_o & q = 1 \\ \sum_{j=1}^{q-1} A_j & q > 1 \end{cases} \quad (4.128)$$

and the current value transversality condition is

$$R(A_q) - PA_q\alpha\kappa^q[x(\tau_q)] - zx(\tau_q)\frac{A_q}{A} - \eta[u^{qs*}(\tau_q)]^3$$

$$+\omega^{qs*}(\tau_q)[g - u^{qs*}(\tau_q)]x^*(\tau_q) - rs_1^q[x(\tau_q)] = 0 \quad (4.129)$$

$$x(\tau_q) = \sum_{i=1}^{q} A_i \quad (4.130)$$

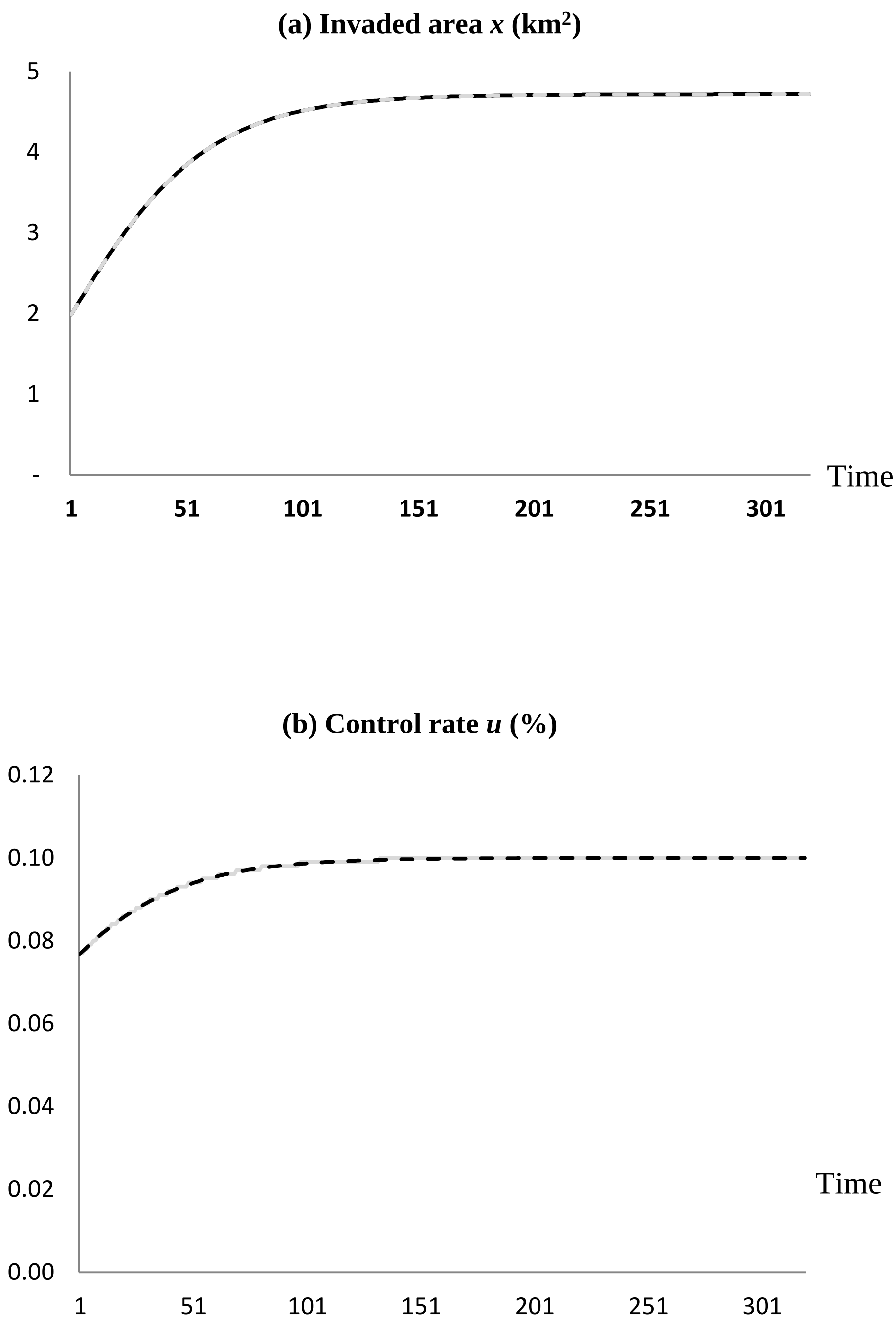


Figure 4.12. Social control and individualistic control with a subsidy.

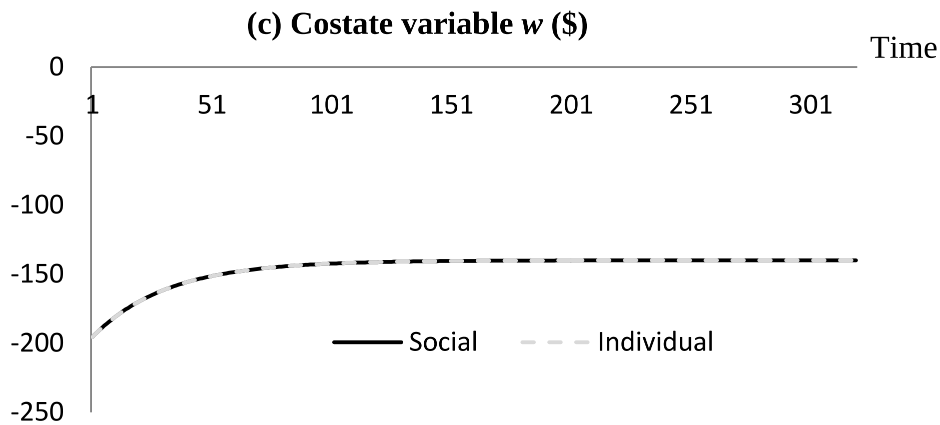


Figure 4.12. (Continual).

The simulation exercise with a subsidy is performed in benchmark case, i.e., three individual owners with 7.5 km^2 parcel each. The results are summarized in Figure 4.12 for the state variable, the control variable and the costate variable. The subsidy fully compensates the externality of individualistic control relay, and brings the individual control back to the socially optimal control path.

This subsidy is funded by multiple sources, i.e., non-controlling individuals and the social planner. The subsidy rate and the funding sources are demonstrated in Figure 4.13 and Figure 4.14. As the invasion enlarges, the subsidy rate is constant in response to the constant marginal damage. The amount of fund from a participant is determined by his/her benefits from the control behavior. The non-controlling individuals compensate the controlling individual for his/her higher level of reduction in the spread of invasive species. Some of non-controlling individuals also provide extra subsidy for delaying or preventing physical damage and control cost otherwise they will occur in individualistic control scheme. This multiple-source subsidy scheme alleviates the tight budget burden, and at the same time internalizes the externality in a way that encourages coordination among participants.

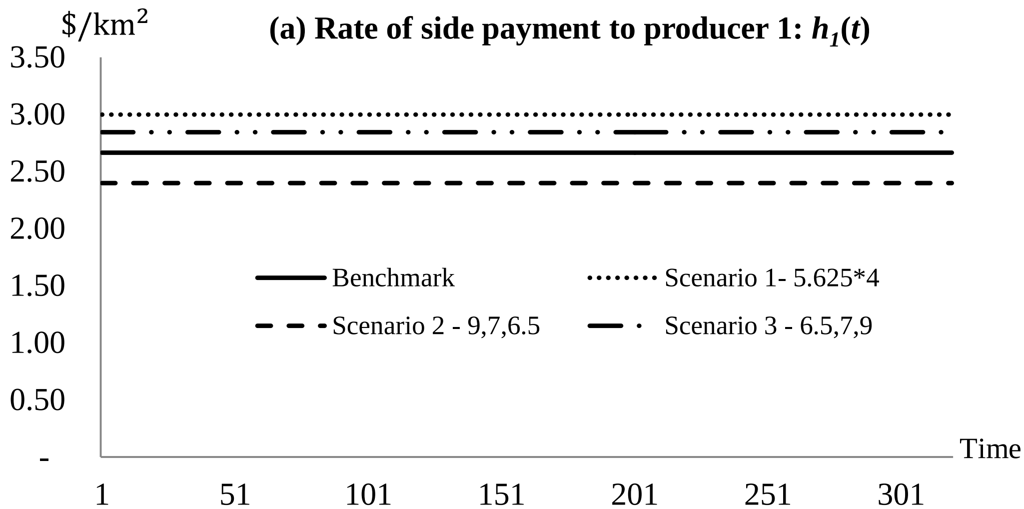


Figure 4.13 Subsidy rate in different scenarios.

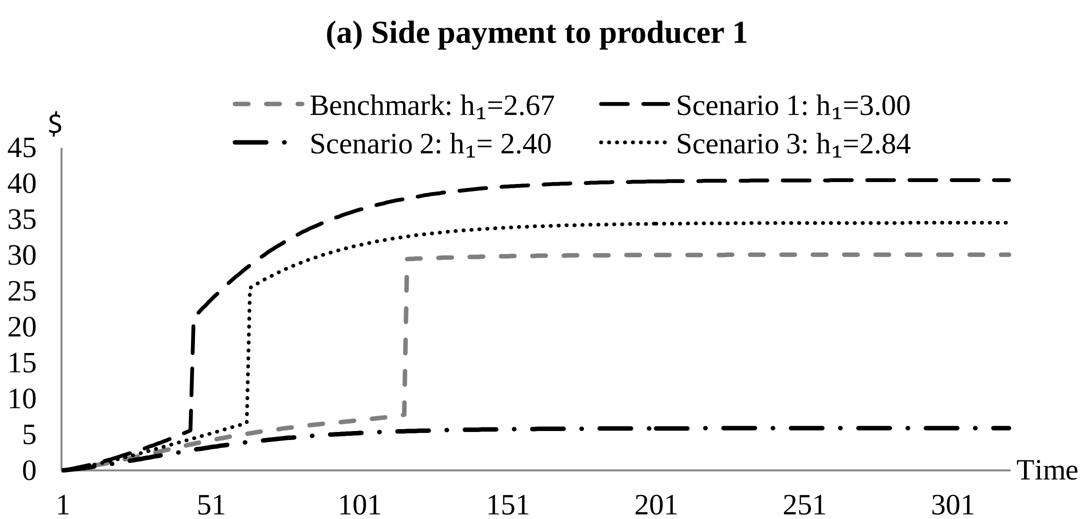
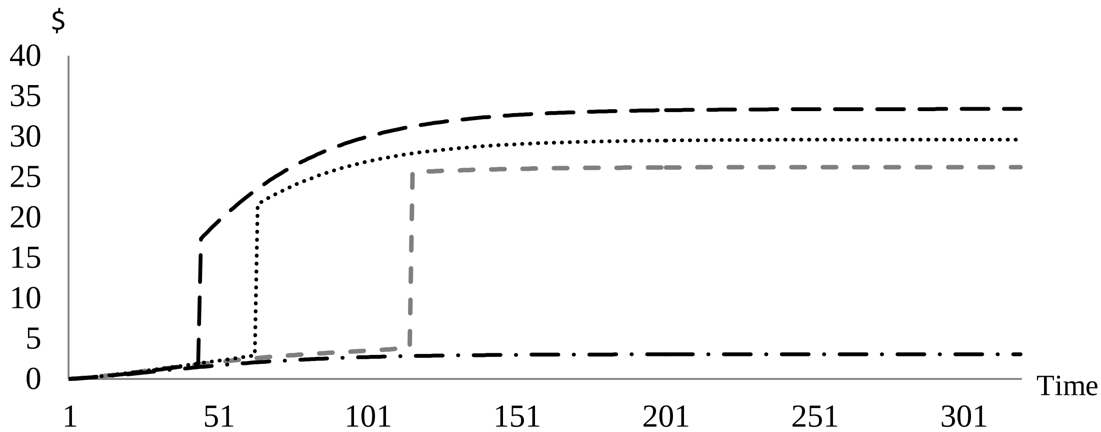


Figure 4.14. Optimal sequences of side payments in different scenarios.

(b) Side payment from producer 2 to producer 1: $F_{2\to1}(t)$



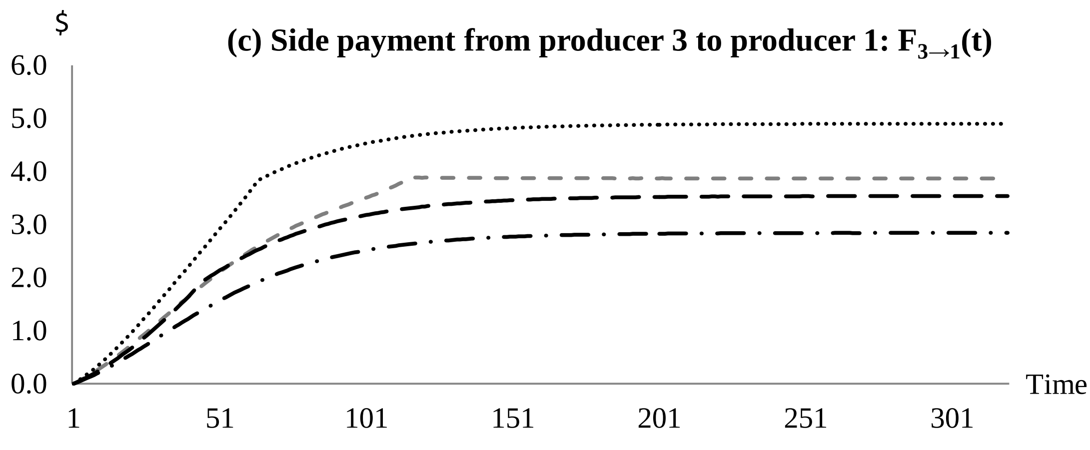


Figure 4.14. (Continual).

8. Conclusion

This paper has developed a dynamic control model to synthesize the biological and economic properties of invasive species, such as the spread rule, market and physical damage, control cost, and the participants' control behaviors. It is found that a spatial externality results from the prevalence of myopic multiple spatially-connected participants in invasive species control. This outcome is shown to be critical because, although the individuals care about the invasion, the limited spatial consideration results in the deficiency of individualistic control and requires an intervention from the management authority. Analysis of a multiple-source subsidy scheme suggests the possibility of coordination among participants. The numerical simulation verifies the theoretical propositions and suggests three conclusions.

First, the control process is determined through the natural spread rule, the discount rate, the damaging pattern, and the control cost of the invasive species. High discount rate and marginal control cost result in a larger invasion area, but high marginal damages expedite the control process and also encourage the preservation of more noninvaded land.

Second, an externality arises due to the different spatial considerations of decision-makers driving a wedge between an individual's and society's damages. The externality of individual control creates an uncompensated benefit spillover to other participants, resulting in a socially suboptimal level of individual control.

Third, the properties of invasive species necessitate the coordination of participant's control in a dynamic setting. A multiple-source subsidy policy instrument, funded by individuals and government, corrects the externality and overcomes the deficiency of individual control. This subsidy scheme expands Wilen's (2007) chained bilateral negotiation system to include all participants directly. Individual funding helps overcome tight budget constraints and eventually accelerates the control process.

The study of invasive species is complex and several factors have been left out for the future research. The role of invasive species spread pattern has not been explicitly addressed in the essay. In practice, linear, logistic spread, or other spread ways may affect the control process. The complicacy and variety of damage and control cost requires a comparative dynamic analysis to gain more insights into the management. More experimental case studies are also important but vacant in lack of data.

References

Bhat, Mahadev G., Huffaker, Ray G., and Lenhart, Suzanne M., 1993. Controlling forest damage by dispersive beaver populations: centralized optimal management strategy. Ecological Applications 3 (3), (Aug.), 518-530.

Bhat, Mahadev G., Huffaker, Ray G., and Lenhart, Suzanne M., 1996. Controlling transboundary wildlife damage: modeling under alternative management scenarios. Ecological Modelling 92, 215-224.

Bhat, Mahadev G.,and Huffaker, Ray G., 2007. Management of a transboundary wildlife population: a self-enforcing cooperative agreement with renegotiation and variable transfer payments. Journal of Environmental Economics and Management 53, 54–67.

Bicknell, Kathryn B., Wilen, James.E., and Howitt, Richard E., 1999. Public policy and individual incentives for livestock disease control. The Australian Journal of Agricultural and Resource Economics 43 (4), 501-521.

Brown, David, 2000. The 'recipe for disaster' that killed 80 and left a £5bn bill. London:

The Daily Telegraph. 27 Oct. <http://www.telegraph.co.uk/news/uknews/1371964/The-recipe-for-disaster-that-killed-80-and-left-a-5bn-bill.html> (accessed 15.02.13).

Burnett, Kimberly M., Evelyn, Sean D, Kaiser, Brooks A., Nantamanasikarn, Porntawee, and Roumasset, James A., 2008. Beyond the lamppost: optimal prevention and control of the Brown Tree Snake in Hawaii. Ecological Economics 67, 66 –74.

Daszak, Peter, Cunningham, Andrew A., and Hyatt, Alex D., 2000. Emerging infectious diseases of wildlife-threats to biodiversity and human health. Science 287, (21 January), 443-449.

Finnoff, David, Horan, Rick, McDermott, Shana, Sims, Charles, and Shogren, Jason F., 2011. Economic Control of Invasive Species. Working Paper.

Hansen, Zeynep K., and Libecap, Gary D., 2004. Small farms, externalities, and the dust bowl of the 1930s. Journal of Political Economy 112 (3), (June), 665-694.

Hastings, Alan, Cuddington, Kim, Davies, Kendi F., Dugaw, Christopher J., Elmendorf, Sarah, Freestone, Amy, Harrison, Susan, Holland, Mathew, Lambrinos, John, Malvadkar, Urmila, Melbourne, Bret A., Moore, Kara, Taylor, Caz, and Thomson, Diane, 2005. The spatial spread of invasions: new developments in theory and evidence. Ecology Letters 8, 91–101.

Homans, Frances, and Horie, Tetsuya, 2011. Optimal detection strategies for an established invasive pest. Ecological Economics 70, 1129–1138.

Horan, Richard D., and Wolf, Christopher A., 2005. The economics of managing infectious wildlife disease. The American Journal of Agricultural Economics 87 (3), (August), 537–551.

Hummel, Natalie, 2009. Rice Water Weevil management using current technology. LSU AgCenter. Feb 11-13.

Kim, C.S., Lubowski, Ruben N., Lewandrowski, Jan, and Eiswerth, Mark E., 2006. Prevention or control: optimal government policies for invasive species management. Agricultural and Resource Economics Review 35 (1), (April), 29–40.

Liebhold, Andrew M., and Tobin, Patrick C., 2008. Population ecology of insect invasions and their management. Annual Review of Entomology 53, 387–408.

Lyon, Kenneth S., 1999. The costate variable in natural resource optimal control problems. Natural Resource Modeling12 (4), (Winter), 413-426.

Mas-Colell, Andreu, Whinston, Michael D., Green, Jerry R., 2009. Microeconomic theory. Oxford University Press.

McCullough, Deborah, Usborne, Robin, 2011. Emerald Ash Borer. Frequently asked questions. <http://www.emeraldashborer.info/faq.cfm> (accessed 12.09.12)

McIntosh, Christopher R., Shogren, Jason F., Finnoff, David C., 2010. Invasive species and delaying the inevitable: valuation evidence from a national survey. Ecological Economics 69, 632-640.

Olson, Lars J., and Roy, Santanu, 2008. Controlling a biological invasion: a non-classical dynamic economic model. Economic Theory 36, 453–469.

Olson, Lars J., and Roy, Santanu, 2010. Dynamic sanitary and phytosanitary trade policy. Journal of Environmental Economics and Management 60, 21–30.

Oregon Sea Grant. Asian Carps - Aquatic invasions! A menace to the West. Species

Guide 11. < http://seagrant.oregonstate.edu/sites/default/files/invasive-species/toolkit/Asian-Carp.pdf > (accessed 05.03.14)

Perrings, C., Williamson M., Barbier E. B., Delfino D., Dalmazzone S., Shogren J., Simmons P., and Watkinson A., 2002. Biological invasion risks and the public good: an economic perspective. Conservation Ecology 6(1),1. URL: <http://www.consecol.org/vol6/iss1/art1/> (accessed 15.02.13)

Pimentel, David, Zuniga, Rodolfo, and Morrison, Doug, 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecological Economics 52, 273– 288.

Rich, Karl M., Winter-Nelson, Alex, and Brozović, Nicholas, 2005. modeling regional externalities with heterogeneous incentives and fixed boundaries: applications to foot and mouth disease control in South America. Review of Agricultural Economics, 27 (3), 456–464.

Sanchirico, James N., and Wilen, James E., 1999. Bioeconomics of spatial exploitation in a patchy environment. Journal of Environmental Economics and Management 37, 129-150.

Sanchirico, James N., and Wilen, James E., 2005. Optimal spatial management of renewable resources: matching policy scope to ecosystem scale. Journal of Environmental Economics and Management 50, 23–46.

Segerson, Kathleen, 1988. Uncertainty and incentives for nonpoint pollution control. Journal of Environmental Economics and Management 15, 87-98.

Sharov, Alexei A., and Liebhold, Andrew M., 1998. Bioeconomics of managing the spread of exotic pest species with barrier zones. Ecological Applications 8 (3), (Aug.), 833-845.

Sims, Charles, and Finnoff, David, 2012. The role of spatial scale in the timing of uncertain environmental policy. Journal of Economic Dynamics and Control 36, 369-382.

Sydnor, Davis T., Bumgardner, Matthew, and Todd, Andrew, 2007. The potential economic impacts of Emerald Ash Borer (Agrilus planipennis) on Ohio, U.S., Communities. Arboriculture & Urban Forestry. 33(1), 48–54.

The National Creutzfeldt-Jakob Disease Surveillance Unit (NCJDSU), University of Edinburgh, 2009. Variant Creutzfeld-Jakob Disease, Current Data (October). <http://www.cjd.ed.ac.uk/vcjdworld.htm> (accessed 15.02.13).

USDA. Animal and Plant Health Inspection Service, 2010. Hungry pests. Emerald Ash Borer. <http://www.aphis.usda.gov/hungrypests/EAB.shtml> (accessed 02.02.12).

Wilen, James E., 2007. Economics of spatial-dynamic processes. The American Journal of Agricultural Economics 89 (5), 1134–1144.

Yu, Haizhong, Yang, Pu, Liu, Huihong, Yang, Xiao, and Xiao, Zuoan, 2008. The research development of control strategies on Rice Water Weevil. Plantquarantine 22(2), 108-111.

CHAPTER 5

SUMMARY AND CONCLUSION

Invasive species have imposed significant damages worldwide in agriculture, fisheries, forestry, and other industries over the past several decades. The prevention and control of invasive species has therefore become an urgent issue in several areas of the world. The purpose of this dissertation was to examine to what extent optimal preventive and control policies depend upon the economic and biological characteristics of the preventing and controlling the process of an invasive-species introduction and spread.

At the time prevention policies are made, the home country (i.e., the effected country) may or may not observe the foreign country’s (i.e., the exporter of an invasive species) abatement efforts. Further, random factors affecting the efficacy of the abatement process impede the home country’s ability to acquire information necessary for optimal control policies. Particularly for risk-averse foreign countries, uncertainty also influences their abatement decisions and complicates the prevention process. The spread of invasive species within a given region is a dynamic process which involves multiple participants, such as individual land owners. The existence of positive externalities results in the insufficiency of individual control from the optimal social perspective. The urgency of controlling the spread of invasive species entails the coordination of these individual participants.

To begin, this study investigates the effectiveness of a traditional tariff on exported goods (levied by the home country) and proposes a targeted invasive-species tariff in a deterministic, perfect-observability setting. I find that in the case of a constant relationship between invasive species level and shipment size, the traditional tariff can be used to optimally control the invasive species level in the short term. However in the long term, the entry condition is distorted and results in a suboptimal industry size in the foreign country, which in turn entails a lump-sum subsidy to correct the distortion. In the case the invasive species level determined directly by the foreign firm's abatement effort (i.e., the invasive species level is not functionally related to shipment size), an invasive-species tariff levied directly on the invasive species level is necessary to attain the home country's optimal invasive species level. The home country's welfare is directly related to the foreign firm's abatement cost, total shipment size, the invasive species level, and the invasive-species tariff rate.

In the case of a home country with imperfect information concerning the abatement efforts of foreign country and the existence of random environmental variables in abatement process, Holmstrom's (1979) framework is adopted to guide the design of contracts to motivate the foreign country to choose an optimal abatement effort. A contract's subsidy from the home country to the foreign country is in general higher than the home country's first-best subsidy under perfect information. A standard tournament scheme is then developed following Nalebuff and Stiglitz (1983) for the case of multiple risk-averse foreign countries facing both individualistic and common random factors. I show that a rank-order tournament is capable of attaining the home country's first-best solution.

In the dissertation's final essay, an incentive scheme is proposed to prompt coordinated control of a spreading invasive species in a region or a country. Biological and economic properties are integrated in order to model a dynamic process of controlling an invasive species, such as the spread rule, market and physical damage, control cost, and the participants' control behaviors. I find that individualized control is deficient, leading to an uncompensated spatial externality. The spatial externality results from the prevalence of myopic, multiple, spatially-connected participants due to their respective limited spatial considerations, which in turn becomes the critical target of an intervention policy. A multiple-source subsidy instrument, aiming to correcting the externality, which is funded by participants and the government, overcomes the deficiency of individual control. This subsidy scheme expands Wilen's (2007) chained bilateral negotiation system to include all participants directly, and attempts to alleviate the regulatory authority's budget burden.

There are several insights from these models of preventing and controlling the spread of an invasive species. First, the discount rate, biological characteristics of invasive species, effectiveness of detection, level of damage, and cost of control determine the prevention and control process. Second, there are multiple choices as a base for a tax or subsidy scheme, such as a tariff on import volume or on invasive species level, a subsidy on the avoided invaded land, or on control rate itself. The economic instrument (e.g., tax or subsidy) should be directly applied to the targeted behavior in order to achieve an efficient outcome.

Lastly, I show that incentive and participation compatibility are important in policy design. For example, in the static contracting models mentioned above, the home country, especially when constrained by imperfect information, must satisfy a participation constraint, and motivate the foreign countries to choose abatement decisions consistent with the home country's objective. With respect to the dynamic spatial externality model, the coordination process similarly relies on encouraging individual participants to internalize social benefits through a voluntary cooperation scheme, which provides at a minimum status quo welfare level for each participant. At the same time, the incentive scheme must bring decentralized, individual control back to the socially optimal control path.

Controlling invasive species involves cooperation among countries, regional authorities, and individual participants. This process is influenced by biological, technological, and economic factors, which requires further studies in the future. For example, spread patterns should be explicitly addressed for different types of invasive species. Basing on the spread pattern, specific and efficient prevention and control polies may then be promulgated to target the specific invasive species. The evaluation and simulation of damage and control cost also provide insights into the management of invasive species. Experimental case studies, which can provide greater understanding of the spread and control of invasive species, need to be undertaken despite limitations due to the lack of data. Cooperation among ecologists, biologists, and economists may lead to a more thorough understanding of specific invasive species problems and how best to solve them.

References

Holmstrom, Bengt, 1979. Moral hazard and observability. The Bell Journal of Economics 10 (1), (Spring), 74-91.

Nalebuff, Barry J., and Stiglitz, Joseph E., 1983. Prizes and incentives: towards a general theory of compensation and competition. The Bell Journal of Economics 14 (1), (Spring), 21-43.

Wilen, James E., 2007. Economics of spatial-dynamic processes. The American Journal of Agricultural Economics 89 (5), 1134–1144.

APPENDICES

Appendix A. Optimal Tariff and Lump-Sum Entry Tax/Subsidy

The simplest way to determine the lump-sum entry tax/subsidy is to begin by assuming there is a global planner, whose goal is to maximize the joint welfare of the home country and the foreign firms.

Joint welfare is defined as,

$$J = W + \pi$$

$$= \int_0^{ns} P(x)dx - nc(s) - D\big(n\big(I(\cdot)\big)\big) - nas \qquad \text{(A1)}$$

Case 1: Fixed Relationship between Invasive-Species Size and Shipment Size

The global planner's objective is then,

$$\max_s J = \int_0^{ns} P(x)dx - nc(s) - D\big(n\big(I(\,s)\big)\big) - nas \qquad \text{(A2)}$$

leading to the first-order conditions for an interior solution,

$$\frac{\partial J}{\partial s} = P(ns) - \frac{\partial c(s)}{\partial s} - \frac{\partial D(nI)}{\partial (nI)}\frac{\partial I(s)}{\partial s} - a = 0 \qquad \text{(A3)}$$

and

$$\frac{\partial J}{\partial n} = P(ns)s - c(s) - \frac{\partial D(nI)}{\partial (nI)} I(s) - as = 0 \qquad \text{(A4)}$$

From (A3), the optimal level of shipment size, therefore satisfies,

$$\frac{\partial c(s)}{\partial s} = P(ns) - \frac{\partial D(nI)}{\partial (nI)}\frac{\partial I(s)}{\partial s} - a \qquad \text{(A3')}$$

Since the foreign firms are each price-takers, in the absence of the social planner their respective problems are,

$$\max_s \pi = ps - c(s) - \tau^s s \qquad \text{(A5)}$$

leading to the first-order condition,

$$\frac{\partial c(s)}{\partial s} = P(ns) - \tau^s \tag{A6}$$

Thus, comparing (A3') and (A6), a tariff rate set as $\tau^s = \frac{\partial D(nI)}{\partial(nI)} \frac{\partial I(s)}{\partial s} + a$ induces each foreign country to export the socially optimal shipment size to the home country. Note that this tariff rate is identical to that derived in the text, equation (2.5). Given this tariff rate, the firms' respective zero-profit conditions become,

$$Ps - c(s) - \frac{\partial D(nI)}{\partial(nI)} \frac{\partial I(s)}{\partial s} s - as = 0 \tag{A7}$$

which differs from the optimal industry size conditions (A4). Therefore, as in Spulber (1985), a lump-sum tax (or subsidy) per firm, T^*, equal to

$$T^* = \text{s}\left[\frac{\partial D(\cdot)}{\partial(nI)} \frac{I(s)}{s} - \frac{\partial D(\cdot)}{\partial(nI)} \frac{\partial I(s)}{\partial s}\right] \tag{A8}$$

is needed, where each function comprising T^* is evaluated at the optimal values of *s* and *n* determined by (A3) and (A4), thus ensuring the optimal number of foreign firms in the market.[55]

Case 2. Non-Fixed Relationship between Contamination Level and Shipment Size

Assume joint welfare is defined the same as in case 1. The foreign firm can control the invasive-species contamination level directly by adjusting its abatement effort. Therefore, the global planner's objective is expressed as,

$$\max_{s,I} J = \int_0^{ns} P(x)dx - nc(s, I) - D(nI) - nas \tag{A9}$$

The first-order conditions for an interior solution are,

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[55] Later in the text it is shown that the home country's optimal "invasive-species tariff" τ^I, i.e., a tariff levied directly on the shipment's invasive-species level rather than on the shipment size itself, is $\tau^I = \partial D(\cdot)/\partial(nI)$. As Spulber (1985) teaches us, plugging this τ^I into (A8) also determines $T^*=0$, i.e., the global planner's problem does not necessarily need to be solved to determine T^*.

$$\frac{\partial J}{\partial s} = P(ns) - \frac{\partial c(s)}{\partial s} - a = 0 \quad \text{(A10)}$$

$$\frac{\partial J}{\partial I} = -\frac{\partial c(\cdot)}{\partial I} - \frac{\partial D(\cdot)}{\partial (nI)} = 0 \quad \text{(A11)}$$

$$\frac{\partial J}{\partial n} = P(ns)s - c(s, I) - \frac{\partial D(nI)}{\partial (nI)} I - as = 0 \quad \text{(A12)}$$

Since the foreign firms are each price-takers, in the absence of the social planner their respective problems are,

$$\max_{s,I} \pi = ps - c(s, I) - \tau^s s - \tau^I I \quad \text{(A13)}$$

leading to the first-order conditions,

$$\frac{\partial \pi}{\partial s} = P(ns) - \frac{\partial c(s,I)}{\partial s} - \tau^s = 0 \quad \text{(A14)}$$

and

$$\frac{\partial \pi}{\partial I} = -\frac{\partial c(s,I)}{\partial I} - \tau^I = 0 \quad \text{(A15)}$$

Thus, comparing (A10) and (A14), (A11) and (A115), a traditional tariff rate set as $\tau^s = a$ and an invasive-species tariff rate set as $\tau^I = \frac{\partial D(\cdot)}{\partial (nI)}$, induces each foreign firm to export both the socially optimal shipment size and the invasive species level to the home country. Note that this tariff rate and the invasive-species tariff rate are identical to those derived in the text, equations (2.18) and (2.19). Given this tariff rate the firms' respective zero-profit conditions become,

$$Ps - c(s, I) - \frac{\partial D(nI)}{\partial (nI)} I - as = 0 \quad \text{(A16)}$$

This zero-profit condition is identical with (A12). Therefore, the traditional tariff and invasive-species tariff scheme induce the optimal number of foreign firms.

Appendix B. Proof of Lemma 3.1.

First, following Holmstrom (1979) we prove that $\omega > 0$.

By first-order stochastic dominance (FOSD), it follows that $\int f(I|g^L)dI \leq \int f(I|g^H)dI$ for every I, and any given $g^H > g^L$. Thus, $\int f_g(I|g)dI \geq 0$, and there must exist an open set of invasive-species sizes$I' = \{I|\, f_g(I|g)dI > 0\}$ for all $I \in I'$. I' is the largest possible sized set satisfying this condition.

Therefore, if $\lambda \leq 0$, then $\omega > 0$. Otherwise, from (3.15), $\frac{1}{V'(\cdot)} = \lambda + \omega \frac{f_g(I|g)}{f(I|g)} \leq 0$ for all $I \in I'$, which contradicts the curvature condition on welfare function $V(\cdot)$, $V'(\cdot) > 0$.

For $\lambda > 0$, assume that $\omega \leq 0$. Using conditions (3.5) and (3.15), we then have,

$$\frac{1}{V'(t^u(I))} = \lambda + \omega \frac{f_g(I|g)}{f(I|g)} \geq \lambda = \frac{1}{V'(t^a(I))} \tag{B1}$$

for $I \in I''$, where I'' satisfies $\{I|f_g(I|g)dI < 0\}$ and $t^a(I)$ is the first-best subsidy. This result occurs because $1/V'(t(I))$ is increasing in $t(I)$, which implies $t^u(I) \geq t^a(I)$ for $I \in I''$. Conversely, $t^u(I) \leq t^a(I)$for $I \in I'$, and $t^u(I) = t^a(I)$for $I \in I'''$, where $I''' = \{I|f_g(I|g)dI = 0\}$. Therefore for all I we obtain,

$\int t^u(I)f_g(I|g)dI \leq \int t^a(I)f_g(I|g)dI$ by FOSD.

Furthermore, since by FOSD $F(I|g^L) \leq F(I|g^H)$ for every I, and $t^a(I)$ is a constant with respect to all I, it implies $\int t^a(I)f_g(I|g)dI = 0$ from the assumption $\int f_g(I|g)dI \geq 0$ (with strict inequality for some I). Thus,

$$\int t^u(I)f_g(I|g)dI \leq \int t^a(I)f_g(I|g)dI = 0 \tag{B2}$$

Also by FOSD and the maintained assumption of increasing damage,

$$\int D(I) f_g(I|g)dI < 0 \tag{B3}$$

From the foreign country's profit maximization problem, we obtain

$$\int V(t^u(I)) f_{gg}(I|g)dI - Z''(g) < 0 \tag{B4}$$

Combining equations (3.16), (B2), (B3), and (B4), we obtain

$$\underbrace{-\int D(I) f_g(I|g)dI - \int t^u(I) f_g(I|g)dI}_{+} + \omega \underbrace{\left\{\int V(t^u(I)) f_{gg}(I|g)dI - Z''(g)\right\}}_{-} = 0.$$

It follows that $\omega > 0$ must hold, which contradicts the assumption $\omega \le 0$. We therefore conclude that $\omega > 0$.

Next, we prove that $\lambda > 0$.

Again by FOSD, it follows that $\int If(I|g^L)dI \ge \int If(I|g^H)dI,$ which implies $\int If_g(I|g)dI \le 0$. Because I can never be negative, we again note the existence of an open set I'' such that $f_g(I|g) < 0$ for all $I \in I''$. If $\lambda \le 0$, when $\omega > 0$, condition (3.15) then implies that $V'\big(t^u(I)\big) < 0$ at any $I \in I''$, which contradicts the maintained curvature conditions on V(.). Thus, $\lambda > 0$.

Q.E.D.

Appendix C. Proof of Lemma 4.1 - Individual Control Deficiency

For the parcel $q \in [1, n-1]$, the individuals not reaching the steady-state, the nonlinear system of differential equations is

$$\frac{du^{q*}(t)}{dt} = \frac{rc_{u^q}(\cdot^*) - D_x^q(\cdot^*)x^*(t)}{c_{u^q u^q}(\cdot^*)} \tag{4.59}$$

$$\frac{dx^*(t)}{dt} = [g - u^{q*}(t)]x^*(t) \tag{4.54}$$

The nonlinear system of differential equations under the social optimal control is

$$\frac{du^*(t)}{dt} = \frac{rc_u(\cdot^*) - D_x(\cdot^*)x^*(t)}{c_{uu}(\cdot^*)}$$

$$= \frac{rc_u(\cdot^*) - \{\sum_{i=1}^{I} D_x^i[x^*(t), A_i] + D_x^e(x^*(t))\}x^*(t)}{c_{uu}(\cdot^*)} \tag{4.12}$$

$$\frac{dx^*(t)}{dt} = [g - u^*(t)]x^*(t) \tag{4.7c}$$

Compare Equation (4.59) with (4.12), at any specific *x*(*t*). If $du^{q*}(t)/dt = 0$, $u^{q*}(t)$ satisfies $rc_{u^q}(\cdot^*) = D_x^q(\cdot^*)x^*(t)$, and if $du(t)/dt = 0$, $u(t)$ ensures $rc_u(\cdot^*) = \{\sum_{i=1}^{I} D_x^i[x^*(t), A_i] + D_x^e(x^*(t))\}x^*(t)$.By the properties of the individual damage function and the social damage function, $\sum_{i=1}^{I} D_x^i[x^*(t), A_i] + D_x^e(x^*(t)) > D_x^q(\cdot^*)$for any $q \in [1, n-1]$, implying that at specific *x*(*t*), $rc_{u^q}(\cdot^*) < rc_u(\cdot^*)$. With non-decreasing marginal control cost functions $u^q|_{\frac{du^{q*}(t)}{dt}=0} < u|_{\frac{du}{dt}=0}$ for the same *x*(*t*).This implies the $du^{q*}(t)/dt = 0$ isocline is below the $du(t)/dt = 0$ isocline for any $q \in [1, n-1]$.

For parcel *n*, the individual reaching the steady-state, the nonlinear system of differential equations under the individual control is

$$\frac{du^{n*}(t)}{dt} = \frac{rc_{u^n}(\cdot^*) - D_x^n(\cdot^*)x^*(t)}{c_{u^n u^n}(\cdot^*)} \tag{4.45}$$

$$\frac{dx^*(t)}{dt} = [g - u^{n*}(t)]x^*(t) \tag{4.40}$$

Compare Equation (4.45) with (4.12), at a specific *x*(*t*), if $du^{n*}(t)/dt = 0$, $u^{n*}(t)$ satisfies $rc_{u^n}(\cdot^*) = D_x^n(\cdot^*)x^*(t)$, and if $du(t)/dt = 0$, $u(t)$ ensures $rc_u(\cdot^*) = \{\sum_{i=1}^{I} D_x^i[x^*(t), A_i] + D_x^e(x^*(t))\}x^*(t)$. By the properties of the individual damage function and the social damage function, $\sum_{i=1}^{I} D_x^i[x^*(t), A_i] + D_x^e(x^*(t)) > D_x^n(\cdot^*)$. Just as the proof of q parcel, $u(t) > u^{n*}(t)$ for any *x*(*t*) implying

$$u(t)|_{\frac{du^*(t)}{dt}=0,x(t)} > u^{n*}(t)|_{\frac{du^{n*}(t)}{dt}=0,x(t)} \tag{C1}$$

which implies the $du^{n*}/dt = 0$ isocline is below the $du/dt = 0$ isocline.

At the social steady-state, $u(t) = g$; and at the individual steady-state, $u^{n*}(t) = g$. The individual and social steady-states are characterized by $rc_{u^n}(g) = rc_u(g)$ and

$$\left\{\sum_{i=1}^{I} D_x^i[x_{ss}(t_{ss}), A_i] + D_x^e\big(x_{ss}(t_{ss})\big)\right\}x_{ss}(t_{ss}) = D_x^n\big(x_{ss}^n(\tau_{ss}^n)\big)x_{ss}^n(\tau_{ss}^n) \tag{C2}$$

But $\sum_{i=1}^{I} D_x^i[x^*(t), A_i] + D_x^e\big(x^*(t)\big) > D_x^n(\cdot^*)$ at any $x(t)$, and we also assume $\underline{x(t)D_{xx}^i(\cdot) + D_{xx}^i(\cdot) > 0}$ for all $i \in [1, I]$ and $\underline{x(t)D_{xx}^e(\cdot) + D_{xx}^e(\cdot) > 0}$. This implies that equation (C2) can only hold when

$$x_{ss}(t_{ss}) < x_{ss}^n(\tau_{ss}^n) \tag{C3}$$

for any $n \in [1, I]$.

Q.E.D

Appendix D. The Backward Algorithm

As in the theoretical analysis, an individual control relay reaches the steady-state at parcel n. The individual owner n starts to solve the problem in Equation (4.36) once invaded. The simulation exercise of all individuals before steady-state is applied by a backward algorithm design. The backward algorithm is performed through these steps:

1. Calculate the control path of individual n and the steady-state of x_{ss}^n.

Calculate individual n's costate variable at τ_{n-1}, the initial costate variable's value under individual n's control. Using Equaltion (4.55) and (4.56) get

$$R(A_{n-1}) - D^{n-1}[x^*(\tau_{n-1}), A_{n-1}] - c[u^{n-1*}(\tau_{n-1})] +$$

$$\omega^{n-1*}(\tau_{n-1})[g - u^{n-1*}(\tau_{n-1})] - rs_1^{n-1}[x(\tau_{n-1})] = 0 \tag{D1}$$

and

$$x(\tau_{n-1}) = \sum_{i=1}^{n-1} A_i \tag{D3}$$

2. Calculate individual $n-1$'s control rate, state variable, and costate variable from time $\tau_{n-1}-1$ to τ_{n-2} by using Equations (4.51) to (4.54) and $\omega^{n-1*}(\tau_{n-1})$, and $x(\tau_{n-1})$.

$$\begin{cases} u^{n-1*}(\tau_{n-1}-1) = \sqrt{\frac{-\omega^{(n-1)*}(\tau_{n-1}-1)x^*(\tau_{n-1}-1)}{3\eta}} \\ \omega^{n-1*}(\tau_{n-1}-1) = \frac{\omega^{n-1*}(\tau_{n-1})-P\alpha-z\frac{A_{n-1}}{A}}{1+r-\left(g-u^{n-1*}(\tau_{n-1}-1)\right)} \\ x(\tau_{n-1}-1) = \frac{x(\tau_{n-1})}{1+g-u^{n-1*}(\tau_{n-1}-1)} \end{cases} \tag{D4}$$

3. Reiterate steps 2 and 3 from individual $n-2$ to the initial invaded owner.

$$R(A_{n-2}) - D^{n-2}[x^*(\tau_{n-2}), A_{n-2}] - c[u^{n-2*}(\tau_{n-2})]$$

$$+\omega^{n-2*}(\tau_{n-2})[g-u^{n-2*}(\tau_{n-2})]x^*(\tau_{n-2}) - rs_1^{n-2}[x(\tau_{n-2})] = 0 \tag{D5}$$

$$x(\tau_{n-2}) = \sum_{i=1}^{n-2} A_i \tag{D6}$$

and

$$\begin{cases} u^{n-2*}(\tau_{n-2}-1) = \sqrt{\frac{-\omega^{(n-2)*}(\tau_{n-2}-1)x^*(\tau_{n-2}-1)}{3\eta}} \\ \omega^{n-2*}(\tau_{n-2}-1) = \frac{\omega^{n-2*}(\tau_{n-2})-P\alpha-z\frac{A_{n-2}}{A}}{1+r-\left(g-u^{n-2*}(\tau_{n-2}-1)\right)} \\ x(\tau_{n-2}-1) = \frac{x(\tau_{n-2})}{1+g-u^{n-2*}(\tau_{n-2}-1)} \end{cases} \tag{D7}$$

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AWARDS

AAEA Trust Committee Travel Grant 2013
Agricultural & Applied Economics Association Milwaukee, WI

Graduate Student Senate (GSS) Conference Travel Awards 2012 and 2013
Utah State University Logan, UT