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Avoiding invasives: trade-related policies for controlling unintentional exotic species introductions ☆

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Abstract

International commodity trade serves as the primary conduit for unintentional introductions of damaging exotic species. We use a simple model of contaminated goods trade to analyze the optimal mix of tariffs and inspections as means of controlling damage from this negative externality. Among other policy-relevant results, we find that (1) while it is always optimal to employ tariffs, there are non-trivial cases in which inspections should optimally be set to zero, (2) a higher infection rate requires a higher tariff, but beyond a point optimal inspections decrease in the infection rate, and finally (3) taking a dynamic view and considering future effects of current introductions leads unambiguously to more stringent inspections, but may give rise to higher or lower tariffs.

Keywords: Environment; Trade; Tariffs; Monitoring; Invasive species

1. Introduction

International trade and transport of goods is a primary conduit for exotic species introductions. This paper examines the substitutability and complementarity between different policy tools aimed at minimizing the introduction of exotic (also called non-native, non-indigenous, or

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introduced) pests. We focus on two policies: trade taxes and port inspections. By viewing exotic species as an unintended byproduct of trade, the traditional economic approach to regulation would rely on identifying the optimal Pigouvian tax to internalize the externality. On the other hand, since trade itself is not the problem, some would argue that trade should not be suppressed, but rather, that inspections should be designed to optimally weed out the most offensive individuals. In the real world, both instruments are utilized to regulate exotic species imports; we derive the optimal mix of these alternatives as a function of key attributes of the importing and exporting countries.

One of the most interesting linkages is between the infectedness of traded goods and the optimal policy responses, analyzed in Sections 2 and 3. In particular, we find that the optimal trade tax is positive and tends to increase in the proportion of imports that harbor (or will become) invasive species, while the optimal level of port inspections is, after a point, decreasing in that proportion. In fact, once the infection rate passes some threshold, it is optimal to not inspect at all and just charge an appropriately high import tariff equal to the anticipated damage from any received good.

Also noteworthy is the relationship between optimal policy and the damage associated with infected units. We show that an importer should always inspect incoming goods more intensively the more damaging would be any undetected contamination, but that she may want to tax those goods more leniently.

We then use these results to determine whether and how the importing country should discriminate against the goods from countries with different characteristics—characteristics such as their infection rates, anticipated damages, and production costs. For example, an importer with two trade partners (supplying unconnected markets) with disparate infection rates may well want to levy a higher tariff on goods from the country with the high infection rate, but choose to subject goods from that same country to less rigorous inspection at its ports. When multiple trade partners vie to supply a single market in Home, we show that Home's 'optimal' trade partner may not be the supplier exhibiting the lowest infection rate or carrying the least damaging pests. We also examine whether Home's optimal partner may be priced out of the market if Home sets identical tariffs on all incoming goods.

Sections 4 and 5 offer extensions and robustness checks of the model. In Section 4, we examine the case of an exporter able, at a cost, to reduce the rate at which its exports are infected. We show that the order of moves and the specificity of policy—specific to individual firms or to an industry as a whole—alters the level of pre-export cleanup undertaken by firms. We find that all players (atomistic foreign firms and the Home government) will set their policy instruments at the levels that maximize the joint welfare of the two countries if Home offers infection-rate contingent taxes and monitoring to foreign firms. If instead Home offers industry wide policies, then Foreign firms will undertake suboptimal levels of pre-export cleanup; if in addition Foreign firms move second (choosing cleanup levels after Home instrument levels have been announced) then Home will also tax and inspect received goods excessively.

Section 5 develops a dynamic analysis incorporating population growth of introduced species. The dynamic model has a dual interpretation to the static model; the social planner's dynamic objective equals her static objective plus an additional non-linear damage term. We analyze this dynamic model and show that accounting for population growth can affect optimal policy design in important, often counterintuitive ways. Section 6 concludes.

1.1. Background

The enormous ecological, agricultural, and other pecuniary damages associated with invasive species are widely recognized. And while ecologists have diligently cataloged the ex post consequences of invasions, ex ante prediction, i.e. forecasting which species will invade and how they will affect the local ecosystem and/or economy, remains a formidable challenge. A widely cited report by the Office of Technology Assessment (OTA) estimates monetary costs of about $5 billion annually [14]. Incorporating some monetized ecological damages and control costs, Pimentel et al. [16] revise the OTA damage estimate to $137 billion annually.

Exotic species are spread throughout the world via intentional and unintentional means. Intentional introductions include imports of new varietals of agricultural crops, ornamental plants, pets, animals for food, and biological control agents. International trade—broadly defined to include transport of commodities, people, shipping containers, and packing material—is responsible for most unintentional introductions [13]. What we have in mind are species introductions that are correlated with trade volume. Examples include the Zebra Mussel (cargo ship ballast), Mexican Rice Borer (traded goods from Mexico), Russian Thistle (imported flax seed), Mediterranean Fruit Fly (infested imported fruit), and the Asian Longhorn Beetle (wood packing material).

Despite the overwhelming amount of attention being paid by the ecology community to the exotic species problem, little policy guidance has been generated. An exception in the ecology literature is Jenkins [9], who argues, without any formal treatment of the economics of trade, that trade bans or restrictions may be necessary to protect biodiversity. While trade is widely accepted as a primary vector for such introductions, the volume edited by Simberloff et al. [22] only peripherally discusses trade in the policy recommendations, and instead focuses on eradication [21] and control [19] protocols, both of which are analyzed analytically by Olson and Roy [15]. Virtually all existing literature in this area assumes away both the economic consequences of altered trade and the observability problem of detecting infected imports, both of which are addressed in our paper.

Given that economic activity is largely responsible for the character and volume of exotic species introductions, economists have been mysteriously absent from the debate. Important recent exceptions include Thomas and Randall [23] who investigate the problem of regulating intentional introductions with incomplete ex ante information in the context of a principle–agent model, and Barbier and Shogren [1] who develop an endogenous growth model where exotic species can affect domestic production and/or domestic consumer utility. Like our model, Barbier and Shogren investigate only unintentional introductions. While focusing on optimal endogenous growth in the local economy, they do not frame their problem as one of trade between two or more countries, and further, do not allow inspections as a means of controlling invasive introductions. These features distinguish our paper from theirs.

This paper fits into a more general economics literature on the detection and control of defective products, a literature spawned in the early 1940s by Robert Dorfman [6]. Building primarily on Dorfman, the statistics, operations research, and insurance literature has focused largely on detection and optimal liability contracts between parties when some products may cause damage (see, for example, the so-called ‘‘ruin’’ problem in operations research [18], a version of which is analyzed by Costello and McAusland [4] who explore the positive effects of tariffs in a model of stochastic exotic species arrivals). Demougin and Fluet [5] analyze a principle–agent problem with moral hazard where the principle can trade off between monitoring and financial incentives to control the agent's effort level. Although not explicitly framed in the context of trade, this is the economics literature that most closely resembles the approach taken in our paper. While the gut reaction of many economists to the externality of unintentional exotic species imports would be to set the optimal Pigouvian tax—"If you want to induce more effort on the part of your agents, you should use stronger money incentives" [5, p. 1742]—in fact, increasing monitoring may be desirable under some circumstances—"If you want to induce more effort on the part of your agents, you should monitor them more closely" [5, p. 1742].

In our model, the externality is caused by traded goods contaminated with damaging exotic species. The Pigouvian approach would be to tax only these items, thereby internalizing the externality. But inspections are required to sort the clean from the dirty goods, so using only one instrument is a second best policy. An informative analog exists in the pollution control literature where taxing emissions requires monitoring [7,20]. While taxing output alone is a second best way to internalize the emissions externality, for sufficiently high monitoring costs, the optimal policy is to cease monitoring and to impose a tax only on output [20]. This is similar, but distinct from, our result that for sufficiently high infectedness the regulator should rely only on tariffs. The difference derives from the reasons for monitoring. In the pollution case, the purpose of monitoring is to determine the level of emissions. In our case, damaging species are bundled (in a lumpy way) with goods, so monitoring allows the regulator to sort infected from clean product. Furthermore, in the pollution case, the regulator may cease inspections if monitoring costs are sufficiently high. In our case, the regulator stops inspecting when a high enough proportion of goods is infected, so he is better off just accepting the infected goods and then charging the tax to pay for the damage.

This paper also contributes to the literature on the use of inspections as a tool for managing international trade; for example border inspections can be pivotal in the control of smuggling [11] and counterfeit goods [8]. And finally, because damages from invasive species can be considered an environmental externality arising from consumption of imported goods, this paper contributes to the literature on trade and the environment. There has been a substantial amount of research on the effects of trade liberalization (or conversely, of trade barriers) on the environment when there are environmental externalities associated with the goods being traded. However, with few exceptions this literature has focused almost exclusively on externalities associated with the *production* of goods; the impact of trade liberalization on environmental quality when traded goods carry consumption-related externalities has been largely ignored.[1]

2. Model of trade and exotic species introductions

In this section we develop a model of trade between Home (importer) and Foreign (exporter) in which some known proportion of goods exported is contaminated with a damaging exotic species.

[1] See McAusland [12] for a survey of this literature. Other exceptions include Krutilla [10]—who examines environmental policy set for strategic trade purposes—and Copeland and Taylor [3] and Rauscher [17], who each examine how regulating consumer-generated pollution affects trade patterns.

In our model, Home has two policy instruments with which to control damage from exotic species: imperfect port inspections, where higher inspections are costly but facilitate a higher detection rate of contaminated goods, and a tariff on exported goods. The notation and assumptions are introduced in four categories. The first category explains the policy alternatives (inspections and tariff) available to the importing country. We next describe the nature of damage caused by introductions of the exotic species. Finally, we outline the production decisions in the exporting country and define demand and imports for the importing (Home) country.

Inspections and tariffs

- I: the intensity with which each unit of received goods is inspected, where I is non-negative;
- $K(I) = kI$: the cost of inspecting one unit of received goods,[2] where $k \geqslant 0$ is a parameter;
- $r(I)$: the fraction of infected goods that get intercepted. We assume r is twice continuously differentiable and that the usual Inada type conditions hold[3]: $r(0) = 0$, $r(\infty) \equiv \bar{r} \leqslant 1$, $r' \geqslant 0$, $r'' < 0$ and $r'(0) = \infty$;
- τ: the tariff rate, which is collected on all units shipped to Home.

Damage from exotic species in Home

- q: the exogenous proportion of goods exported/received that are infected;
- N: number of invasives/pests that are accepted by Home (either undetected or detected and accepted nonetheless);
- Each unit of a good can carry at most one infectious pest; hence if, for example, all known-infected goods are discarded after inspection, then

$$N = Xq[1 - r(I)], \tag{1}$$

  where X is the number of units exported by Foreign;
- $D(N) = \delta N$: damage from exotics, where $\delta \geqslant 0$ is a known parameter.

Production and exports from Foreign

- X: number of units of the good exported by Foreign and received by Home;
- Foreign's export sector is perfectly competitive with constant marginal cost of production c;
- Foreign firms are atomistic, taking the price in Home as exogenous to themselves.

Demand and imports from Home

- M: number of units accepted for import by Home;
- Goods found to be infected are discarded,[4] hence

$$M = X[1 - qr]; \tag{2}$$

- P: the price paid by Home consumers for a unit of the good;

[2] We model inspections as occurring instantaneously. In practice some methods of monitoring, for example quarantine, impose costs by delaying the delivery of goods to market. Forgone interest on the value of the goods in quarantine would be best modeled by adding to the unit production cost an additional I contingent cost term; delay costs that are instead borne by the importing country can easily be included in our generic inspection cost term k.

[3] The last of these assumptions is made for computational ease. See footnote 8.

[4] See footnotes 11 and 12 for further discussion.

- Home (inverse) demand depends only on, and is decreasing in, M: $P'(M)<0$. Define $\varepsilon \equiv -\frac{P}{P'(M)M}>0$ as the price elasticity of demand.

2.1. Analysis

We start with the case in which Home faces a single trade partner, Foreign. We assume throughout the remainder of Section 2 that Foreign exports are positive; cases in which Home's optimal policy mix is prohibitive—and so $X=0$—are discussed in Section 3.5. Begin by considering how quantity exported responds to prices. Zero profits in Foreign require $PM - [c+\tau]X = 0$ and so by (2) $P = \frac{c+\tau}{1-qr}$ in equilibrium.

Next, we examine Home's policy choices. We assume Home welfare W is the sum of consumer surplus and tax revenue less damage from introductions of undetected pests. Using Eq. (1) this gives

$$W(I,\tau) = \int_0^M P(s)\,\mathrm{d}s - PM + \tau X - kIX - \delta N \tag{3}$$

$$= \int_0^M P(s)\,\mathrm{d}s - PM + X[\tau - kI - \delta q[1-r]]. \tag{4}$$

Differentiating (4) with respect to τ gives

$$\frac{dW}{d\tau} = \frac{\partial X}{\partial \tau}[\tau - kI - \delta q[1-r]] + X - \frac{P[1-qr]\partial X}{\varepsilon \quad \partial \tau}. \tag{5}$$

Because[5] $\frac{\partial X}{\partial \tau} = \frac{-\varepsilon X}{c+\tau}$, setting (5) equal to zero and solving for τ gives the optimal tariff as a function of inspections:[6]

$$\tau(I) = kI + \delta q[1-r] \geqslant 0. \tag{6}$$

Substituting (6) into (4) allows us to rewrite Home welfare conditional on $\tau = \tau(I)$:

$$W(I) \equiv W(I,\tau)|_{\tau=\tau(I)} = \int_0^M P(s)\,\mathrm{d}s - P(I)M, \tag{7}$$

where

$$P(I) \equiv \frac{c+\tau(I)}{1-qr} = \frac{c + kI + \delta q[1-r]}{1-qr}. \tag{8}$$

Differentiating $W(I)$ using (7) and canceling like terms gives

$$\frac{dW(I)}{dI} = -M\frac{dP(I)}{dI} \tag{9}$$

$$= -X[(P(I)-\delta)qr' + k]. \tag{10}$$

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[5] Given that $M = X[1-qr]$ is an implicit function of prices, $\frac{\partial X}{\partial \tau} = -\frac{\varepsilon X}{c+\tau}$ is found by partially differentiating the zero profit condition.

[6] The sufficient condition for an interior optimum is satisfied since $\left.\frac{d^2W}{d\tau^2}\right|_{\tau=\tau(I)} = -\frac{\varepsilon X}{c+\tau}$.

Let I^* denote Home's optimal monitoring intensity. Then $I^* = \max\{I(q,\delta,c),0\}$ where $I(q,\delta,c)$ solves (10) when set equal to zero;[7] similarly define $\tau^* = \tau(I^*)$ as Home's optimal trade tax. Note that I^* and τ^* are implicit functions of q, δ and c; we economize on notation by suppressing these arguments wherever possible. These relations generate the following proposition.

Proposition 1. *Under the assumptions of the model defined in Section* 2, *when* $X>0$, $q>0$ *and* $\delta>0$ *the optimal policy mix* τ^*, I^* *for Home to control exotic species introductions has the following properties.*

1. *The optimal tariff is non-negative*: $\tau^* \geqslant 0$ *with equality only if both* $k=0$ *and* $\bar{r}=1$;
2. *Optimal monitoring intensity* I^* *is positive whenever* $q \in (\underline{q}, \bar{q})$ *and is zero otherwise, where* $\underline{q}$ *and* $\bar{q}$ *are the roots of the expression* $c + \frac{k}{qr'(0)} - \delta[1-q] = 0$. *Under our maintained assumption*[8] *of* $r'(0) = \infty$ *then* $\underline{q} = 0$ *and* $\bar{q} = 1 - \frac{c}{\delta}$ *and so* $I^*>0$ *whenever* $0<q<\bar{q}$.
3. *It is never optimal to exhaust all detection opportunities unless inspection is costless*: $r(I^*) \leqslant \bar{r}$ *with equality only if* $k=0$.

Proof. 1. $\tau^* = \tau(I^*) = kI^* + \delta q[1-r(I^*)]$. If $k=0$ then $r(I^*) = \bar{r}$ and so $\tau = \delta q[1-\bar{r}]$ which is positive unless $\bar{r}=1$. If $\bar{r}=1$ but $k>0$ then, by part 3 of this proposition, $r(I^*)<\bar{r}$ and so τ^* is again positive.

2. When τ is set optimally, then by (8) and(10)

$$\frac{dW(I)}{dI} = -X\left[\left(\frac{c+kI+\delta q[1-r]}{1-qr} - \delta\right)qr' + k\right].$$

Evaluate at $I=0$ to get $\left.\frac{dW(I)}{dI}\right|_{I=0} = -X[(c-\delta[1-q])qr'(0)+k]$. By construction $\left.\frac{dW(I)}{dI}\right|_{I=0}$ equals zero when q equals $\underline{q}$ or $\bar{q}$. Since $W(I)$ is twice continuously differentiable and locally concave in I then $\left.\frac{dW(I)}{dI}\right|_{I=0}>0$ for $q\in(\underline{q},\bar{q})$ and $\left.\frac{dW(I)}{dI}\right|_{I=0}<0$ for $q<\underline{q}$ or $q>\bar{q}$. Since I is constrained to be non-negative, then it follows that I^* is positive whenever $q\in(\underline{q},\bar{q})$ and zero otherwise.

3. If all opportunities for greater monitoring effectiveness are exhausted then $r'(I^*)=0$ and by (10) $\frac{dW(I)}{dI} = -Xk$ which is negative—i.e. Home would prefer to monitor less—unless $k=0$. □

Proposition 1 can be interpreted as follows. Firstly, the importer should apply a positive tariff on incoming goods, and that tariff is set at the Pigouvian level:[9] τ^* is set equal to the sum of

[7] Again, the second-order condition for an interior maximum is satisfied since $\frac{d^2W(I)}{dI^2} = \frac{r''kX}{r'}<0$ when $I = I(q,\delta,c)$.

[8] If instead $r'(0)$ were finite then $0<\underline{q}<\bar{q}<1-c/\delta$ and there would also exist a range of positive but small values of q at which it would be optimal to not inspect at all.

[9] There is a substantial literature examining incentives for governments to set environmental taxes different from their Pigouvian levels for strategic purposes. For example, if Foreign export supply were less than perfectly elastic then Home would have an incentive to manipulate its environmental taxes so as to suppress the world price of its imports; see, e.g., [10]. This would reduce Foreign welfare and simultaneously introduce distortions in the importing country. Similarly, if Home hosted an import competing sector earning positive profits, Home may face incentives to set environmental taxes

inspection costs and the anticipated damage from received[10] goods. If Home chooses not to inspect incoming goods, the first part of the Pigouvian tariff is zero (since there are no monitoring costs to recover) and the Pigouvian charge is simply expected damage from accepting each unit received. If instead Home does monitor incoming goods, so long as $k>0$ Home's monitoring is (optimally) imperfect. Consequently, when $I^*>0$ then the Pigouvian tariff both recovers the costs of inspection and the damage expected from goods that have not been rejected by an imperfect inspection process.[11]

And secondly, although goods may be contaminated it is not necessarily in the importer's interest to look for contaminated units. If the fraction of contaminated goods is sufficiently high, or alternately if the marginal production cost is high or the marginal damage from an exotic is low then it is preferable to simply accept all goods received uninspected, charge an appropriately high tax to cover expected damage, and enjoy the resulting consumption.

3. Adapting policy according to Foreign's attributes

In this section we analyze how changes in Foreign's attributes—the rate of infection, the unit cost of production, and the damage per undetected infection—affect Home's optimal policy levels and ultimately Home welfare.

3.1. Policy responses to changes in the infection rate

We begin with the relationship between Home's instrument levels and the infection rate of Foreign exports, showing in particular that the optimal inspection level is not always increasing in the infectedness of received goods.

(*footnote continued*)
above or below the Pigouvian level so as to shift market share, and hence profits, to its own producers, again to the detriment of Foreign welfare and Home consumers; see Barrett [2].

[10] Home may equivalently impose a two part tariff: a tax $\tau_X = kI$ on units received so as to recover the cost of port inspections, and a tax $\tau_M = \frac{\delta q[1-r]}{1-qr}$ on units *accepted*, set equal to expected damage from units not identified as infected at the port. This two-part tax would yield identical revenue and have identical impact on the export decisions of Foreign's firms.

[11] Suppose that instead of discarding known-infected goods, Home accepts these goods conditional on firms paying a higher tax rate on them. For example, the post-inspection Pigouvian taxes on goods detected and not-detected as infected would be, respectively, $\tau^{\mathrm{d}} = kI + \delta$ and $\tau^{\mathrm{nd}} = kI + \delta\frac{q[1-r]}{1-qr}$ (for this we assume the pre-inspection tax is zero). Because damage is external to the consumer, then all goods would sell for the same price P and the ex ante zero profit condition would be $P = c + qr\tau^{\mathrm{d}} + [1-qr]\tau^{\mathrm{nd}}$, or, equivalently, $P = c + kI + \delta q$. Now consider whether an exporter would be willing to pay the tax τ^{d} on a unit detected as contaminated. Since the production cost c is sunk at this point, she would pay the tax only if $\tau^{\mathrm{d}} \leqslant P$ which is equivalent to the condition $1-\frac{c}{\delta}\leqslant q$. Recognizing that $1-\frac{c}{\delta}\geqslant \bar{q}$ (with equality when $r'(0)=\infty$), then the exporter would choose to pay τ^{d} only in cases where the infection rate is so high that Home independently rejects inspections as inefficient to begin with. If instead $1-\frac{c}{\delta}>q$ then, even though I^* may be positive, exporters would not find it profitable to pay τ^{d} and would themselves discard goods detected as contaminated. In sum, in cases where Home does indeed choose to inspect incoming goods, goods detected as contaminated will be discarded even when the choice to do so is made by the exporting firm.

Proposition 2. *Under the assumptions of the model defined in Section* 2, *when* $X>0$ *the optimal monitoring intensity is single peaked in the infection rate* q. *In particular,* $\exists \tilde{q} \in (\underline{q}, \bar{q})$ *for which* $\frac{dI^*}{dq} \geqslant 0$ *when* $q<\tilde{q}$ *and* $\frac{dI^*}{dq} \leqslant 0$ *when* $q>\tilde{q}$; *for* $q \notin [\underline{q}, \bar{q}]$, $\frac{dI^*}{dq} = 0$.

Proof. Define $\tilde{q}$ as the infection rate at which $\frac{dI(q,\delta,c)}{dq} = 0$. Because $\frac{dI(q,\delta,c)}{dq} = -\frac{\frac{\partial}{\partial q}\frac{dW}{dI}}{\frac{d^2W}{dI^2}}$ then partially differentiating (10) with respect to q using (8) gives

$$\frac{dI(q,\delta,c)}{dq} = \frac{Xr'}{\frac{d^2W}{dI^2}} \frac{P-\delta[1-q]}{1-qr}. \tag{11}$$

Define the infection rate at which (11) is zero as $\tilde{q}$. Differentiating (11) with respect to q and evaluating at $\tilde{q}$ gives

$$\left.\frac{d^2I(q,\delta,c)}{dq^2}\right|_{q=\tilde{q}} = \frac{Xr'}{1-qr} \frac{\left[\frac{Pr+\delta[1-r]}{1-qr} + \delta\right]}{\frac{d^2W}{dI^2}} < 0.$$

Because $I(q,\delta,c)$ is twice continuously differentiable and locally concave at any extremum, then $I(q,\delta,c)$, and hence I^*, is single peaked in the infection rate q. □

Two opposing factors are responsible for this non-monotonicity. First, as the infection rate rises then a given level of inspection is more productive in terms of contaminated units detected, making inspections more attractive. But, second, as more infections are detected then more units are subsequently barred entry to the importing country. This reduces the quantity of units consumed and so raises their domestic price, and hence the marginal value of the last unit rejected for import. This is equivalent to an increase in the opportunity cost of rejecting a unit of incoming goods, making inspections less attractive. Which effect dominates depends on the initial level of infection. When q is low to begin with then the consumer price and the rate at which prices respond to curtailment in supply are also low: the first effect dominates. But when q is high to begin with then the consumer price and the rate of change in that price are also high; as a result the effect of an higher opportunity cost of rejecting goods—the latter effect—dominates, and Home's optimal response to a higher rate of infection is to curtail its inspections.[12]

Next we examine how changes in q simultaneously affect the optimal tariff.

[12] How would our analysis of the optimal I be altered if there existed some backstop technology that could be used to perfectly disinfect goods? If only goods known to be dirty were eligible for cleaning, at some per unit cost T, then it is straightforward to show that Home would want to clean all known-infected goods whenever the domestic price of goods P exceeded the cost of cleaning. For q, c, δ generating $P>T$, then Home's welfare maximizing choice of I is increasing in q. In short, the result that I is after some point decreasing in q does not follow through with a backstop cleaning technology of this sort. If, however, all goods are eligible for cleaning (both those already detected as dirty and those not detected as infected) then for q, δ for which $q\delta>T$, then the anticipated damage from incoming goods exceeds the cost of cleaning incoming goods and it is preferable for Home to subject *all* goods received to cleaning and not to inspect any of them. With this sort of cleaning technology, then for q sufficiently high—i.e. whenever $T<q\delta$—then it is again optimal to forego inspecting completely.

Proposition 3. *Under the assumptions of the model defined in Section* 2, *when* $X>0$ *Home*'s *optimal tariff*, τ^*, *tends to increase with* q. *More precisely, for* $q \notin [\underline{q}, \tilde{q}]$, $\frac{d\tau}{dq}>0$; *for any* $q^{\mathrm{o}} \in (\underline{q}, \tilde{q})$, $\exists q' < \bar{q}$ *such that* $\tau^*(q) > \tau^*(q^{\mathrm{o}})$ *whenever* $q \geqslant q'$.

Proof. Evaluate (6) at $I = I^*$ to get

$$\frac{d\tau^*}{dq} = [k - \delta q r'] \frac{dI^*}{dq} + \delta[1 - r].$$

When $q \notin [\underline{q}, \bar{q}]$, $\frac{dI^*}{dq} = 0$ and $I^* = 0$ and so $\frac{d\tau^*}{dq} = \delta[1 - r] = \delta > 0$. When $q \in [\tilde{q}, \bar{q})$ then $\frac{dI^*}{dq} \leqslant 0$ and so $\frac{d\tau^*}{dq} > 0$ since $k - \delta q r' = -Pqr' < 0$ when τ and I are set optimally. However, when $q \in (\underline{q}, \tilde{q})$, $\frac{dI^*}{dq} \geqslant 0$ and we are unable to verify that $\frac{d\tau^*}{dq} \geqslant 0$. However, because I^* is single peaked and continuous in q, because I^* reaches a minimum value of zero in each partition $[0, \tilde{q}]$, $[\tilde{q}, 1]$ of the support of q, and because $d\tau^*/dq > 0$ when $q > \tilde{q}$, then for any $q^{\mathrm{o}} \in (\underline{q}, \tilde{q})$ there exists a $q' > q^{\mathrm{o}}$ for which $I^*(q^{\mathrm{o}}) = I^*(q')$ and so $\tau^*(q^{\mathrm{o}}) = \tau^*(q') + \delta[1 - r(I(q'))][q^{\mathrm{o}} - q'] < \tau^*(q')$ and $\tau^*(q) > \tau^*(q^{\mathrm{o}})$ for any $q \geqslant q'$. □

The intuition behind Proposition 3 is as follows. Consider the case where the infection rate is so high as to make monitoring unattractive ($I^* = 0$). Then the rate at which the tariff increases in the infection rate is simply the marginal damage of another infected unit being accepted, δ. Similarly, when infectedness is already high, then Home optimally responds to higher infectedness by relaxing inspections—why spend so much money to confirm that most goods received are infected?—and uses a higher tariff to cover higher expected marginal damage. And finally, when infectedness is relatively low (i.e. $q \in (\underline{q}, \tilde{q})$) there are counteracting forces affecting the optimal trade tax. Firstly, as q rises, Home's optimal response is to inspect more, raising the cost-recovery portion of the trade tax. Secondly, received goods are more likely to be infected, and so the expected damage from a unit *received* is higher. But thirdly, because there is more monitoring a higher fraction of contaminated goods are detected, possibly reducing the expected damage from an *accepted* unit. Consequently we are unable to verify that $\frac{d\tau^*}{dq} \geqslant 0$ when $q \in (\underline{q}, \tilde{q})$.[13] Instead we show that τ *tends* to decline in q, that is, for any infection rate q^{o} there is a set of higher infection rates that carry higher optimal taxes.

Combining results from Propositions 2 and 3, we are now able to characterize how Home should alter its policy levels when a particular attribute of its trade partner—Foreign's infection rate—changes. When the infection rate is relatively low to begin with—$q < \tilde{q}$—then Home should respond to a higher infection rate abroad by inspecting more (but perhaps not by taxing more). If the infection rate is relatively high to begin with—$q \in [\tilde{q}, \bar{q})$—then Home should respond to higher infectedness by unambiguously increasing its import tax but by reducing the intensity of its port inspections. If the infection rate is sufficiently high to begin with ($q \geqslant \bar{q}$), a marginal increase in q should be addressed solely with an increase in the tariff that offsets the additional anticipated damage. And if there is a discrete increase in Foreign's infection rate, it is possible that Home's

[13] Numerical simulations (not shown) suggest that $\frac{d\tau}{dq}$ is often positive. For example when $r(I) = 1 - e^{-\mu I}$ (the exponential cumulative density function with mean $\frac{1}{\mu}$) we were unable to find any parameter values under which $\frac{d\tau}{dq} < 0$.

optimal response would be to raise the tariff rate but leave its monitoring intensity completely unchanged.[14]

3.2. Policy responses to changes in the damage rate δ

Next we examine how an increase in the marginal damage, δ, from accepting another infected good affects optimal policy levels.

Proposition 4. *Under the assumptions of the model defined in Section 2, when $X > 0$*

1. *An increase in per unit damage from infected goods expands the range of infection rates for which Home will offer positive inspections*: $\frac{d\bar{q}}{d\delta} > 0$;
2. *Home's optimal monitoring intensity is non-decreasing in per unit damage from infected units*: $\frac{dI^*}{d\delta} \geqslant 0$;
3. *Home's optimal trade tax may be increasing or decreasing in per unit damage from infected units.*

Proof. 1. Differentiating the expression $\bar{q} = 1 - \frac{c}{\delta}$ gives $\frac{d\bar{q}}{d\delta} = \frac{c}{\delta^2} > 0$.

2. Recall $I^* = \max\{I(q, \delta, c), 0\}$. Differentiating $I(q, \delta, c)$, as defined by (10) when set equal to zero, reveals $\frac{dI(q,\delta,c)}{d\delta} = -\frac{q[r']^2[1-q]}{r''k[1-qr]} > 0$. Since unconstrained monitoring intensity $I(q, \delta, c)$ rises with δ and, from part 1 of this proposition, the range of infection rates where $I(q, \delta, c)$ is positive expands, then I^* is non-decreasing in δ.

3. Differentiate (6) and make use of $-Pqr' = k - \delta qr'$ from (10) to get

$$\frac{d\tau^*}{d\delta} = q[1-r] + \frac{Pq^2[r']^3[1-q]}{r''k[1-qr]},$$

the first term of which is positive and the second term of which is negative. To see that $\frac{d\tau^*}{d\delta}$ can be negative, consider the value of $\frac{d\tau^*}{d\delta}$ at $\bar{q}$. Because $r'(0) = \infty$, as q approaches $\bar{q}$ then $\frac{d\tau^*}{d\delta}$ approaches negative infinity and so, near the cutoff infection rate, the optimal response to a higher damage rate is a lower tariff. To see that $\frac{d\tau^*}{d\delta}$ can be positive, consider its value at $q = 1$. Then $r = 0$, so $\frac{d\tau^*}{d\delta}|_{q=1} = 1 > 0$. □

[14] If q were instead a random variable with commonly known distribution then a risk-neutral Home will maximize expected welfare and optimal values of τ and I would depend on the distribution of q, not just its expected value. In several numerical simulations (not shown) we find only a small quantitative influence of the distribution of q on τ and I; and qualitative results are as in Propositions 1 and 3. Alternately, if q is instead a probability, rather than a proportion, then the number of infected units is a binomial random variable with parameters X and q. The analytics are significantly complicated by this assumption, but numerical simulations again generate relationships as described in Propositions 1 and 3. A third possibility is that q is an unknown parameter whose value can be learned over time by sampling (monitoring). Although we did not analyze that case, it seems likely that this would tend to make monitoring more attractive.

That I^* is (weakly) increasing in δ is exactly as one would expect: when infected units impose greater damage, Home is willing to allocate more effort to looking for them. But as Proposition 4 shows, as δ rises Home will not necessarily impose a larger trade tax. Given that τ^* is set equal to the marginal damage from received goods, the possibility that $\frac{d\tau^*}{d\delta}$ is negative may seem surprising: one might expect that the Home government would already have utilized any opportunities—i.e. adjustments to I—to lower marginal damage, and would not need a higher δ to spur this action. But the explanation is simply that Home does not choose I to minimize damages from received goods, Home chooses I to maximize benefits from trade. To see this, differentiate (8) with respect to I to get $\frac{dP(I)}{dI} = \frac{[P(I)-\delta]qr'+k}{1-qr}$ and use this to rewrite (10) as

$$\left.\frac{\partial W}{\partial I}\right|_{\tau=\tau(I)} = -X[1-qr]\frac{dP(I)}{dI} = 0. \tag{12}$$

This reveals that Home chooses I so as to minimize[15] the cost of consumer goods P. Moreover, we can write $\frac{dP(I)}{dI} = \frac{1}{1-qr}\left[\frac{d\tau}{dI} + Pqr'\right]$, revealing I is chosen so that $\frac{d\tau}{dI} = -Pqr' < 0$: I is set so as to *not* minimize τ. Consequently, as Home raises I in response to an increase in δ, marginal damage from received goods, and hence the tariff, is (indirectly) reduced, a reduction that may more than fully offset the direct effect of a change in δ on τ. Numerical simulations (not shown) reveal that this response—the lowering of τ in response to an increase in δ—is not restricted to limiting cases: it occurs over a wide range of parameter values.

In summary, an increase in the marginal damage from infected imports unambiguously requires greater monitoring intensity, but because stricter monitoring reduces the proportion of received units that will be accepted to begin with, the optimal trade tax may instead become smaller. That is, an importer may want to treat goods harboring more dangerous contaminants with harsher inspections but *gentler* trade taxes.

3.3. Policy responses to changes in Foreign's production cost

We next examine how variation in another key attribute of Foreign—the marginal production cost c—affects Home's optimal instrument levels.

Proposition 5. *Under the assumptions of the model defined in Section* 2, *when* $X > 0$ *an increase in Foreign's production cost* c

1. *expands the range of infection rates over which Home will not monitor at all*: $\frac{d\bar{q}}{dc} < 0$;
2. (*weakly*) *reduces Home's monitoring intensity*: $\frac{dI^*}{dc} \leqslant 0$;
3. (*weakly*) *raises Home's trade taxes*: $\frac{d\tau^*}{dc} \geqslant 0$.

[15] To confirm that $P(I)$ is locally convex in I, examine the second derivative evaluated at $I(q, \delta, c)$:

$$\left.\frac{d^2P}{dI^2}\right|_{\tau=\tau(I), I=I(q,\delta,c)} = \frac{P-\delta}{1-qr}qr''$$

which is positive since $P - \delta = -\frac{k}{qr'} < 0$ at $I(q, \delta, c)$.

Proof. 1. Differentiate $\bar{q} = 1 - c/\delta$ to get $\frac{d\bar{q}}{dc} = -1/\delta < 0$.

2. Fully differentiating (10) when set equal to zero, using (8) and collecting terms gives $\frac{dI(q,\delta,c)}{dc} = -\frac{\frac{\partial dW/dI}{\partial c}}{\frac{d^2W}{dI^2}} = \left[\frac{Xqr'}{1-qr}\right] / \left[\frac{d^2W}{dI^2}\right] < 0$.

3. When $I^* > 0$ $\frac{d\tau^*}{dc} = \frac{\partial \tau(I)}{\partial I}\frac{dI(q,\delta,c)}{dc} + \frac{\partial \tau}{\partial c}$; given $\frac{\partial \tau}{\partial c} = 0$ then $\frac{d\tau^*}{dc} = \frac{-PX[qr']^2}{[1-qr]\frac{d^2W}{dI^2}} > 0$. □

As Proposition 5 indicates, as the marginal cost of production in Foreign rises Home's optimal response is to reduce the intensity of its port inspections but to raise its import tariff. At first glance these responses may seem perverse, since the Foreign attribute in question—its marginal production cost—arguably has nothing to do with infection or damage from undetected infected goods. But production costs do affect the quantity of goods sent by Foreign, and hence the number of goods accepted by Home and ultimately made available to Home consumers. Simply, an increase in c lowers exports and imports, ceteris paribus, and so raises the consumer surplus from the last unit accepted. Consequently, as c rises then the marginal cost—the foregone consumer surplus—of the last unit rejected via Home inspections also rises, making rejection of goods (and hence detection of infections) less attractive on the margin. And so Home lowers I. Since c does not affect the choice of τ directly, but raises the likelihood that an accepted unit will cause ecological damage (via $\frac{dr}{dc} = r'\frac{dI}{dc} < 0$), then Home simultaneously raises τ. In sum, changes in Foreign's characteristics that would appear on the surface to have no relevance for ecologically motivated trade policy are indeed pertinent: they affect how Home values the opportunity cost of ecological protection—foregone consumption—and hence how much protection it wants to pursue in the first place.

3.4. *Domestic price and Home welfare*

Having completed our analysis of how changes in q, δ and c affect Home's optimal policy mix, it is appropriate to discuss how each of these changes carry through to affect Home consumers and Home welfare.

Define by $P(q,\delta,c)$ the function $P(I)$ evaluated at I^* given parameters (q,δ,c). Because choosing τ and I optimally simultaneously minimizes $P(I)$ with respect to I (see Eq. (9)), then changes in exogenous parameters affect $P(q,\delta,c)$ only via direct channels. For example, an increase in the infection rate necessarily raises the price of imported goods: $\frac{dP(q,\delta,c)}{dq} = \frac{\delta[1-r]+Pr}{1-qr} > 0$. The same is true for increases in per unit damage or Foreign's production cost: $\frac{dP(q,\delta,c)}{d\delta} = \frac{q[1-r]}{1-qr} > 0$ and $\frac{dP(q,\delta,c)}{dc} = \frac{1}{1-qr} > 0$. That is, an increase in any of Foreign's key parameters raises the Home price of dirty goods when policy is set optimally. Moreover, when τ is set optimally Home's welfare is simply its consumer surplus. And because Home's consumer surplus is inversely related to the price of imported goods then an increase in $P(q,\delta,c)$ reduces Home welfare. Thus Home is made unambiguously worse off by an increase in any of the parameters q, δ or c.

3.5. Prohibitive tariffs

In the preceeding analysis we restricted our attention to cases in which Foreign exports, X, are positive. This implicitly assumed that the price $P(q, \delta, c)$ resulting from optimal Home policy is below the choke price, $\bar{P}$, associated with Home demand. If Home demand satisfied $P(M) = M^{-\frac{1}{\varepsilon}}$, i.e. demand is isoelastic, then $\bar{P}$ would be infinite and $X > 0$ would hold for all values of q, δ, c. However if instead $\bar{P}$ is finite, as would be the case with demand $P(M) = \bar{P}e^{-aM}$, then there are parameter values at which Home's optimal policy mix prohibits trade. Specifically, whenever $\bar{P} \leqslant \frac{kI^* + \delta q[1 - r(I^*)] + c}{1 - qr(I^*)}$ then $M = X = 0$ and trade does not occur. Moreover, because $P(q, \delta, c)$ is increasing in each of its arguments, once marginal damage δ, for example, exceeds some critical threshold justifying prohibitive instrument levels, any higher level of marginal damages similarly justifies prohibitive tariffs/inspections. For completeness we note that if the optimal policy mix τ^*, I^* is prohibitive, any sequence τ, I satisfying $\tau \geqslant [1 - qr(I)]\bar{P} - c$ generates identical welfare and so optimal instrument levels are no longer unique.

3.6. Multiple partners

Above we have assessed how changes in the attributes of a single partner alter the optimal instrument levels that should be applied to that partner's exports. These results have direct implications for how multiple trade partners serving unconnected Home markets should be treated. But what about when Home's multiple trade partners mean to supply the same market? Then the question arises as to whether Home, merely by setting country specific policy levels as prescribed in (6) and (10), can obtain the "right" trade partner—the one offering Home the largest welfare gain from trade. The answer is yes.

Recalling that welfare and the consumer price are inversely related when τ is set optimally, then Home's preferred trade partner is the one with attributes q, δ, c generating the lowest $P(q, \delta, c)$.[16] Hence, if Home is permitted to set policy differentially, then by setting τ and I for each partner according to (6) and (10) it will automatically exclude all suboptimal trade partners—because the breakeven price for such partners would exceed the market price—and so Home can continue to treat its preferred partner optimally.

Because the level of infectedness of ones' partners is, in practice, not perfectly observable through time, there is some question about whether trade organizations such as the WTO would permit q-contingent trade policies. For example Article 2.3 of the WTO Agreement on the Application of Sanitary and Phytosanitary Measures states that parties cannot "arbitrarily or unjustifiably discriminate between members", the primary concern being that such discrimination could be acting as disguised protectionism. Whether the WTO would allow discriminatory policies solely on the basis of predicted infectedness is not clear. Below we briefly examine the case in which discriminatory policies are forbidden.

[16] We recognize that more than one country may offer the same minimum price but ignore this possibility in the interest of brevity. Note also that Home's preferred partner does not necessarily offer either the lowest q or δ. Indeed, although the preferred partner clearly cannot have c, q and δ all higher than that of another country, it need beat its competitors only along one dimension: it may have lower production costs but higher infection rates and higher damage, or some alternate combination.

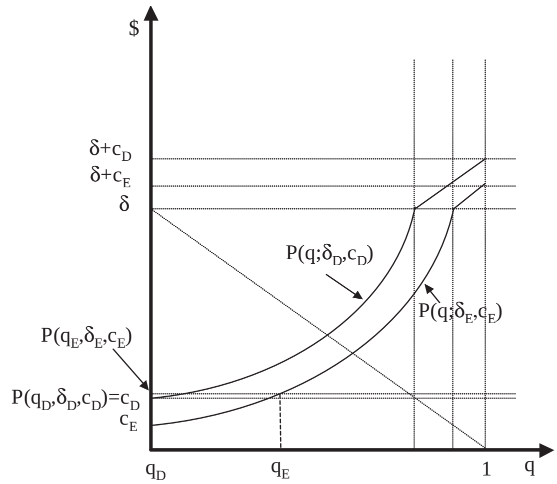

Fig. 1. Price functions $P(q, \delta, c)$ for possible trading partners D and E.

If Home were constrained to offer uniform instrument levels to all countries, it is easy to show that Home may lose its ability to both obtain and treat optimally its preferred trade partner. Consider the following example of two potential trade partners, countries D and E. Suppose $c_D > c_E$ but $q_E > q_D = 0$. For the sake of argument, suppose $\delta_D = \delta_E$ and $c_D = P(q_E, \delta_E, c_E) - \mu$ where $\mu > 0$ is arbitrarily small. Fig. 1 draws the function $P(q, \delta, c)$ for each country. Since $P(q_D = 0, \delta_D, c_D) = c_D < P(q_E, \delta_E, c_E)$ then Home prefers to trade with country D and would set $\tau_D = I_D = 0$ if allowed to discriminate. However, if Home were to offer those same conditions of trade for both countries, then country E with its lower production cost would offer goods at price $c_E < c_D$ and displace country D, reducing Home's welfare relative to the case where Home traded only with country D.[17]

We point out though that Home can still achieve its maximum welfare if permitted to discriminate only along the tariff dimension. This is trivial, since Home could set τ arbitrarily high for all but its optimal partner, thus shutting those countries out of the market even when I is identical for all. In contrast, if Home may discriminate only in its setting of I, it may again be prevented from trading optimally with its preferred partner.[18,19]

[17] Note that if Home were entitled to supplement its tariff and inspection program with ecology-related standards q' and δ' which cap the infection rate and marginal damage that may be associated with incoming units, Home would be able to ensure its optimal trade partner is not priced out of its market even when Home is constrained to set identical I and τ for all. This is trivial when every challenger exhibits either a higher infection rate q or damage rate δ than the optimal trade partner; when instead the challenger is sub-optimal only because it has high marginal production costs c, it is straightforward to show that, at the tax and inspection rates optimal for the targeted trade partner, the challenger is uncompetitive.

[18] To see this, consider countries D and E once again. Even if $\bar{r} = 1$, when $\tau = 0$ the price offered by country E's producers is $\frac{c_E}{1-q^E}$, which is less than $c_D = P(q_E, \delta_E, c_E) - \mu$ whenever $I(q_E, \delta_E, c_E) > 0$ for μ sufficiently small. That is, so long as the infection rate of E is not so large as to make inspecting E pointless when dealing with E alone, then it is not possible to set the optimal policy for D without also having E price D out of Home's market.

[19] If Home instead set a two part tariff as described in footnote 10 but was only bound to keep the value of τ_M, the tax on accepted goods, identical across trade partners, then it could again obtain trade with only its preferred partner(s) without being forced to set policy suboptimally. This would be achieved merely by setting I arbitrarily high for all other

4. If Foreign can reduce infectedness

In this section we analyze how foreign firms would vary q if each had access to some pre-export cleaning technology. Assume the per unit cost of producing a good with infectedness q would be $c = \bar{c} + d(q)$ where $d' < 0, d'' > 0$.

Before analyzing the decisions of the firms in Foreign, consider the choice of q, X and I that would maximize the welfare of Home and Foreign. Denote this sum by $J = W + \Pi$ where $\Pi \equiv PM - [c + \tau + d(q)]X$ and W is as defined in (4). Canceling like terms gives

$$J = \int_0^M P(s)\,ds - X[c + kI + \delta q[1 - r] + d(q)].$$

Maximizing this with respect to q, X and I gives first-order conditions for an interior optimum

$$\frac{\partial J}{\partial q} = -X[Pr + d'(q) + \delta[1 - r]] = 0, \tag{13}$$

$$\frac{\partial J}{\partial X} = P[1 - qr] - [c + kI + \delta q[1 - r] + d(q)] = 0, \tag{14}$$

$$\frac{\partial J}{\partial I} = -X[[P - \delta]qr' + k]] = 0. \tag{15}$$

Notably, (14) and (15) are equivalent to conditions (6) and (10) when evaluated at $c = \bar{c} + d(q)$; this implies that if $d' = 0$ then the policy mix maximizing Home welfare simultaneously maximizes joint welfare of the two countries.[20] Define the values satisfying (13)–(15) as q^J, X^J, I^J. We next examine how τ, I and q will be set in a decentralized world economy.

4.1. Industry-wide instruments, Home moves first

We begin with the case in which Home moves first, announcing industry-wide I and τ for all incoming goods. Moving second, each foreign firm chooses its own level of cleanup (and hence its own level of q) to maximize own per-unit profits $\pi = P[1 - qr] - [c + \tau + d(q)]$ taking P, I and τ as given. This problem has the associated first-order condition for an interior maximum[21]

$$\frac{\partial \pi}{\partial q} = -Pr - d'(q) = 0 \tag{16}$$

and so foreign firms choose q so as to balance the marginal cost of cleanup with the increased revenue associated with more goods making it through the inspection process. However, evaluating $\frac{\partial \pi}{\partial q}$ at q^J gives $\left.\frac{\partial \pi}{\partial q}\right|_{q^J} = \delta[1 - r] > 0$ revealing that foreign firms want to undertake less

(*footnote continued*)
partners and charging τ_X equal to k times that arbitrarily high level of inspection intensity. That is, if Home is permitted to vary the recovery fee that it charges for inspection costs, it will impose prohibitively high recovery costs on all its non-preferred partners.

[20] If Home had strategic incentives to manipulate τ for terms of trade or profit shifting purposes (as in the cases discussed in footnote 9), the policy mix chosen by Home would cease to maximize J even when $d' = 0$.

[21] Since $\frac{\partial^2 \pi}{\partial q^2} = -d''(q) < 0$ then the per unit profit function is globally concave in q for given I and τ.

cleanup than maximizes joint welfare. This occurs because individual firms are not compensated (via lower τ or I) for reductions in δN arising from their own cleanup when τ and I are pre-set for the industry as a whole, and so firms clean too little.

Anticipating that foreign firms can clean goods prior to export, Home sets I and τ in the first stage by taking q as endogenous and differentiating (4):

$$\frac{\partial W}{\partial \tau} = [\tau - kI - \delta q[1-r]]\frac{\partial X}{\partial \tau} + \frac{\partial[\delta N]}{\partial q}\frac{dq}{d\tau} \tag{17}$$

and

$$\frac{\partial W}{\partial I} = -X[[P-\delta]qr' + k] + [\tau - kI - \delta q[1-r]]\frac{\partial X}{\partial I} + \frac{\partial[\delta N]}{\partial q}\frac{dq}{dI}. \tag{18}$$

To see whether Home, when acting so as to maximize W alone, wants to tax and/or inspect incoming goods excessively, differentiate the system formed by (16) and the zero profit condition $P = \frac{\tau+\bar{c}+d(q)}{1-qr}$ to get

$$\frac{dq}{d\tau} = \frac{r}{d''(q)[1-qr]} \quad \text{and} \quad \frac{dq}{dI} = \frac{Pr'}{d''(q)[1-qr]}. \tag{19}$$

Then evaluate (17) and (18) at X^J and I^J and make use of (19):

$$\left.\frac{\partial W}{\partial \tau}\right|_{X^J,I^J} = \frac{\partial[\delta N]}{\partial q}\frac{dq}{d\tau} = \frac{\delta[1-r]Xr}{[1-qr]d''} > 0,$$

$$\left.\frac{\partial W}{\partial I}\right|_{X^J,I^J} = \frac{\partial[\delta N]}{\partial q}\frac{dq}{dI} = \frac{\delta[1-r]XPr'}{[1-qr]d''} > 0.$$

Because $\frac{\partial W}{\partial \tau}|_{X^J,I^J} > 0$, $\frac{\partial W}{\partial I}|_{X^J,I^J} > 0$ then Home prefers an import tax above the Pigouvian level and may perceive the joint-welfare maximizing level of inspections, I^J as too lax. This reflects strategic considerations on Home's part. Home recognizes that τ and I induce positive (but insufficient) cleaning by Foreign firms: as mentioned above foreign firms clean so as to increase the likelihood of their goods making it to market, but they do not take into account how lower q reduces δN and so clean too little. Home then has an incentive to manipulate I and τ from the joint welfare maximizing levels so as to induce some additional cleaning overseas. As a result, when Home moves first and offers industry-wide τ and I, Home views the joint-welfare maximizing trade instruments as too lenient while foreign firms view the joint-welfare maximizing infection rate q^J as too low.

4.2. Industry-wide instruments, Home moves second

Next consider the following variation on the game: Home continues to offer industry-wide τ and I but now Home moves second. Since firms are atomistic and instruments are set for the entire industry, foreign firms continue to perceive P, τ and I as exogenous to themselves and so continue to choose q to satisfy (16). However, since Home is unable to influence q via its choices of τ and I, it faces the identical problem as in Section 2.1. Evaluating (5), (10) and (10) at q^J, X^J, I^J gives $\frac{\partial W}{\partial \tau}|_{q^J,X^J,I^J} = \frac{\partial W}{\partial I}|_{q^J,X^J,I^J} = 0 > \left.\frac{\partial \pi}{\partial q}\right|_{q^J,X^J,I^J} = -X\delta[1-r]$ revealing that when Home is second-mover and offers industry-wide policies, the strategic incentives it faced when acting as a first-mover are absent—instead, Home sets a Pigouvian tax and price-minimizing inspection level—even though foreign firms continue to undertake too little cleaning of traded goods.

4.3. Home offers q contingent policies to individual firms

In each of the preceeding sections Home is modeled as offering industry-wide policies. And even though the number of distortions arising in the decentralized setting depends on the order of moves, the result that joint welfare is not maximized does not. However suppose instead that Home offers q-contingent policies for *each* foreign firm. For simplicity continue to assume that Home is second-mover. Then Home's optimization problem is identical to that in Section 2.1 while each foreign firm's optimization problem is $\max_q \pi$ with associated first-order condition

$$\frac{\partial \pi}{\partial q} = -Pqr' \frac{dI}{dq} - Pr - \frac{d\tau}{dq} - d'(q) = 0.$$

Substituting in for $\frac{d\tau}{dq} = \frac{\partial \tau}{\partial q} + \frac{d\tau}{dI}\frac{dI}{dq}$ where $\frac{d\tau(I)}{dI} = k - \delta qr'$, canceling terms and making use of $[P - \delta]qr' + k = 0$ by (10) gives

$$\frac{\partial \pi}{\partial q} = -Pr - \delta[1 - r] - d'(q) \tag{20}$$

which, when set equal to zero, defines each firm's choice of q. Setting (5), (10) and (20) each equal to zero and evaluating at q^J, X^J, I^J gives $\frac{\partial W}{\partial q}\Big|_{q^J,X^J,I^J} = \frac{\partial W}{\partial \tau}\Big|_{q^J,X^J,I^J} = \frac{\partial W}{\partial I}\Big|_{q^J,X^J,I^J} = 0$, illustrating that when Home moves second and offers q-contingent policies to individual firms, both Home and the foreign firms maximize their own welfare by choosing the joint-welfare maximizing policy levels. Intuitively, the joint- and individual-welfare maximizing policies coincide because firm-specific policies effectively reward firms for undertaking pre-export cleanup of their goods. Essentially, firm-specific q-contingent policies induce foreign firms to internalize the benefits to Home of reduced damages from received goods. This eliminates any strategic incentives for Home to further manipulate q via τ and I and so Home sets τ at the Pigouvian level and chooses I to minimize consumer prices, maximizing joint welfare along the way.

We summarize the results of this section as follows. When Home sets instrument levels for the foreign industry as a whole, firms are not adequately compensated for benefits associated with costly cleanup of their goods and so permit infection rates $q > q^J$. Given that foreign firms undertake insufficient cleanup, when Home is first-mover it strategically manipulates τ and I so as to induce additional foreign cleanup, creating further distortions. However, if instead Home offers firm-specific q-contingent policies, then firms will internalize the benefits that lower q confers on Home—i.e. reduced δN—and set $q = q^J$. And, accordingly, because firms already take into account reductions in δN when setting q, Home no longer needs to manipulate τ and I for strategic purposes, and joint welfare is maximized even though policy setting is decentralized.[22]

[22] Notably, when Home offers firm-specific q-contingent policies, the order of moves is unimportant in our model. To see this, recognize that when Home moves first it can offer the schedule $\hat{\tau}$, $\hat{I}$ if $q = \hat{q}$ and $\tau = I = \infty$ whenever $q \neq \hat{q}$. At the second stage each foreign firm will choose $q = \hat{q}$ or be taxed and inspected out of the market. Then Home need only

5. Dynamic trade policy

In this section we examine a dynamic version of the model in which exotic species populations grow and trade exist in two adjacent periods. Home's objective is to maximize the net present value of welfare (consumer surplus from consumption minus damage from exotic species) over a two-period planning horizon by choosing a tariff and inspections intensity in each period. While including dynamics unambiguously amplifies the magnitude of the exotic species damage, we show below that some optimal trade policies may be weaker in the dynamic, rather than the static, case.

5.1. A dynamic model

We specify the timing as follows. The initial pest population (Y_0) is observed by the Home regulator, τ_0 and I_0 are chosen, and exports are sent to Home. Upon arrival of the goods, inspections take place, and the newly introduced individuals (N_0) mix with the previous individuals causing period 0 damage $\delta(N_0 + Y_0)$. Population growth then occurs according to a known growth function $f(y)$, where y is the population of the exotic species, and the usual assumptions hold: $f' > 0$ and $f'' < 0$. The next period begins with population $Y_1 = f(Y_0 + N_0)$, and the process is repeated.

A two-period model is sufficient to capture the important (and, in some cases, counter-intuitive) dynamic characteristics of this model. The two-period dynamic programming equation is

$$V(Y_0) = \max_{\tau_0, I_0} W(I_0, \tau_0; q, \delta, c) - \delta Y_0 + \theta(W^* - \delta Y_1), \tag{22}$$

where V is the value function in the initial period, $W(\cdot)$ is the welfare expression from the static model (4), W^* is the maximized static welfare, and θ is the discount factor. Substituting $Y_1 = f(Y_0 + N_0)$, and collecting terms that depend on τ_0 and I_0, the dynamic programming equation is rewritten as follows:

$$V(Y_0) = \max_{\tau_0, I_0} \left[\underbrace{W(I_0, \tau_0; q, \delta, c) - \delta\theta f(Y_0 + N_0(I_0, \tau_0))}_{\mathbf{W}(\tau_0, I_0)} \right] + \theta W^* - \delta Y_0, \tag{23}$$

where the bracketed term $\mathbf{W}(\tau_0, I_0)$ contains all variables that depend on the control variables (i.e. those present in the first-order condition).

(*footnote continued*)
choose $\hat{\tau}, \hat{I}, \hat{q}$ that maximize W subject to the participation constraint $P = \frac{\tau + \bar{c} + d(q)}{1 - qr}$. Differentiating W with respect to τ and I gives (5) and (10), respectively, while $\frac{\partial W}{\partial q} = -M \frac{\partial P}{\partial q} - \frac{\partial X}{\partial q}[\tau - kI - \delta q[1-r]] - X\delta[1-r]$. Given that $\frac{\partial P}{\partial q} = \frac{d'(q) + Pr}{1 - qr}$ and $\tau = kI + \delta q[1-r]$ then

$$\frac{\partial W}{\partial q} = -X[d'(q) + Pr + \delta[1-r]]. \tag{21}$$

Given the participation constraint $P = \frac{\tau + \bar{c} + d(q)}{1 - qr}$ then (5), (10) and (21) have the same solutions as do (13)–(15) and again, when Home offers q-contingent policies to individual firms, even if Home moves first joint welfare is still maximized.

Expressing the regulator's problem in this way allows us to explicitly compare the static versus dynamic objectives of Home. While each additional individual causes only δ worth of damage in period 0 itself, population growth implies future damage, and therefore each additional individual causes greater than δ in present value damage. With this in mind, we can reinterpret the dynamic trade policy problem as a static trade policy problem plus the non-linear damage term: $-\delta\theta f(Y_0 + N_0(I_0, \tau_0))$.

5.2. Optimal dynamic policy mix

In this section we derive the optimal mix of a tariff (τ_0) and monitoring intensity (I_0) in a dynamic setting, and compare these results with those from the static model (from this point forward, we omit subscripts since, unless otherwise noted, we refer to period 0). The optimal tariff is given by

$$\tau = kI + \delta q(1 - r)(1 + \theta f'). \tag{24}$$

Eq. (24) suggests that just as in the static case, the regulator should equate the tariff to the marginal damage of an import. Note that for a discount factor of 0, the tariff given above equals the optimal static tariff.

The optimal port inspections satisfy the following first-order condition:

$$-X[(P - \delta(1 + \theta f'))qr' + k] + \frac{\partial X}{\partial I}[\tau - kI - \delta q(1 - r)(1 + \theta f')] = 0. \tag{25}$$

Using (24), optimal port inspections must satisfy

$$qr'(\delta(1 + \theta f') - P) = k \tag{26}$$

which states that given that the tariff has been optimally set, inspections should be set so the net marginal damage equals the marginal cost of inspections.

Eqs. (24) and (26) are comparable to Eqs. (6) and (12) in the static case, with the additional marginal damage term $\theta\delta f'$ that reflects the contribution to present value damages of an additional individual today. Because the dynamic model effectively amplifies the damage term, it might seem that the trade policies should be more stringent in the dynamic case than in the static case; we find that this is not always true. Denoting the static tariff and inspections by τ_s and I_s, the proposition below summarizes our results:

Proposition 6. *In comparing the static and dynamic trade policies, we find*:

1. *The optimal dynamic inspections level is at least as large as the optimal static inspections level*: $I_0 \geqslant I_s$.
2. *The optimal dynamic tariff may be larger than, or smaller than the optimal static tariff*: $\tau_0 \gtreqless \tau_s$.

Proof. 1. The optimal static inspections solves

$$\frac{qr'(I_s)}{1 - qr(I_s)}[c + kI_s + \delta(q - 1)] + k = 0. \tag{27}$$

Eq. (26) implicitly defines optimal dynamic inspections where price can be written as follows:

$$P(I_0; q, \delta, c) = \frac{c + kI_0 + \delta q(1-r)(1+\theta f')}{1-qr}. \tag{28}$$

Rewritten, the necessary condition for optimal dynamic inspections is

$$\left.\frac{\partial \mathbf{W}}{\partial I}\right|_{\tau_0} = -X\left[\frac{qr'}{1-qr}(c + kI_0 + \delta(q(1+\theta f') - (1+\theta f'))) + k\right] = 0. \tag{29}$$

This derivative can conveniently be broken into two terms, and rewritten as follows:

$$\left.\frac{\partial \mathbf{W}}{\partial I}\right|_{\tau_0} = -X\left[\frac{qr'}{1-qr}(c + kI_0 + \delta(q-1)) + \frac{qr'}{1-qr}(\delta\theta f'(q-1)) + k\right]. \tag{30}$$

We wish to evaluate $\frac{\partial \mathbf{W}}{\partial I}\big|_{\tau_0}$ at I_s. Inserting Eq. (27) into Eq. (30), the first term inside the brackets equals zero, and we have the following:

$$\left.\frac{\partial \mathbf{W}}{\partial I}\right|_{\tau_0, I_s} = -X\left[\frac{qr'}{1-qr}(\delta\theta f'(q-1))\right] \geqslant 0 \tag{31}$$

with equality if and only if $q = 1$ or the non-negativity constraint on I_0 and I_s is binding. Since $\frac{\partial \mathbf{W}}{\partial I}\big|_{\tau_0, I_s} \geqslant 0$, we indeed find $I_0 \geqslant I_s$.

2. Using (3) and (24), we can express the difference between the optimal static tariff and optimal dynamic tariff as follows:

$$\Delta\tau \equiv \tau_s - \tau_0 = k(I_s - I_0) + \delta q(r(I_0) - r(I_s) + \theta f'(r(I_0) - 1)). \tag{32}$$

We begin by identifying a sufficient condition for $\Delta\tau < 0$. Recall the term $\bar{q}$ which is the value of q where $I_s = 0$ (with negative slope). Define by $\bar{q}_0$ the dynamic analog to $\bar{q}$, where $\bar{q}_0 = 1 - \frac{c}{\delta(1+\theta f')} > 1 - \frac{c}{\delta} = \bar{q}$. Evaluating $\Delta\tau$ at values of $q \geqslant \bar{q}_0$, where $I_0 = I_s = 0$ (as a consequence of part (a) of this proposition), we have $\Delta\tau = -\delta\theta f' < 0$.

To prove the possibility that $\Delta\tau > 0$, consider values of $q \in [\bar{q}, \bar{q}_0]$ (between the values of q for which inspections are just zero in the static and dynamic cases, respectively). Denote some value of q in this range by $\hat{q}$. By the above arguments, $I_0|_{q=\hat{q}} = 0$ and $I_0|_{q=\hat{q}} > 0$. The comparison of optimal tariffs is then $\Delta\tau = -kI_0 + \delta\hat{q}[r(I_0) + \theta f'(r(I_0) - 1)]$. Numerical simulations reveal that this term is typically, but not always positive. Moreover, under the assumption that $r'(0) = \infty$, it is straightforward to show that the left-hand derivative $\frac{d\tau_0}{dq}\big|_{\bar{q}_0}$ equals ∞, while the derivative $\frac{d\tau_s}{dq}\big|_{\bar{q}_0}$ equals δ, a fact that lends further evidence that, in this region for q, τ_s may exceed τ_0. Although we have not provided a full characterization of the necessary and sufficient conditions for $\Delta\tau > 0$, the slopes of $\tau_0(q)$ and $\tau_s(q)$ evaluated at $\bar{q}_0$ make it unsurprising that cases under which $\Delta\tau > 0$ are simple to identify. An straightforward example is the case in which $f(y) = \beta y$: population growth is linear. In light of the duality between the dynamic and static models, with a reinterpreted damage term (23), this is simply the static case with a larger δ, and the result is proven in Section 3.2 for linear damage terms. □

We have shown that, while inspections are uniformly more stringent in the dynamic case, the optimal dynamic tariff may be higher or lower than the static tariff.

5.3. Discussion of dynamic vs. static cases

We showed above that the dynamic optimization problem facing the regulator is equivalent to the static optimization problem with an additional damage term. Although that damage term is non-linear (because $f(y)$ is nonlinear), it is akin to scaling up the damage term, δ, in the static model. Therefore, the Proposition 6 result is consistent with our Section 3.2 analysis on the comparative statics of τ_s and I_s with respect to the damage term, δ.

It is worth noting the existence of other asymmetries in the response of policy instruments to exogenous changes. For example, we might be interested in determining how τ_0 and I_0 depend on the state variable Y_0; should a higher initial pest population give rise to more lenient or more restrictive trade policy? Real-world policy for controlling damage from introduced species seems to be more reactive than proactive, suggesting higher initial populations correspond to more restrictive policies. On the other hand, economic intuition suggests that, since the growth function in our model is concave, higher initial populations reduce the marginal damage, and should therefore correspond to less restrictive trade policy.

Olson and Roy [15] show that optimal eradication efforts hinge critically on both biological (population size and growth rate) and economic (control costs and damage) variables. For example, there is often an economic rationale for eradicating when the species population is small, but not when the population is large, though they also provide conditions under which global eradication, or no eradication at all, are optimal. In our model, a larger initial population should be met with lower monitoring inspections, but the optimal tariff may be weaker or stronger. Essentially, a higher initial population means that the marginal damage is smaller (since f' is smaller). As we showed above, a reduction in δ leads to an unambiguous decrease in I, but may increase or decrease τ. Qualitatively similar responses with respect to Y_0 can be reconciled in this light.

6. Conclusions

We have constructed a simple model of goods trade and detection and damage from exotic pests. Using this model we characterized the optimal levels of two instruments useful in minimizing the damage from contaminated trade: tariffs and port inspections.

We found that the optimal tariff on imported goods is positive, despite the absence of any motive for the importing country to use a distortionary tariff to extract rents from overseas producers or shift market share to domestic firms. In particular, we found that the importing country should set the tariff at the Pigouvian level, equal to the sum of expected damages from contaminated units not detected during inspections plus the costs of inspections in the first place. We also found that the importer's optimal tariff tends to increase in the rate at which received goods are infected with pests.

Given that the trade tax is set at the Pigouvian level, Home's only incentive to undertake port inspections is to minimize the costs associated with trade in infected goods, by balancing the cost of additional inspections and more rejections of incoming goods with the benefits of fewer infected units making it past inspectors. At low infection rates, we found that, similar to the optimal tariff, the importer's optimal level of inspection intensity is increasing in the infectedness of incoming goods. However at higher infection rates the relationship is reversed: for intermediate levels of infectedness the importer's optimal level of inspection intensity is decreasing in the rate at which incoming goods are infected with damaging pests. And after some threshold it is optimal for the importer to cease all inspections; instead the importer optimally accepts all incoming goods but charges an appropriately high tariff equal to the damage expected from incoming units. We also analyzed the relationship between the optimal tariff, optimal intensity of port inspections, and per-infection damage. While we found that a higher damage rate unambiguously requires greater monitoring intensity, it may necessitate a lower, rather than higher, tariff rate.

Given that the importer's optimal instrument levels depend on the characteristics of its trade partner—goods imported from countries with higher rates of infection and/or higher production costs should face higher taxes but possibly face weaker port inspections—we then discussed the extent to which non-discrimination policies embedded in trade agreements limit the ability of importing countries to select and manage their trade partners optimally. We found that if the importer is permitted to discriminate only along the tariff dimension, or is allowed to set caps on infection and damage rates, then the joint welfare of the importer and its trade partners will be maximized. But when caps are not employed and differentiation is permitted only in the dimension of port inspections then cases are easily found in which the importer must choose between trading with a suboptimal trade partner or setting suboptimal instrument levels for its proper partner.

And finally, we offered extensions and robustness checks of the model. First, we examined the case in which the exporting firms are able to, at a cost, reduce their infection rates prior to export. We found that the joint welfare of the importing and exporting countries will be maximized only if the importer offers infection-rate contingent instrument levels to exporting firms. If instead the importer sets instrument levels in advance of the exporters' cleaning decision then the importer will set inefficiently high tax and inspection levels while the exporter will undertake insufficient levels of pre-cleaning. We then generalized the model to account for population growth of introduced species. That analysis revealed a duality between the static and dynamic views, and suggested that although inspections should become unambiguously more stringent (when taking a dynamic view), tariffs may be strengthened or weakened.

Given the magnitude of damages from exotic species introductions (perhaps $137 billion annually) and the realization that economic activity (primarily international commodity trade) drives these introductions, it is surprising that economists have been largely absent from the policy debate about how to reduce harmful introductions. Our analysis attempts to conceptually link and formally model the relationship between international trade and damage from exotic species introductions. Although our approach is simple, it yields important insights into policy design to control damage from unintentional introductions of exotic species.

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