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Abstract

This paper analyzes border protection policies for managing risk of unintended imports of invasive species. Previous work typically assumes invasive species risk to be exogenous and commonly known. Here, we examine cases in which endogenous actions (exporter abatement) affect risk and allow for unobservable differences in exporter abatement cost. We show how the optimal inspection/penalty regime differs in such cases from that derived for homogeneous exporters. The information asymmetry also makes it optimal for the regulator to provide technical assistance grants even if it would be otherwise inefficient to do so. Further, we show that the fungibility of technical assistance with inputs in other sectors of the exporting economy significantly affects the qualitative nature of the optimal policy. If it has no outside value in the exporter's country, the optimal policy is characterized by a menu of contracts trading off higher tariffs with lower penalties for being caught with an invasive. If technical assistance can be used in other sectors of the exporter's economy, it introduces countervailing incentives that make it optimal for the regulator to use a uniform tariff/penalty combination for all exporters.

Key words: Asymmetric Information, Inspection, International Trade, Invasive Species,

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Introducing non-native flora and fauna can potentially cause severe disruptions in both domestic ecosystems and domestic economic production. Although some invasive species are deliberately imported (such as for horticultural purposes), many are unintended passengers on other traded goods or their packaging. Recognizing this threat, many countries have introduced phytosanitary border control measures comprising random inspections, penalties (e.g., requirements that cargo infected with invasive species be fumigated or destroyed), as well as alternative approaches such as providing training or other forms of technical assistance to help exporters reduce the threat of infection before the good arrives. Departing from earlier literature, we analyze the optimal mix of such instruments, paying particular attention to cases where there is asymmetric information. Due to local conditions affecting pest populations, for example, the exporter may be better informed than the regulator regarding both the cost of abating invasive risk and the amount of abatement undertaken.

There are two broad categories of policy instruments for managing invasive species, those focused on controlling populations after arrival, and those focused on preventing arrival. One branch of the economics literature addressing invasive species (e.g., Shogren, 2000; Olson and Roy, 2005; Kim et al., 2006; Burnett et al., 2008) uses bio-economic modeling to analyze the optimal mix of generic control and prevention strategies. Another branch (e.g., Eiswerth and Johnson, 2002; Olson and Roy, 2002; Buhle et al., 2005) exclusively examines control strategies for established invasives.

A third branch, to which this paper belongs, analyzes relative merits of specific border control mechanisms such as import tariffs (e.g., Costello and McCausland, 2003; Batabyal and Beladi, 2009), risk abatement subsidies (e.g., Horan and Lupi, 2005), and random inspections and possible penalties (e.g., McAusland and Costello, 2004; Mérel and Carter, 2008). Costello and McCausland (2003) show that purely protectionist measures (such as import tariffs) may reduce damages from invasives, but can also potentially *increase* expected damages by increasing the size of the vulnerable import-competing sector. In a two country model, Batabyal and Beladi (2009) show that the optimal import tariff taking into account invasive damages can vary depending upon market structure (e.g., country size or monopoly power).

Although tariffs can potentially reduce risk by restricting trade, they are blunt instruments and do not give exporters an incentive to undertake risk abating activity. Horan and Lupi (2005) consider the problem of inducing exporters to undertake such measures. In a simulation of ballast water-borne invasive species in the Great Lakes, they compare the cost reduction of a performance-proxy based subsidy (which allows exporters flexibility in their choice of action) relative to a subsidy linked to a particular technology. These importer-provided subsidies are analogous to the technical assistance instrument used in our analysis.

McAusland and Costello (2004) and Mérel and Carter (2008) are the two papers most closely related to our model. McAusland and Costello (2004) develop a model of a regulator tasked with choosing tariffs and inspection intensity to maximize domestic consumer surplus and tax revenue, less expected damages from invasives. Implicitly, an exporter's penalty for being discovered with an invasive is destruction of the shipment. Mérel and Carter (2008) extend this model, analyzing an optimal penalty with endogenous exporter response.

Our model extends McAusland and Costello (2004) and Mérel and Carter (2008) to characterize fully an optimal policy if the regulator cannot observe exporter heterogeneity.[1] Costello et al. (2007) provide evidence that invasive risk varies by trading partner. Information on an exporter's idiosyncratic risk may be asymmetric if, for example, the invasive species is an insect pest. Pest populations can vary both across time and space with current local environmental conditions leading to risk-reduction costs that vary by producer. As a result, they may undertake different levels of effort and thus have better knowledge about the ultimate riskiness of their cargo than the regulator.

Our work in this area is also related to the food safety literature (e.g., Starbird, 2005; Gramig et al., 2009; Sheriff and Osgood, 2010). Starbird (2005) addresses optimal monitoring and penalties with endogenous risk abatement taken by homogenous producers. Sheriff and Osgood (2010) examine optimal testing for livestock disease when exposure is privately known by heterogeneous producers, but risk abatement is not possible. Gramig et al. (2009) assume that producers are ex ante homogenous, but product quality is heterogeneous after endogenous risk abatement takes place. Our model differs from these earlier approaches both in the array of instruments at the regulator's disposal (in particular the inspection intensity and technical assistance) as well as their assumption that producers know their own product quality as well as their abatement action (in our model exporters know costs and actions, but not the ultimate status of their cargo).

In addition to considering information asymmetry, we extend the model to include the additional policy option of technical assistance. Importing countries often undertake technical assistance to prevent or minimize domestic harm from invasives. Since 1967, for example, the North American Plant Protection Organization (NAPPO), has led both regional (Canada, Mexico, and United States) and international efforts to harmonize protection of agricultural, forest and other plant resources against regulated pests while facilitating trade. NAPPO has sponsored technical assistance and preclearance to prevent the introduction and spread of regulated pests as a cost-effective alternative to eradication.[2] NAPPO has funded Canadian experts to provide technical assistance for Peru,

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[1] McAusland and Costello (2004) briefly discuss an example in which differences in exporter characteristics may lead to a suboptimal outcome without formally solving the regulator's problem.

[2] Eradication efforts have had only limited success once an invasive species becomes established.

Argentina, China, Korea, Russia, Malaysia and others to help them meet international standards for treatment of wood-packaging material to kill wood-boring insects (International Standards for Packaging Material [ISPM] #15). Another example of technical assistance involves *Dracaena*, an ornamental plant that can carry invasive grasshoppers, cycadelits, scales, and snails. U.S. Animal and Plant Health Inspection Service specialists from the Port of Miami have been providing training to Costa Rican exporters for development of a Clean Stock program to reduce invasive risk at each stage of the production and export process.

In our model, technical assistance can be thought of as a payment-in-kind of abatement effort. We consider two classes of technical assistance depending upon its outside value. Some forms of technical assistance may be highly specialized, reducing abatement costs without providing inputs that could be used for other purposes. For example, an importing country may provide assistance in the design, construction, or operation of a fumigation facility in a exporting country's port for cargo destined for its borders that has little value in other sectors in the country of origin. Alternatively, technical assistance may be unspecialized, having value in the exporting country outside of the export sector. An example might be training in entomology, pest control, or best management practices that could also be useful in non-exported agricultural production.

We provide a possible explanation for existing technical assistance programs such as those mentioned above. We focus attention on cases for which technical assistance is so costly that it is not efficient for the importer to provide it if there were symmetric information regarding risk abatement costs. Even in such cases, it is optimal for the importer to provide technical assistance if this information is in fact privately held by the exporter. We also find that the difference in outside value of technical assistance to other sectors in the exporting country can have an important effect on the qualitative characteristics of an optimal border protection policy. If technical assistance has no outside value, it is optimal for the regulator to offer exporters a choice of contracts in which a relatively low tariff is paired with a relatively high penalty if caught with an invasive. If technical assistance is fungible, however, it introduces countervailing incentives that make it optimal for the regulator to use a one-size-fits-all policy involving a single tariff/penalty combination for all exporters.

Section 2 describes the basic model. Sections 3 and 4 respectively characterize the optimal policy for specialized and unspecialized technical assistance. Section 5 concludes.

1 Model

We consider a fixed population (normalized to one) of exporters each of whom makes a single shipment.[3] Each exporter is small enough that he considers equilibrium prices to be exogenous to his own actions. For convenience, we assume transport costs are zero and exporters have an identical opportunity cost (normalized to zero) of providing the good. They are differentiated only by an abatement cost parameter $\theta \in \Theta \equiv (0, 1]$, which we refer to as an exporter's *type*. The regulator and exporters share common beliefs regarding the probability distribution of types, $G(\theta)$, with $\mathrm{d}G(\theta) \equiv g(\theta)\mathrm{d}\theta$.

An exporter's cargo is either infected with invasive species or not, with a probability of infection q. Exporters can undertake unobservable (to the regulator) abatement effort, $e(\theta) \geq 0$ to reduce q below its baseline level, $\bar{q} < 1$. Abatement effort has a type-dependent constant marginal cost of θ. The regulator may provide a technical assistance grant ϕ to all exporters. We assume that the grant is a payment-in-kind perfectly substituting abatement effort such that an exporter's risk of infection function is $q\Big(e(\theta) + \phi\Big)$ with $q' < 0, q'' > 0, \lim_{z\to\infty} q(z) > 0$. The constant marginal cost to the regulator of providing technical assistance is normalized to the average cost of effort over all possible exporters, $\bar{\theta} = \int_0^1 \theta \mathrm{d}G(\theta)$.[4]

If an infected shipment enters the importer's market undetected it causes damage δ. The importing country's border protection agency, referred to as the regulator, can conduct a costly imperfect border inspection. The probability of revealing an invasive (if present) is $r(I) \in [0, 1)$, where I is the inspection intensity and $r(0) = 0, r' > 0, \lim_{I\to 0} r'(I) = \infty$, and $r'' < 0$. The constant marginal cost of inspection intensity is k.

Once discovered by the regulator, an infected good is destroyed. If all exporters ship their cargo, imports are thus $M = \int_0^1 \Big[1 - q\Big(e(\theta) + \phi\Big)r(I)\Big] \mathrm{d}G(\theta)$.[5] $P(M)$ denotes the importing country's inverse demand curve, with $P' < 0$ and $\lim_{M\to 0} P(M) < \delta$.

The regulator can levy a tariff τ on all goods (regardless of inspection outcome), and, as in Mérel and Carter (2008) impose a penalty t on goods revealed to be infected. In practice, a border protection agency is unlikely to have latitude to impose import tariffs at its discretion. The analysis remains fundamentally unchanged, however, if τ is given the interpretation of a service that is costly

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[3] An important difference between our model and the previous literature is our implicit assumption of barriers to entry. McAusland and Costello (2004) and Mérel and Carter (2008) assume perfect competition with free entry and a corresponding zero profit condition. Such a framework does not allow for an equilibrium with heterogeneous exporters since those with low-costs would drive their competitors out of the market.

[4] As shown below, these assumptions ensure that under symmetric information it is optimal for the government to provide no technical assistance.

[5] We allow for the possibility that the regulator may design a policy such that some potential exporters may not wish to ship their cargo.

for the regulator to provide, but valuable for the exporter. For example, the regulator may be able to devote resources to cover part of the cost of pre-clearance efforts in which domestic inspectors are sent overseas (such as exists for Canadian and U.S. imports of tulip bulbs from the Netherlands) or other measures (such as increased staffing of "fast lanes") designed to reduce inspection waiting times.[6] However, for expositional ease, and consistency with the preceding literature, we preserve the label of τ as an import tariff.

The penalty may take the form of a bond requirement that exporters would forfeit if an invasive were found. Alternatively, it could be interpreted as a stylized depiction of expenditures the exporter must incur to regain access to the importer's market after an invasive has been found. Mexico, for example, has required that Canadian seed potato exporters discovered to have potato cyst nematodes demonstrate they are cyst free before new shipments are allowed.

We assume I and ϕ are endogenously set by the regulator at a uniform level for all exporters. The regulator can, however, offer a menu of options over which t and τ can vary, effectively allowing exporters to trade off a lower tariff for a higher penalty (or vice versa). Regulators are typically constrained by trade agreements (e.g., membership in the World Trade Organization) that limit their ability to use phytosanitary measures as a barrier to trade. To reflect this fact, we impose a participation constraint; all exporters must earn weakly positive expected profit by sending a shipment to the importing country.

We model the interaction between the regulator and exporters (all parties risk neutral) as a non-repeated Stackelberg game in which the regulator is the first mover. The timing of the game is as follows. The regulator first announces the inspection intensity and technical assistance grant, then "assigns" a contract to each type exporter consisting of a tariff-penalty pair $\langle \tau(\theta), t(\theta) \rangle$.[7] We refer to a contract assigned to an exporter of cost type θ as a type θ contract. Then exporters learn their type and choose their contract. Finally, goods are exported, inspected, and monetary transfers take place. We derive the optimal regulatory policy through backwards induction. We identify the exporters' best response to any set of policy instruments proposed by the regulator, then use this information to derive the regulator's optimal set of policy instruments.

For ease of exposition, we assume satisfaction of all second-order conditions for a unique optimum. We also assume that the problem satisfies potential separation (Jullien, 2000), ensuring that a partial pooling equilibrium does not arise simply due to the shape of the distribution function $G(\theta)$.[8]

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[6] If the regulator's cost of expediting inspections by a unit of time is τ, and is equal to the value of time to the exporter, then even the notation goes through unaltered.

[7] The contract "assignment" refers to the contract that the regulator wishes each type of exporter to choose.

[8] Specifically, we require $\mathrm{d}[G(\theta)/g(\theta)]/\mathrm{d}\theta$ and $\mathrm{d}\big[[G(\theta)-1]/g(\theta)\big]/\mathrm{d}\theta > G(\theta)/g(\theta)\theta$. See Bagnoli and Bergstrom (2005) for properties of likelihood ratios for many common distribution functions. For details regarding solution

2 Specialized technical assistance

In this section, we consider technical assistance with no value to other sectors of the exporting country. For example, this might be provision of a highly specialized piece of equipment used for detection of an invasive on a particular export crop.

For any given contract terms $\langle \tau(\tilde{\theta}), t(\tilde{\theta})\rangle$, an exporter of cost type θ chooses abatement effort to maximize profit, solving

$$\text{(1)} \qquad \max_{e} P - rq(e+\phi)[P + t(\tilde{\theta})] - \tau(\tilde{\theta}) - \theta e.$$

The first-order conditions for (1) are

$$\begin{aligned} &\text{(2)} \qquad & -rq'(e+\phi)[P + t(\tilde{\theta})] - \theta &\leq 0 \\ &\text{(3)} \qquad & e[rq'(e+\phi)[P + t(\tilde{\theta})] + \theta] &= 0. \end{aligned}$$

For positive levels of effort, $\partial e/\partial \phi = -1$; increasing technical assistance offsets exporter effort without reducing risk. Only if there is a corner solution with zero effort will a marginal increase in technical assistance reduce overall risk.

Exporter expected profit from choosing his assigned contract is

$$\text{(4)} \qquad \pi(\theta) = P - rq \;\; e(\theta) + \phi \;\; [P + t(\theta)] - \tau(\theta) - \theta e(\theta).$$

The regulator seeks to maximize the importing country's consumer surplus, less damage caused by invasives and net transfers abroad:

$$\begin{aligned} \text{(5)} \quad \max_{t(\theta),\phi,I,\tau(\theta)} \; & {}_{0}^{M} P(z)\mathrm{d}z - {}_{0}^{1} \Big\{P - rq(e(\theta)+\phi)[P + t(\theta)] - \tau(\theta) + q(e(\theta)+\phi)[1-r]\delta\Big\}\mathrm{d}G(\theta) \\ & -kI - \bar{\theta}\phi, \end{aligned}$$

subject to the no protectionism constraint $\pi(\theta) \geq 0$. Using Eq. (4), this expression simplifies to

$$\text{(6)} \quad \max_{t(\theta),\phi,I,\pi(\theta)} \int_{0}^{M} P(z)\mathrm{d}z - \int_{0}^{1} \Big\{q(e(\theta)+\phi)[1-r]\delta + \theta e(\theta) - \pi(\theta)\Big\}\mathrm{d}G(\theta) - kI - \bar{\theta}\phi,$$

subject to $\pi(\theta) \geq 0$.

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algorithms if potential separation does not hold, see Guesnerie and Laffont (1984).

2.1 Benchmark (commonly known risk abatement cost types)

As a benchmark, suppose the regulator can observe and make contracts contingent upon cost type. Since transfers are costly, she reduces $\tau(\theta)$ as far as possible, leaving all exporters with zero expected profit. Let $t^*(\theta), I^*$, and ϕ^* denote the optimal contract values of the penalty, inspection intensity and technical assistance, and $e^*(\theta)$ be the effort induced by the optimal contract. Using pointwise optimization, the first order conditions for $t^*(\theta)$ are[9]

$$-q'(e^*(\theta)+\phi)[r(I^*)P + [1-r(I^*)]\delta] - \theta \quad \leq \quad 0 \tag{7}$$

$$e^*(\theta)\,[-q'(e(\theta)+\phi)[r(I^*)P + [1-r(I^*)]\delta] - \theta] \quad = \quad 0. \tag{8}$$

Combined with the first order condition for (1) this condition implies

$$e^*(\theta)\,[[1-r(I^*)]\delta - r(I^*)t^*(\theta)] = 0. \tag{9}$$

This result is a straightforward manifestation of the equimarginal principle. For an interior solution, the optimal penalty $t^* = [1-r(I^*)]\delta/r(I^*)$ is chosen such that each exporter's marginal benefit of effort, the reduction in expected fees $r(I^*)t^*$, is equated to the regulator's marginal benefit, the reduction in expected damage $[1-r(I^*)]\delta$.

Consequently $t^{*\prime}(\theta) = 0$ and Eq. (2) implies $\mathrm{d}e(\theta)/\mathrm{d}\theta \leq 0$. Let $e_0^*(\theta)$ denote the optimally induced effort if there were no technical assistance. Since effort is non-increasing in θ there is at most one threshold type $\hat{\theta}^*(\phi) = \inf\{\theta : \phi = e_0^*(\theta)\}$ below which $e_0^*(\theta)$ exceeds actual technical assistance, and above which technical assistance exceeds $e_0^*(\theta)$. The assumptions on $q(\cdot)$ ensure that $\hat{\theta}^*(0) = 1$.

Recalling that $\bar{\theta} = {}_0^1\, \theta \mathrm{d}G(\theta)$, the first order conditions for technical assistance are then

$$ {}_{\hat{\theta}^*(\phi^*)}^{1} \quad - q'(\phi^*)\big[r(I^*)P + [1-r(I^*)]\delta\big] - \theta \;\; \mathrm{d}G(\theta) \quad \leq \quad 0 \tag{10}$$

$$\phi^* \left[{}_{\hat{\theta}^*(\phi^*)}^{1} \quad - q'(\phi^*)\big[r(I^*)P + [1-r(I^*)]\delta\big] - \theta \;\; \mathrm{d}G(\theta) \right] \quad = \quad 0. \tag{11}$$

Intuitively, the benefit to the regulator of a marginal increase in technical assistance varies by exporter cost type. For types below the threshold, technical assistance merely offsets exporter effort. Therefore there is no benefit in terms of risk reduction for these types. There is, however, a monetary benefit inasmuch as the regulator can increase the tariff by the value of the reduced effort. The

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[9] Recall that $M = \int_0^1 \left[1 - q\Big(e(\theta)+\phi\Big)r(I)\right] \mathrm{d}G(\theta)$, so that by Liebniz' rule, $\mathrm{d}/\mathrm{d}t \left[\int_0^M P(z)\mathrm{d}z\right] = P(M)\int_0^1 -q'(e(\theta)+\phi)r(I)\partial e/\partial t \mathrm{d}G(\theta)$.

sum of this marginal benefit is ${}^{\hat{\theta}^*(\phi^*)}_{0}\ \theta \mathrm{d}G(\theta)$. For types above the threshold, the opposite is true. Increasing technical assistance reduces risk, for a marginal benefit of ${}^{1}_{\hat{\theta}^*(\phi^*)}\ \big\{ -q'(\phi^*)\ r(I^*)P + [1 - r(I^*)]\delta \big\} \mathrm{d}G(\theta)$, but does not have a direct monetary benefit. Since the penalty is optimally set to ensure that the marginal benefit of risk reduction equals its marginal cost for all types, this additional risk reduction is inefficient. Recalling that $\bar{\theta} = {}^{1}_{0}\ \theta \mathrm{d}G(\theta)$, and using Eq. (2) implies that condition (10) can be restated as

$$(12) \qquad {}^{1}_{\hat{\theta}^*(\phi^*)} \quad -q'(\phi^*)r(I^*)\ \ P + t(\theta)\ \ -\theta\ \ \mathrm{d}G(\theta) \leq 0.$$

The first order conditions for the optimal penalty (7) and (8) ensure that this expression is a strict inequality for all $\phi^* > 0$. Consequently $\phi^* = 0$, and all exporters supply strictly positive effort.

The optimal inspection rate is chosen simultaneously with $t^*(\theta)$ to solve[10]

$$(13) \qquad {}^{1}_{0}\ r'(I^*)q[\delta - P]\mathrm{d}G(\theta) - k \quad = \quad 0.$$

The expected marginal benefit from avoided net damage is set equal to the marginal inspection cost.[11]

In addition to setting the stage for analysis with private information, this benchmark case serves to highlight the implications of differences between our modeling framework and that of McAusland and Costello (2004) and Mérel and Carter (2008). Regarding the optimal values of the penalty variable, t, and inspection intensity, I, our results are identical to those of Mérel and Carter (2008). The main difference is with respect to the optimal tariff. The free entry assumption in previous work implies that the only benefit of a tariff is to restrict trade (and its associated costs). In our framework, tariffs do not restrict trade, but only serve to transfer rents from exporters to the regulator. Our optimal tariff (unlike the optimal penalty) is therefore different for each type of exporter.

2.2 Privately known risk abatement cost types

We now consider the case of both cost type and effort being privately known by the exporter. For a contract allocation to be feasible, exporters must maximize profit by choosing their assigned contract. With a slight abuse of notation, let $e(\tilde{\theta}, \theta)$ denote the effort provided by an exporter of

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[10] Recall that $M = \int_0^1 \Big[1 - q\Big(e(\theta) + \phi\Big) r(I)\Big] \mathrm{d}G(\theta)$, so that by Liebniz' rule, $\mathrm{d}/\mathrm{d}I \Big[\int_0^M P(z)\mathrm{d}z\Big] = P(M) \int_0^1 -q\Big(e(\theta) + \phi\Big) r'(I)\mathrm{d}G(\theta)$.

[11] It is not necessarily optimal for the regulator to set the penalty arbitrarily high in order to eliminate inspection costs; since q is strictly positive it may still be optimal to inspect even as abatement effort approaches infinity.

type θ with a contract of type $\tilde{\theta}$. This requirement implies the following incentive compatibility constraints:

$$\theta \in \arg\max_{\tilde{\theta}} \quad P - rq(e(\tilde{\theta},\theta)+\phi)[P+t(\tilde{\theta})] - \tau(\tilde{\theta}) - \theta e(\tilde{\theta},\theta) \quad \text{for all } (\theta,\tilde{\theta}). \tag{14}$$

Using (2), the first order condition of the maximization problem in (14) is

$$-rq(e(\theta)+\phi)t'(\theta) - \tau'(\theta) = 0 \text{ for all } \theta. \tag{15}$$

After totally differentiating this expression, the second order condition can be expressed as

$$-\frac{t'(\theta)q'(e(\theta)+\phi)}{q''(e(\theta)+\phi)} \leq 0. \tag{16}$$

Consequently, incentive compatibility requires

$$t'(\theta) \leq 0. \tag{17}$$

That is, the penalty must be non-increasing in type.

Differentiating (4) and using (15) implies that equilibrium profit is non-increasing in type at rate

$$\pi'(\theta) = -e(\theta). \tag{18}$$

Let $e_0(\theta)$ denote the effort induced by an optimal contract under asymmetric information with no technical assistance. The regulator could eliminate the hidden information problem altogether by setting $\phi = \max_\theta\{e_0(\theta)\}$, i.e., providing so much technical assistance that no exporter provides any effort. Since technical assistance is costly, however, such a strategy is generally not optimal.

Since the regulator's welfare function is decreasing in profit, it is optimal for the regulator to select $\tau(1)$ to leave the highest type with zero profit. Using (18), exporter profit can then be expressed as:

$$\pi(\theta) = \int_\theta^1 e(z)\mathrm{d}z. \tag{19}$$

Incorporating participation and incentive compatibility constraints the regulator's problem is

$$(20)\quad \max_{t(\theta),I,\phi} \int_0^M P(z)\mathrm{d}z - \int_0^1 \left\{ q(e(\theta)+\phi)[1-r]\delta + \theta e(\theta) + \int_\theta^1 e(z)\mathrm{d}z \right\} \mathrm{d}G(\theta) - kI - \bar{\theta}\phi.$$

After integrating by parts, this expression simplifies to

$$(21)\quad \max_{t(\theta),I,\phi} \int_0^M P(z)\mathrm{d}z - \int_0^1 \left\{ q(e(\theta)+\phi)[1-r]\delta + e(\theta)\left[\theta + \frac{G(\theta)}{g(\theta)}\right] \right\} \mathrm{d}G(\theta) - kI - \bar{\theta}\phi.$$

The first-order conditions for $t(\theta)$ are

$$\begin{aligned} &(22) & -q'(e(\theta)+\phi)[rP+[1-r]\delta] - \theta &\leq \frac{G(\theta)}{g(\theta)} \\ &(23) & e(\theta)\left[-q'(e(\theta)+\phi)[rP+[1-r]\delta] - \theta - \frac{G(\theta)}{g(\theta)}\right] &= 0. \end{aligned}$$

The right hand side (RHS) of (22) indicates the distortion induced by asymmetric information. Using (2), Eq. (23) simplifies to

$$(24)\quad e(\theta)\left[-q'(e(\theta)+\phi)[[1-r]\delta - rt] - \frac{G(\theta)}{g(\theta)}\right] = 0.$$

For a given inspection rate, the interior solution equilibrium value of the penalty is lower than the benchmark case for all but the lowest type. Also, unlike the benchmark case, the penalty is decreasing (rather than constant) in type.

Eq. (2) then implies $\mathrm{d}e(\theta)/\mathrm{d}\theta \leq 0$. Since effort is non-increasing in θ there is at most one threshold type $\hat{\theta}(\phi) = \inf\{\theta : \phi = e_0(\theta)\}$. Similarly to the case without private information, the assumptions on $q(\cdot)$ ensure that $\hat{\theta}(0) = 1$.

The first order conditions for technical assistance are

$$\begin{aligned} &(25) & \int_0^{\hat{\theta}(\phi)} \left\{\theta + \frac{G(\theta)}{g(\theta)}\right\} \mathrm{d}G(\theta) + \int_{\hat{\theta}(\phi)}^1 \quad - q'(\phi)\left[rP + [1-r]\delta\right] \quad \mathrm{d}G(\theta) - \overline{\theta} &\leq 0 \\ &(26) & \phi \int_0^{\hat{\theta}(\phi)} \frac{G(\theta)}{g(\theta)} \mathrm{d}G(\theta) + \int_{\hat{\theta}(\phi)}^1 \{-q'(\phi)\left[rP + [1-r]\delta\right] - \theta\}\mathrm{d}G(\theta) &= 0. \end{aligned}$$

Unlike in the benchmark case, technical assistance has two marginal benefits with respect to types below the threshold $\hat{\theta}(\phi)$. As before, the effective subsidy causes exporters to reduce their effort, allowing the regulator to increase the tariff by θ. In addition, this reduction in effort further reduces payments to firms caused by the information asymmetry by $G(\theta)/g(\theta)$. With respect to types above the threshold the marginal benefits of technical assistance are to reduce the risk of infection. With private information, it is optimal for the regulator to set $\phi > 0$. To see this note that, in contrast to the benchmark case, the left hand side of (25) is strictly positive if there is no technical assistance, i.e., the highest type is the threshold.

Using, Eq. (22), the first order condition for I is

$$\int_0^1 \{r'(I)q(e(\theta)+\phi)[\delta - P] - k\}\,\mathrm{d}G(\theta) \quad = \quad 0, \tag{27}$$

i.e., the same expression (up to $e(\theta)$ and ϕ) as in the benchmark case. The distortion in inspection intensity caused by private information is felt only indirectly through the effect on penalties and technical assistance. The fact that penalties (and hence induced effort) are lower than under the benchmark case places an upward distortion on inspection rates. This effect may be counterbalanced by technical assistance. If the increase in abatement caused by technical assistance for $\theta > \theta(\phi)$ results in a higher total abatement for these types than in the benchmark case it will place downward pressure on inspection rates.

3 Unspecialized technical assistance

We now consider the possibility that technical assistance has a value to producers in other sectors of the exporter's country. We assume that this outside value is positively correlated with the exporter's cost type. For example, if entomological expertise is relatively valuable to an exporter in a particular country it may also be relatively valuable to other producers in the same country, such as farmers of a crop for domestic consumption. In this case, technical assistance can be thought of as a lump sum transfer whose value is a function of an exporter's type. For simplicity, we assume that this outside value is $\theta\phi$.

In this case, the exporter's effort level solves

$$\max_e P - rq(e)[P + t(\tilde{\theta})] - \tau(\tilde{\theta}) - \theta[e - \phi], \tag{28}$$

and is not a function of technical assistance. The first-order conditions for (28) are

$$-q'(e)r[P + t(\tilde{\theta})] \quad \leq \quad \theta \tag{29}$$

$$e \quad -q'(e)r[P + t(\tilde{\theta})] - \theta \quad = \quad 0 \tag{30}$$

Equilibrium exporter expected profit is

$$\pi(\theta) = P - rq(e(\theta))[P + t(\theta)] - \tau(\theta) - \theta[e(\theta) - \phi]. \tag{31}$$

The regulator seeks to maximize the importing country's consumer surplus, less damage caused by invasives and net transfers abroad:

$$\max_{t(\theta),I,\phi} \int_0^M P(z)\mathrm{d}z - \int_0^1 \{q(e(\theta))[1-r]\delta + \theta e(\theta) - \pi(\theta)\}\,\mathrm{d}G(\theta) - kI - \bar{\theta}\phi. \tag{32}$$

3.1 Commonly known risk abatement cost types

Recall from Section 2.1 that if technical assistance has no outside value, it can potentially increase the amount of abatement undertaken by some exporters. In that case, it was not optimal for the regulator to provide assistance if cost types were commonly known. If it has an outside value, however, we have just shown that it does not affect the abatement of *any* exporter. Thus, the benefit to the regulator of providing it is even lower. Consequently, the regulator has no incentive to provide technical assistance with an outside value if exporter type is commonly known.

3.2 Privately known risk abatement cost types

If type is privately known, a feasible contract must satisfy incentive compatibility. Since trade is voluntary, exporters only send shipments if their expected profit is positive. For a contract allocation to be feasible, exporters must maximize profit by choosing their assigned contract. This requirement implies the following incentive compatibility constraints:

$$\theta \in \arg\max_{\tilde{\theta}} \quad P - rq(e(\tilde{\theta},\theta))[P + t(\tilde{\theta})] - \tau(\tilde{\theta}) - \theta[e(\tilde{\theta},\theta) - \phi] \quad \text{for all } (\theta,\tilde{\theta}); \tag{33}$$

Using the same steps as Eqs. (15)-(18), it can be shown that incentive compatibility requires that the penalty be non-increasing in type (i.e., satisfies condition (17)), and that equilibrium profit change in type at rate

$$\pi'(\theta) = \phi - e(\theta). \tag{34}$$

In contrast to the case for specialized technical assistance, profit is increasing in type if the exporter's effort is less than the level of technical assistance. Intuitively, exporters face countervailing incentives as in Lewis and Sappington (1989). One incentive is as before; exporters have an underlying incentive to overstate type to obtain higher compensation for their cost of effort. Exporters also face an incentive to understate type, however. Doing so understates the value of the technical assistance received. With specialized technical assistance, the former incentive dominates the latter for all types. If technical assistance is unspecialized, however, its outside value makes it even more valuable for high cost types. For those types with technical assistance "left over," i.e., whose effort is less than ϕ, the latter incentive dominates.

For those exporters whose effort exactly equals the technical assistance, the two incentives cancel out. Since $e(\theta)$ is non-increasing in type, $\pi(\theta)$ is convex.[12] The regulator's welfare function is decreasing in profit. Consequently, the best she can do is reduce the profit of this last set (if it exists) to zero. Condition (2) implies that effort is decreasing in θ and increasing in t. Combined with (17), a further implication is that the set of types receiving zero profit in equilibrium is a singleton.[13] That is to say, maintaining a constant level of effort across an interval of types would require the penalty to be *increasing* in type, which would violate incentive compatibility condition (17). Let $\theta^0(\phi)$, denote the zero profit type, and t^0 denote the penalty assigned to θ^0. Using (34), exporter profit can then be expressed:

$$\pi(\theta) = \begin{cases} \int_{\theta}^{\theta^0(\phi)} \{e(z) - \phi\}\mathrm{d}z & \text{for } \theta < \theta^0(\phi) \\ 0 & \text{for } \theta^0(\phi) \\ \int_{\theta^0(\phi)}^{\theta} \{\phi - e(z)\}\mathrm{d}z & \text{for } \theta^0(\phi) < \theta. \end{cases} \tag{35}$$

After incorporating participation and incentive compatibility constraints and integrating by parts, the regulator's problem is

$$\max_{t(\theta),\phi,I} \int_0^M P(z)\mathrm{d}z - \int_0^1 \{q(e(\theta))[1-r]\delta + \theta e(\theta)\}\,\mathrm{d}G(\theta) - kI \tag{36}$$

$$- \int_0^{\theta^0(\phi)} \frac{G(\theta)}{g(\theta)}[e(\theta) - \phi]\mathrm{d}G(\theta) - \int_{\theta^0(\phi)}^{1} \frac{1-G(\theta)}{g(\theta)}[\phi - e(\theta)]\mathrm{d}G(\theta)$$

$$\text{subject to} \quad t(\theta) > t^0 \text{ for } \theta < \theta^0 \tag{37}$$

$$t^0 > t(\theta) \text{ for } \theta > \theta^0. \tag{38}$$

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[12] As Lewis and Sappington (1989) provide an in-depth formal analysis of a problem with similar structure, here we only provide a sketch of the proofs required to characterize the equilibrium contract. For a treatment of more general classes of problems exhibiting countervailing incentives, see Maggi and Rodríguez-Clare (1995) and Jullien (2000).

[13] If profit is either increasing or decreasing over the entire support, then it is optimal for one of the extreme types to receive zero surplus.

Let $\lambda(\theta)$ and $\mu(\theta)$ be Lagrange multipliers for (37) and (38). The first-order conditions for $t(\theta)$ are

$$-q'(e(\theta))[rP + [1-r]\delta] - \theta - \frac{G(\theta)}{g(\theta)} \; \tfrac{\partial e(\theta)}{\partial t} + \lambda(\theta) \quad = 0 \quad \text{for } \theta < \theta^0(\phi) \tag{39}$$

$$-q'(e(\theta))[rP + [1-r]\delta] - \theta - \frac{G(\theta)-1}{g(\theta)} \; \tfrac{\partial e(\theta)}{\partial t} - \mu(\theta) \quad = 0 \quad \text{for } \theta > \theta^0(\phi). \tag{40}$$

It is straightforward to show (see Lewis and Sappington, 1989, Lemma 5) that if $\theta^0(\phi) \in (0,1)$ then there will be one and only one pooling interval over which the penalty is constant. Moreover, that interval contains $\theta^0(\phi)$, and the pooling penalty is optimally set to $t_0 = [1-r]\delta/r$. Note that this amount is the same as under no adverse selection (conditional on I).

Intuitively, whenever constraints (37) and (38) do not bind, the Potential Separation assumption ensures that the paths for $t(\theta)$ as defined by Eqs. (39) and (40) are strictly decreasing. Thus there can be no pooling interval that does not contain $\theta^0(\phi)$.

Let $t^G(\theta)$ denote the penalty path defined by Eq. (39), setting $\lambda(\theta) = 0$. Note that on that path,

$$-q'(e(\theta))[rP + [1-r]\delta] - \theta = \frac{G(\theta)}{g(\theta)} > 0. \tag{41}$$

Similarly, let $t^{G-1}(\theta)$ denote the penalty path defined by Eq. (40), with $\mu(\theta)$ set to zero. Note that in this case

$$-q'(e(\theta))[rP + [1-r]\delta] - \theta = \frac{G(\theta)-1}{g(\theta)} < 0. \tag{42}$$

Since $q''\partial e/\partial t > 0$, for any given θ, it follows that $t^G(\theta) < t^{G-1}(\theta)$. Thus, if there is no pooling (both Lagrange multipliers are zero) then the value of $t^G(\theta)$ as θ approaches $\theta^0(\phi)$ from below is strictly lower than the limit of $t^{G-1}(\theta)$ as θ approaches $\theta^0(\phi)$ from above. Such a result, however would violate the monotonicity condition $t'(\theta) < 0$. Thus, the two constraints must bind (i.e., there is pooling, and the Lagrange multipliers are non-zero) for some non-degenerate interval around $\theta^0(\phi)$.

Gathering these results, and letting $\theta^\alpha(\phi)$ and $\theta^\beta(\phi)$ denote the lower and upper bounds of the pooling interval, we have

$$t(\theta) \quad = \begin{cases} t^G(\theta) = \dfrac{[1-r]\delta - \frac{PrG(\theta)}{g(\theta)\theta}}{r\left[1+\frac{G(\theta)}{g(\theta)\theta}\right]} & \text{for } \theta < \theta^\alpha(\phi) \\ t^0 = \dfrac{[1-r]\delta}{r} & \text{for } \theta^\alpha(\phi) \le \theta \le \theta^\beta(\phi) \\ t^{G-1}(\theta) = \dfrac{[1-r]\delta - \frac{Pr[1-G(\theta)]}{g(\theta)\theta}}{r\left[1+\frac{1-G(\theta)}{g(\theta)\theta}\right]} & \text{for } \theta > \theta_\beta(\phi). \end{cases} \tag{43}$$

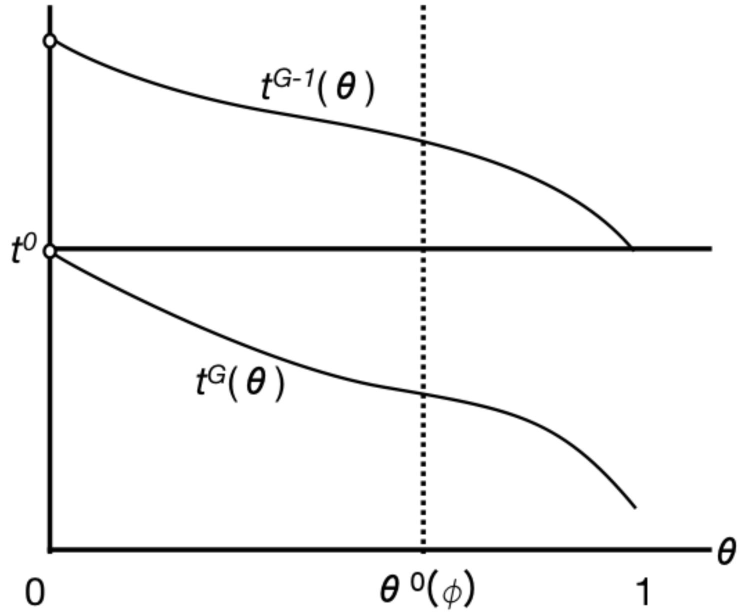

Figure 1: If technical assistance is fungible, there is a uniform optimal penalty, t_0, for being caught with an invasive.

As depicted in Figure 1, the equilibrium pooling interval comprises the entire support for all ϕ since $\lim_{\theta\to 0} t^G(\theta) < t^0$ and $t^{G-1}(1) = t^0$, and the potential separation property requires that both t^G and t^{G-1} be non-increasing in θ. Consequently, the regulator can do no better than offer the same penalty, $[1 - r(I)]\delta/r(I)$, to all exporters.

The optimal levels of ϕ and I are then obtained by solving

$$\text{(44)}\qquad \begin{aligned} \max_{\phi,I} & \int_0^M P(z)\mathrm{d}z - \int_0^1 \{q(e(\theta))[1 - r(I)]\delta + \theta e(\theta)\}\,\mathrm{d}G(\theta) - kI \\ & - \int_0^{\theta^0(\phi)} \tfrac{G(\theta)}{g(\theta)}[e(\theta) - \phi]\mathrm{d}G(\theta) - \int_{\theta^0(\phi)}^1 \tfrac{1-G(\theta)}{g(\theta)}[\phi - e(\theta)]\mathrm{d}G(\theta) \\ \text{subject to} & \quad t(\theta) = \frac{[1 - r(I)]\delta}{r(I)} \text{ for all } \theta. \end{aligned}$$

The first-order condition for ϕ is

$$\text{(45)}\qquad \int_0^{\theta^0(\phi)} G(\theta)\mathrm{d}\theta - \int_{\theta^0(\phi)}^1 [1 - G(\theta)]\mathrm{d}\theta = 0.$$

By Eq. (34), a marginal increase in technical assistance alters the rate at which surplus profit changes over type, reducing it (in absolute value) for $\theta < \theta^0(\phi)$ and increasing it for $\theta > \theta^0(\phi)$. The marginal reduction in surplus payments for the former interval is $\int_0^{\theta^0(\phi)} G(\theta)\mathrm{d}\theta$ and the marginal increase for the latter is $\int_{\theta^0(\phi)}^{1}[1-G(\theta)]\mathrm{d}\theta$. Optimally, the regulator chooses ϕ such that the net marginal effect is zero. Since $\theta^0(0)=1$, the net marginal effect of increasing technical assistance from zero is strictly positive, implying that in equilibrium $\phi > 0$.

The first-order condition for I is

$$\begin{aligned}\int_0^1 r'(I)q(e(\theta)+\phi)[\delta-P]\mathrm{d}G(\theta)-k &= \int_0^{\theta^0(\phi)} G(\theta)\tfrac{\partial e}{\partial r}r'(I)\mathrm{d}\theta - \int_{\theta^0(\phi)}^{1}[1-G(\theta)]\tfrac{\partial e}{\partial r}r'(I)\mathrm{d}\theta \\ &= \int_0^{\theta^0(\phi)} \tfrac{G(\theta)q'(e(\theta))r'(I)}{r(I)q''(e(\theta))}\mathrm{d}\theta - \int_{\theta^0(\phi)}^{1} \tfrac{[1-G(\theta)]q'(e(\theta))r'(I)}{r(I)q''(e(\theta))}\mathrm{d}\theta. \end{aligned} \tag{46}$$

Notice that in contrast with Eqs. (13) and (27), asymmetric information introduces a distortion in the optimal inspection level, indicated by the right hand side of Eq. (46). With commonly held information it is optimal to have a uniform penalty for all exporters. In the case in which technical assistance has no outside value, private information introduces a distortion, making it optimal to vary the penalty by exporter type. The optimal inspection rate is not directly distorted, however. If technical assistance has an outside value, the situation is reversed. The countervailing incentive provided by the technical assistance grant creates a pooling equilibrium in which it is not optimal to vary penalties by exporter. The optimal inspection intensity is distorted since it affects the type that receives zero surplus and hence the accumulated surplus over the whole support. Whether it is distorted upwards or downwards depends upon the distribution of exporter types.

4 Conclusion

Implementation of border control measures to reduce the risk of unintentional entry of invasive species is likely to be affected by both hidden actions and private information. Hidden actions occur if exporters can undertake unobservable (to the importing country's border protection agency) effort to reduce the risk of an invasive being on their shipment. Private information exists if exporters are heterogeneous in their cost of undertaking such actions.

In this paper we have characterized an optimal border control strategy under such conditions. The border control strategy consists of an inspection intensity, a penalty levied if inspections reveal the presence of an invasive, technical assistance provided by the regulator, and a transfer.

The transfer is not necessarily an import tariff, and can be interpreted as other types of existing policies that are more likely to be under the discretion of a regulating agency, such as pre-clearance inspections. Dating from 1951, the oldest North American pre-clearance program involves inspectors being sent to the Netherlands to prevent importation of pests on plant bulbs. The program benefits

Dutch exporters by reducing inspection time and lost product (rejected bulbs can be used in another market). This program involves coordination between the Dutch government, exporters, and U.S. and Canadian inspectors.

We model inspection intensity and technical assistance as being applied equally to all exporters. We also consider a policy innovation that would allow exporters to voluntarily reduce their import tariff in exchange for an increased penalty to be levied in the event that an invasive is found in their shipment.

We consider this set of policy tools under two settings regarding technical assistance relevant to real world agricultural trade in North America. In the first, technical assistance takes the form of a highly specialized type of training or equipment that has no value outside the exporting firm, such as pest control for a specific grower's location only. Under the second, technical assistance does have an outside value that is correlated with the exporter's risk abatement cost. We compare these outcomes to a benchmark case in which there is no private information.

Without private information, there is need for neither technical assistance nor variation in tariffs and penalties. The penalty is set at a level sufficient to induce the optimal level of risk abatement effort. It is similar to a Pigouvian tax in that producers choose abatement such that their marginal cost is equated to the expected penalty. At the optimum, the regulator sets the penalty equal to expected marginal benefit of abatement so that in equilibrium the equimarginal principle is satisfied and the expected marginal costs are equal across firms and equal expected marginal benefit.

With private information, the problem becomes more complicated. In the absence of technical assistance firms have an underlying incentive to behave in a manner that overstates abatement costs. Doing so limits the maximum tariff that the regulator is willing to impose. The best that the regulator can do is to allow exporters to select a tariff/penalty combination from a menu of options. Such a strategy sacrifices economic efficiency (arising from violation of the equimarginal principal) in exchange for a reduction in information rents paid to exporters. In contrast to cases examined in previous literature in which both the regulator and exporter are equally informed, we find that asymmetric information provides a strong incentive for the regulator to provide positive levels of technical assistance. This result may help explain the existence of policies such as the Clean Stock program and importer financed support for treatment to meet ISPM #15.

We find that the outside value of technical assistance crucially affects the optimal regulatory structure. If technical assistance is highly specialized, it is in the regulator's interest to provide a strictly positive amount. Technical assistance helps the regulator since its value to firms is an increasing function of abatement costs. Intuitively, if firms claim to have high abatement costs, they are also claiming that the technical assistance is valuable to them. The higher the value of the technical assistance, the higher the tariff that the regulator can levy and still have the exporter be willing to ship the good.

If technical assistance is unspecialized, the problem is more complicated, but the solution is simpler. Without an outside value, the upper bound of the value of technical assistance to the exporter is the amount of effort that it displaces. If it has an outside value, this is no longer the case. Even if a firm undertakes no effort, it can resell the technical assistance in its home market. In practice, this distinction is important since it introduces the potential for countervailing incentives. Very low-cost exporters have high levels of abatement and use all their technical assistance. Since it has a low value, however, their dominant incentive is to overstate their true cost to get a lower tariff. At the opposite extreme, very high-cost exporters have low levels of abatement, but receive a relatively large income from reselling technical assistance. Consequently, their dominant incentive is to understate their true cost to get a lower tariff. For some intermediate type these two incentives can exactly counteract each other, leaving them with no incentive pulling in either direction. We show that under these conditions the optimal policy exhibits pooling over the entire range of types: they all have the same penalty and tariff. Qualitatively, the policy resembles that under conditions without private information except that there is strictly positive provision of technical assistance. In practice, it would be simpler to administer than if technical assistance were specialized and may yield higher expected welfare for the regulator. It also has the possible advantage of being non-discriminatory with respect to trading partners. Perhaps counter-intuitively, in some circumstances it may be in the regulator's interest to provide technical assistance in a manner that the recipient can resell it.

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