Invasive Species Management: Importers, Border Enforcement, and Risk

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Selected Paper prepared for presentation at the Annual Meeting of the American Agricultural Economics Association, Portland, Oregon, July 29 – August 1, 2007

An overwhelming number of shipments of goods are imported into the country every day. With each shipment comes the risk that an invasive species is entering the country, either intentionally or unintentionally. Policies aimed at excluding these invasive species or pests from entering the country include pre-shipment treatment requirements, varied inspection schemes, treatment at the border, penalties, and import bans or restrictions. These pest exclusion policies, viewed by some as veiled barriers to trade, have been developed primarily based on scientific risk assessment without economic analysis of the response of importers to border enforcement policies. Existing policies are based on the reasoning that increased enforcement effort will result in higher detection levels, or more specifically, that increased inspection will result in a higher number of interceptions and, in turn, higher compliance.

Instead of responding to increased enforcement with increased due care with respect to pest control, importers may respond in ways that regulators do not intend, expending effort to avoid enforcement. For example, importers may not export goods, may ship a reduced amount, or may switch ports of entry. Different types of firms are likely to avoid enforcement in different ways. High-risk firms, in particular, may engage in "port shopping," routing shipments through ports where enforcement is perceived to be weakest, or timing their shipments to arrive at a port when inspection staffs are low. Low-risk firms, with little to hide but wanting to avoid costly inspections nonetheless, may choose low-enforcement ports to a lesser degree. These decisions concerning port choice may have significant supply and pest risk effects as well as spatial damage or vulnerability effects.

Limited theoretical and empirical work exists in the enforcement and deterrence literature that evaluates the role of firm response in an environmental context. Inspections are a complicated enforcement tool, examined in a limited way in the economics of invasive species literature. Port shopping is a type of avoidance behavior, not discussed in the enforcement literature nor in the economics of invasive species literature.

This paper presents a theoretical model of firm response to border enforcement. The model considers two inspection and enforcement schemes for imports of a single commodity (destroy versus treat contaminated goods) and reveals both the intended and unintended effects of this enforcement. We analyze optimal firm response to changes in enforcement, economic and biological parameters (i.e., pest populations), how regulator behavior (i.e., inspection, penalties) affects social welfare, and the nature of the tradeoffs associated with location.

In response to an increase in inspection, we find that firms will reduce the amount they ship for export, an unintended response, and may increase or decrease pre-entry treatment depending on the elasticity of the marginal cost of treatment with respect to output. Firms consider the tradeoffs associated with changes in tariffs, penalties, and output price, as well as with the costs and benefits associated with location – i.e., inspection intensity versus distance to port-of-entry and final market. Different types of firms will weigh these tradeoffs differently. The present analysis implies that high-risk firms are likely to select ports that are perceived to be low-enforcement ports, rather than pre-entry treatment, and perhaps forfeiting travel distance. Low-risk firms are likely to value transportation cost savings versus avoiding enforcement. Thus, increased enforcement may not result in reduced pest risk. Although an increase in enforcement or port-specific costs at a particular port has the obvious result that firms are more likely switch away from that port, even a uniform change in enforcement may lead to changes in port choices. Further implications of the model are that Scenario 1 (destroy) is likely to be optimal to Scenario 2 when response costs and potential damages are high, and consumer surplus impacts are low, and that optimal inspection and penalties increase, as does the optimality of Scenario 1 (destroy), as *ex post* damages increase and effectiveness of *ex post* treatment decreases. Thus, the intensity and effectiveness of border inspections affects the decisions of the firm and in turn, the optimal levels of *ex post* monitoring and response effort.

Literature Review

The basis of economics of enforcement research is the concept that achieving optimal enforcement is simply a matter of balancing the level of fines and probability of detection (Becker 1968) while minimizing government monitoring costs. This body of research generally assumes that the effectiveness of enforcement is entirely determined by the regulator (i.e., exogenous to the firm) and that firms are limited to choosing the level of a single action such as pollution or output levels. Malik (1990) suggested that detection probabilities are actually endogenous to firms, that firm response in the form of "avoidance" activities can reduce the probability of detection and thus the effectiveness of enforcement measures. In contrast to Becker's conclusion that fines should be set arbitrarily high, Malik showed that optimal fines may actually be lower because of avoidance by firms.[1] Even if firms are assumed to be risk-neutral, higher fines may induce firms to exert effort to lower the probability of being fined.

In the environmental enforcement literature, several authors have found that stricter environmental regulations, in the form of higher emissions penalties or stricter standards, produce not only a desired direct effect but also an indirect effect of increasing incentives for regulated parties to reduce the probability of detection (Lee 1984; Kambhu 1990; Oh 1995; Huang 1996; Kadambe and Segerson 1998). Lee concluded that in response to higher emission taxes, firms may find it profitable to invest in efforts to evade a pollution tax rather than reduce

[1] Polinsky and Shavell (1979) argued that optimal fines are relatively lower (not arbitrarily high) if agents are assumed to be risk averse. Further, Polinsky and Shavell (1992) showed results similar to Malik (1990) concerning firm avoidance behavior.

emissions, so optimal levels of pollution will not be achieved. Similarly, Oh and Huang found that raising pollution fees may actually increase pollution levels. Although this literature provides a foundation for our analysis, we could not find any publications in the general economics literature nor the environmental enforcement literature that considered how changes in monitoring effort on the part of regulators (instead of monetary incentives) may result in unintended firm response. While Bhagwati and Hansen (1973) and Thursby, Jensen, and Thursby (1991) provided an analysis of market structure under smuggling, firm response to enforcement measures was not explicitly evaluated.

The environmental enforcement literature that examines monitoring as an enforcement tool again provides a foundation for our research. These analyses generally couple monitoring with either emission taxes (when pollution is observable) or output taxes (when pollution is unobservable). A recent example of this research using mechanism design with moral hazard is Demougin and Fluet (2001). Specific to invasive species, McAusland and Costello (2004) analyzed the optimal mix of tariffs (essentially an output tax) and inspections to control invasive species introductions. This analysis, however, did not evaluate the tradeoff between inspections and sanctions or fines nor did it consider potential avoidance behavior in response to enforcement.

In the economics of invasive species literature, research on prevention and control does not address the specifics of border enforcement (Kim et al. 2006; Horan et al. 2002; Olson and Roy 2005). The tradeoffs between the costs and benefits of inspection policies in an invasive species context were considered by Batabyal (2004a; 2004b) and Moffit et al. (2005). While Batabyal provided details on how maritime inspections are carried out and accounted for economic losses due to delay, this work primarily presented a queuing theory approach and included a very simple implicit assumption that less stringent inspections lead to more damages from biological invasions. Moffit et al. (2005) focused on dealing with the limited knowledge that policy makers have concerning risks and policies that involve achieving threshold levels of risk.

McAusland and Costello (2004) analyzed the optimal mix of tariffs (not penalties/fines) and inspection to control invasive species introductions. Using a two-country trade model, they found that although at low rates of infection, inspection increases as the proportion of infected goods increases, this relationship is reversed at higher rates and there should be no inspections past a certain threshold. This non-monotonicity stems from the assumption that infected good are barred from importation. Thus, as more infected shipment are detected, consumers in the importing country suffer. The analysis also found that as marginal damages from infected imports increases, monitoring unambiguously increases, while the optimal tariff decreases, again due to the cost of refusing infected goods. Often, however, infected goods are treated and then allowed entry. This analysis did not evaluate the tradeoff between inspections and sanctions or fines nor did it consider potential avoidance behavior in response to enforcement.

Research on border control measures and invasive species, such as that by McAusland and Costello, has not considered heterogeneity of ports nor how this heterogeneity is linked spatially to damages. While spatial and dynamic analyses of damages from invasive species and pests are becoming more common (Barbier and Shogren 2004) these analyses generally do not consider border measures. Spatial damage analyses of invasive species and pests, however, especially those focusing on specific species and landscapes (e.g., Brown, Lynch, and Zilberman (2002) focused on Pierce's disease in grapes) would inform development of a simulation model that integrates border enforcement and spatial pest damages.

The Model

The basis of our theoretical analysis builds on previous work by Ameden *et al.* (under review), and is a model of importing firm and government inspection agency behavior. Assume there are $i = 1,...,I$ importing firms that handle a specific agricultural product and assume that pest risk increases with i. These firms ship their product through ports of entry, $k = 1,...,K$. The model has three stages (see Figure 1):

- Stage 1: Pre-border firm decisions- production, treatment and shipment to border,
- Stage 2: At the border regulator decisions- border inspections and enforcement, and
- Stage 3: Post-border firm and regulator decisions- shipment to final market, environmental damage, monitoring and control.

Stage 1: Pre-border

In Stage 1, we assume each firm is making post-harvest decisions. Each firm's output has an associated initial pest population, $n_i(0)$, known to the firm. Each firm chooses:

- to which port to ship
- how many units to ship through the port to the importing country, y_{ik}, and
- point-of-origin treatment effort per unit, e_{ik}.

After the firm applies point-of-origin treatment, the pest population per unit is:

$$n_{ik}(1) = n_i(0)g(e_{ik})$$

where $g(e_{ik})$ is a kill (survival) function bounded between 0 and 1, $\partial g(e_{ik}) / \partial e_{ik} < 0$, thus $\partial n_{ik}(1) / \partial e_{ik} < 0$. After point-of-origin treatment, the output is shipped to the chosen port of entry. Transportation cost from the point of origin for firm i to the port is τ_{ik}. Initial cost of production is $c_i(y_{ik}, e_{ik})$. Total initial costs are $c_i(y_{ik}, e_{ik}) + \tau_{ik}$.

Stage 2: At the border

Government inspection at the port will lead to discovery of $h(n_{ik}(1), w_k)y_{ik}$ contaminated units of output where $h(n_{ik}(1), w_k)$ is a fraction between 0 to 1 and w_k is the port-specific value of inspection effort per unit of output, i.e., w_k is a measure of inspection intensity. Total inspection costs for the regulator are $Inspect = \sum_{k=1}^{K}\sum_{i=1}^{I} w_k y_{ik}$. We assume:

$$0 \le h(n_{ik}(1), w_k) \le 1, \frac{\partial h(n_{ik}(1), w_k)}{\partial n_{ik}(1)} > 0, \frac{\partial h(n_{ik}(1), w_k)}{\partial w_k} > 0\ , \frac{\partial^2 h(n_{ik}(1), w_k)}{\partial^2 w_k} < 0\ .$$

These assumptions suggest that higher investment leads to higher discovery but the marginal productivity of investment is decreasing. This discovery function is a stylized representation of the actual discovery process which usually involves inspection of a limited portion of the shipment and declaration that an entire shipment is either cleared for entry or not based on this limited inspection. In our stylized model, the units of output could be interpreted as a stream of identical shipments and thus the discovery function indicates how many of these shipments are identified as contaminated. We compare two alternative scenarios when pests are discovered on shipments.

Scenario 1. Shipments are destroyed

In this case, units that are discovered to be contaminated are destroyed, actual quantity supplied by the *i*th firm is $s_{ik}^1 = (1 - h(n_{ik}(1), w_k))y_{ik}$, and the firm will pay a penalty of $Penalty_{ik}^1 = t^1 h(n_{ik}(1), w_k)y_{ik}$ where t^1 is the penalty per unit of contaminated output under Scenario 1. The total penalties collected from all firms are: $TotPenalty^1 = \sum_{i=1}^{I}\sum_{k=1}^{K} Penalty_{ik}^1$.

Firms are charged a tariff, j ,on only those shipments allowed entry, $j(1 - h(n_{ik}(1), w_k))y_{ik}$.

Scenario 2. Shipments are treated

Under Scenario 2, units discovered to be contaminated are treated and the quantity supplied by the *i*th firm is $s_{ik}^2 = y_{ik}$, total tariffs paid are jy_{ik}. The cost of treatment at the border is x per unit with total cost of treatment equal to $xh(n_{ik}(1), w_k)y_{ik}$. The firm pays a per unit penalty of t^2 under Scenario 2. The penalty for the firm in this case will be

$Penalty_{ik}^2 = t^2 h(n_{ik}(1), w_k)y_{ik}$ with total penalties collected, $PenaltyTot^2 = \sum_{k=1}^{K}\sum_{1=i}^{I} Penalty_{ik}^2$. The total enforcement cost for the firm will be $(x+t^2)h(n_{ik}(1), w_k)y_{ik}$. Treatment may not be completely effective. After treatment, pest populations on the output discovered to be contaminated are $h(n_{ik}(1), w_k)n_{ik}(1)z(x)$, where $z(x)$ is the Scenario 2, Stage 2 kill function bounded between 0 and 1, and $\partial z/\partial x < 0$.

Stage 3: Post-border

The firm's output is shipped to a final market with per unit transportation cost from the port of l_k, and sold for price, p. Total supply $S_T(p; w, t, \tau, x, j, l)$ comes from two sources, domestic supply, $S_D(p)$, and expected foreign importer supply. Pest detection and damage are random variables as are all other variables affected by damage. To simplify the analysis, we consider the expected value of the foreign supply function and resulting prices and quantities. Thus *p* is the price that occurs given foreign supply is at its expected level for every p. Expected total supply is:

Scenario 1: $S_T^1(p;\bullet) = S_D(p) + S_F^1$, and

Scenario 2: $S_T^2(p;\bullet) = S_D(p) + S_F^2$,

where S_F^1 and S_F^2 are the profit maximizing supply from foreign importing firms under Scenario 1 and Scenario 2. In equilibrium, total supply intersects domestic demand under each

Scenario, $S_T^1(p;\bullet) = D(p)$, $S_T^2(p;\bullet) = D(p)$ to generate equilibrium prices and quantities, $S_D^1(p^{1*})$, S_F^{1*} , p^{1*} , and $S_D^2(p^{2*})$, S_F^{2*} , p^{2*} . We can now derive expected consumer surplus:

$$CS = \int_0^{S_T(p^*)} [D(p) - p^*]ds ,$$

and expected domestic producer surplus:

$$PS_D = \int_0^{S_D^*(p)} [p^* - S_D(p)]ds .$$

Environmental damages depend on the number of pests arriving on imported goods, *N*, as well as the level of responsive treatment, *R*. We assume that environmental damage $V(N, R)$ increases with pest populations and declines with treatment ($\partial V / \partial N > 0, \partial V / \partial R < 0$). We further assume increasing marginal damage with respect to N , $\partial^2 V / \partial N^2 > 0$ and decreasing efficacy of treatment, $\partial^2 V / \partial R^2 < 0$.

The Firm's Decision

The *i*th firm determines through which port to ship, how much to export, and how much to treat. The firm is assumed to maximize expected profit taking prices as given and given the risk that contaminated produce may be detected. Under Scenario 1, output that is discovered to be contaminated is destroyed, under Scenario 2, contaminated output is treated. It is a discrete/continuous choice problem:

Scenario 1: $\Pi_i^1 = \underset{k}{Max}\left\{ \underset{y_{ik}, e_{ik}}{\max} \left[\left\{ (p - j - l_k)(1 - h(n_{ik}(1), w_k)) - t^1 h(n_{ik}(1), w_k) - \tau_{ik} \right\} y_{ik} - c_i(y_{ik}, e_{ik}) \right] \right\}$

Scenario 2: $\Pi_i^2 = \underset{k}{Max}\left\{ \underset{y_{ik}, e_{ik}}{\max} \left[\left\{ p - (x + t^2) h(n_{ik}(1), w_k) - j - l_k - \tau_{ik} \right\} y_{ik} - c_i(y_{ik}, e_{ik}) \right] \right\}$

This optimization problem can be broken down to sub-problems where:

Scenario 1: $\pi_{ik}^{1} = \underset{y_{ik}, e_{ik}}{\max} \left[\left\{ (p - j - l_k)(1 - h(n_{ik}(1), w_k)) - t^1 h(n_{ik}(1), w_k) - \tau_{ik} \right\} y_{ik} - c_i(y_{ik}, e_{ik}) \right]$

Scenario 2: $\pi_{ik}^{2} = \underset{y_{ik}, e_{ik}}{\max} \left[\left\{ p - (x + t^2) h(n_{ik}(1), w_k) - j - l_k - \tau_{ik} \right\} y_{ik} - c_i(y_{ik}, e_{ik}) \right]$

are solved first and then the optimal port is selected by solving

$\Pi_i^1 = \underset{k}{Max} \left\{ \pi_{ik}^1 \right\}$, or $\Pi_i^2 = \underset{k}{Max} \left\{ \pi_{ik}^2 \right\}$.

The optimal decision rules for each importing firm are:

Scenario 1:

(1) $\partial \pi_{ik}^1 / \partial y_{ik} = 0 \Rightarrow p(1 - h(n_{ik}(1), w_k)) = (j + l_k)(1 - h(n_{ik}(1), w_k)) + t^1 h(n_{ik}(1), w_k) + \tau_{ik} + \partial c_i / \partial y_{ik}$,

(2) $\partial \pi_k^1 / \partial e_{ik} = 0 \Rightarrow (p + t^1)\left(-\partial h / \partial n_{ik}(1) \; \partial n_{ik}(1) / \partial e_{ik} \right) y_{ik} = (j + l_k)\left(-\partial h / \partial n_{ik}(1) \; \partial n_{ik}(1) / \partial e_{ik} \right) y_{ik} + \partial c_i / \partial e_{ik}$,

Scenario 2:

(3) $\partial \pi_{ik}^2 / \partial y_{ik} = 0 \Rightarrow p = (x + t^2) h(n_{ik}(1), w_k) + j + l_k + \tau_{ik} + \partial c_{ik} / \partial y_{ik}$, and

(4) $\partial \pi_{ik}^2 / \partial e_{ik} = 0 \Rightarrow (x + t^2)\left(-\partial h / \partial n_{ik}(1) \; \partial n_{ik}(1) / \partial e_{ik} \right) y_{ik} = \partial c_{ik} / \partial e_{ik}$.

Equations (1) and (2) define y_{ik}^{1*} and e_{ik}^{1*}, optimal firm output and point-of-origin treatment for all firms at each port under Scenario 1, and similarly, equations (3) and (4) define y_{ik}^{2*} and e_{ik}^{2*}. Each firm then chooses to ship through the profit-maximizing port of entry. Solving equations (1) and (2) for optimal output under Scenario 1 and Scenario 2 gives:

(5) $$y_{ik}^{1*} = \left[\begin{array}{l}(p-j-l_k)(1-h(n_{ik}(1),w_k))-t^1 h(n_{ik}(1),w_k) \\ -\tau_{ik} - \partial c_i / \partial y_{ik} + \partial c_i / \partial e_{ik}\end{array}\right] \Big/ (p+t^1-j-l_k))\left(-\partial h / \partial n_{ik}(1) \; \partial n_{ik}(1) / \partial e_{ik}\right),$$

and

(6) $$y_{ik}^{2*} = \left[\begin{array}{l}p-(x+t^2)h(n_{ik}(1),w_k)-j-l_k \\ -\tau_{ik} - \partial c_{ik} / \partial y_{ik} + \partial c_{ik} / \partial e_{ik}\end{array}\right] \Big/ (x+t^2)\left(-\partial h / \partial n_{ik}(1) \; \partial n_{ik}(1) / \partial e_{ik}\right) y_{ik}.$$

Equations (1) through (4) show that at optimal levels of output and point-of-origin treatment, the marginal benefits of the firm's action will equal its cost. Equation (1) shows that under Scenario 1, the marginal increase in revenue associated with an increase in output is tempered by the losses of contaminated goods that are destroyed. The marginal cost of increased output consists of higher production and transportation costs and higher penalties. Equation (2) shows that the marginal benefits of an increase in point-of-origin treatment are reduced discovery and thus increased revenue and decreased penalties, while the marginal costs are increased transportation costs from the port to market, and higher production costs. Under Scenario 2, the marginal benefit of increasing output is not tempered by destroyed product because contaminated output is treated rather than destroyed. The marginal costs of increased output are not only higher production costs, transportation costs, and penalties, but also treatment costs. Equations (5) and (6) show that if the lower marginal benefit of an additional unit of output under Scenario 1 versus Scenario 2 is not offset by sufficiently low marginal cost, then optimal output under Scenario 1 is less than that under Scenario 2.

Proposition 1: If $(p-j-l_k) > x$ and $t^1 = t^2$ then $y_{ik}^{1*} < y_{ik}^{2*}$.

Single Port-of-Entry

Regulators determine the intensity of inspections and border treatment, and set tariffs and penalties. Assume for now there is a single port-of-entry, $k = 1$, so firms choose the amount of output and pre-entry treatment only. Based on comparative statics analysis of equations (1) and (2) for Scenario 1, and equations (3) and (4) for Scenario 2, we evaluate how firm i responds to changes made by regulators in inspection levels, tariffs, penalties, as well as changes in economic conditions, and pest populations (details are not presented here, contact authors for math appendix). To specify these relationships we first define several conditions.

Condition 1: $\partial^2 h \big/ \partial n_i(1) \partial w_k = 0$.

Condition 1 means that the relationship between pest population levels on shipments at the border and the level of discovery does not change as inspection levels change, or alternatively that the slope of the discovery function with respect to inspection does not change as initial pest populations change.

Condition 2: $\varepsilon = y_{ik} \left(\frac{\partial^2 c_i}{\partial y_{ik} \partial e_{ik}}\right) \Big/ \frac{\partial c_i}{\partial e_{ik}} > 1$.

Condition 3: $\varepsilon = y_{ik} \left(\frac{\partial^2 c_i}{\partial y_{ik} \partial e_{ik}}\right) \Big/ \frac{\partial c_i}{\partial e_{ik}} < 1$.

Conditions 2 and 3 involve a key parameter - the elasticity of the marginal cost of treatment with respect to output, denoted by $\varepsilon = y_{ik} \left(\frac{\partial^2 c_i}{\partial y_{ik} \partial e_{ik}}\right) \Big/ \frac{\partial c_i}{\partial e_{ik}}$. When ε is greater than unity, marginal treatment cost with respect to output is greater than average treatment cost with respect to output. This suggests a strong positive relationship between the cost of treatment and the scale of production. When ε is small, marginal treatment cost with respect to output is not responsive to a change in the scale of output. This corresponds to a situation where high initial costs are associated with point-of-origin treatment. We cannot rule out either situation as infeasible *a* *priori*. These conditions relate to signs of the off-diagonal elements of the Hessian matrix in the comparative statics analysis.

Several propositions concerning inspection intensity follow.

Proposition 2a: An increase in inspection will always decrease the optimal level of output under both Scenario 1 and 2 ($dy_{ik}^{*}/dw_k < 0$) if Condition 1 holds.

Proposition 2b: Assume Condition 1 holds. An increase in inspection will lead to an *increase* in point-of-origin treatment $(de_{ik}^{*}/dw_k > 0)$, if Condition 2 holds $(\varepsilon > 1)$.

Behind Proposition 2a is the reasoning the that an increase in inspection is equivalent to a decrease in the price received by firms, and firms reduce their output accordingly. The reasoning behind Proposition 2b is more subtle. When the response of the marginal cost of treatment with respect to output is elastic, the average cost of treatment declines, meaning that profits increase with more treatment. This leads to the intuitive result that an increase in inspection will encourage firms to take more care before shipment. Total point-of-origin treatment applied by the firm may either increase or decrease, however, because output declines. When the response of the marginal cost of treatment with respect to output is inelastic, however, we obtain an opposite result – firms' profits will increase with less point-of-origin treatment. Under these conditions, total point-of-origin treatment applied decreases.`

If Condition 1 is relaxed so that $\partial^2 h / \partial n_i(1) \partial w_k \geq 0$, meaning that as Stage 2 pest populations increase, each unit of inspection effort becomes more effective, the results in the case that $\varepsilon > 1$ do not change while the results in the case that $\varepsilon < 1$ (there is not a strong relationship between scale of production and marginal cost of treatment) do. In the second case, inspection intensity may be positively or negatively related to output and point-of-origin treatment depending, in part, on the relative magnitudes of the slope of the discovery function with respect to inspection, $\partial h / \partial w_k$, and the relationship, $\partial^2 h / \partial n_i(1)\partial w_k \; \partial n_i(1) / \partial e_{ik}$, where $\partial n_i(1) / \partial e_{ik} = n_i(0) \, \partial g / \partial e_{ik}$, and $\partial g / \partial e_{ik}$ is the slope of the point-of-origin treatment function. This means that inspection and output level could be positively related if marginal cost of treatment does not rise with production, the slope of discovery function with respect to inspection is shallow, and the point-of-origin treatment function is steep.

The regulator's choice of enforcement scenario will affect the impact of other policy tools. In this model, the response of firms to changes in inspection intensity will be different under a policy of destroying contaminated shipments versus treating these shipments. If Condition 1 holds, the difference between the two scenarios is clear. If Condition 1 is relaxed so that that $\partial^2 h / \partial n_i(1)\partial w_k \geq 0$, the results do not change unless $\varepsilon < 1$ and thus inspection intensity may be positively or negatively related to output and point-of-origin treatment as just discussed.

> Proposition 2c: The response of output and point-of-origin treatment to changes in inspection intensity will be greater under Scenario 1(destroy) than Scenario 2 (treat) if $(p - j - l_k + t^1) > (x + t^2)$ and if Condition 1 holds.

Under Scenario 1, because output discovered to be contaminated is destroyed and is not part of total supply, the firm response to increases in inspection intensity is affected by lost revenue, avoided tariff and transportation costs and penalties levied on this output.

Under Scenario 2, output discovered to be contaminated is treated and remains part of total supply.

Tariffs have a clear effect on the choices made by firms. An increase in a tariff is essentially a reduction in price per unit of output or marginal revenue thus an increase in the per unit tariff unambiguously decreases both output and point-of-origin treatment.

Proposition 3a: An increase in tariffs will decrease the optimal level of output and point-of-origin treatment under Scenario 1 and 2 ($\partial y_i^* / \partial j < 0, \partial e_i^* / \partial j < 0$) .

The effect of a change in penalties on firm behavior is not as clear because a change in the level of the per unit penalty has a different effects on the marginal benefit of output and treatment. In this model, penalties are levied on each unit of output discovered to be contaminated, so an increase in penalties decreases the marginal revenue of output, leading to a decrease in both output and treatment. An increase in penalties, however, also increases the marginal benefit of point-of-origin treatment in the form of avoided penalties which would lead to an increase in treatment and output. Thus, if the effect of increased penalties on the marginal benefit of point-of-origin treatment is great enough to overcome the effect on the loss in marginal revenue of output, output and point-of-origin treatment will increase.

Proposition 3b: If Condition 2 holds $(\varepsilon > 1)$, an increase in penalties will lead to an decrease in output ($dy_{ik}^* / dt^1 > 0$, $dy_{ik}^* / dt^2 > 0$) and may increase or decrease pre-entry output. If Condition 3 holds $(\varepsilon < 1)$, an increase in inspection will lead a *decrease* in point-of-origin treatment ($de_{ik}^* / dw_k < 0$).

Economic conditions determine transportation costs from the origin to the border, and from the border to market, as well as prices. As with inspection intensity, an increase in transportation cost to the border essentially reduces per unit revenue and as such is negatively related to output. The effect on point-of-origin treatment depends on whether the elasticity of the marginal cost of treatment with respect to output is greater or less than unity.

Proposition 4a: An increase in transportation cost from the origin to the border will decrease the optimal level of output under both Scenario 1 and 2 ($dy_{ik}^{*}/d\tau_k < 0$).

Proposition 4b: Under Condition 2 $(\varepsilon > 1)$, an increase in the cost of transportation from the point of origin to the border will lead to an *increase* in point-of-origin treatment , i.e., $de_{ik}^{*}/d\tau_k > 0$. Under Condition 3 $(\varepsilon < 1)$, an increase in transportation cost will lead to a *decrease* in point-of-origin treatment ($de_{ik}^{*}/d\tau_k < 0$).

In contrast, transportation cost from the port of entry to market, l_k, has an unambiguous negative relationship to output and point-of-origin treatment.

Proposition 4c: An increase in transportation cost from the port of entry to the border will decrease the optimal level of output and point-of-origin treatment under Scenario 1 and 2 $(\partial y_{ik}^{*}/\partial l_k < 0, \partial e_{ik}^{*}/\partial l_k < 0)$.

Output price, p, is positively related to point-of-origin treatment and output levels given Condition 2 holds.

Proposition 4d: An increase in output price will lead to an increase in output and point-of-origin treatment ($dy_{ik}^{*}/dp > 0$, $de_{ik}^{*}/dp > 0$) under Scenarios 1 and 2, if Condition 3 $(\varepsilon < 1)$ holds.

At the point of origin, post-harvest, each firm's output has an associated initial pest population.

Proposition 5a: An increase in initial pest populations will decrease the optimal level of output under both Scenario 1 and 2 ($dy_{ik}^{*}/dn_i(0) < 0$) if Condition 2 holds.

Proposition 5b: An increase in initial pest populations may lead to an increase or *decrease* in point-of-origin treatment ($de_{ik}^{*}/dn_i(0) ? 0$) if Condition 2 holds. If Condition 3 holds, an increase in initial pest populations will lead to an *increase* in point-of-origin treatment ($de_{ik}^{*}/dn_i(0) > 0$).

As with inspection intensity, the relationship in Proposition 5a holds because an increase in initial pest populations is equivalent to a decrease in price, so firms reduce output supplied. Proposition 5b indicates that when the marginal cost of treatment with respect to output is greater than unity, the average cost of treatment declines with a drop in output, and point-of-origin treatment becomes more cost-effective. Thus, in response to an increase in initial pest populations, firms will employ more treatment. If instead the marginal cost of treatment with respect to output is less than unity, firms may respond to higher initial pest populations by increasing or reducing point-of-origin treatment, depending, in part, on the relative magnitudes of the point-of-origin kill function, $g(e_{ik})$ and its slope, $\partial g/\partial e_{ik}$. If the kill function is effective, i.e., $g(e_i)$ is relatively small, and $\partial g/\partial e_{ik}$ is steep, then firms are likely to respond to increases in inspection intensity by increasing point-of-origin treatment ($de_{ik}^{*}/dn_i(0) > 0$).

The model specifies that for the $i = 1, ..., I$ importing firms that handle a specific agricultural product, and pest risk increases with i. This could be represented by further assuming that initial pest populations, $n_i(0)$, increase with i. Thus, low-risk firms have lower initial pest populations, $n_L(0) < n_H(0)$, where the L and H subscripts denote that of low- or high-risk firms, and the comparative statics analysis on firm response to changes in $n_i(0)$ can serve as an analysis of firm heterogeneity. Assume for now that $c_i(y_{ik}, e_{ik})$ and the discovery function, $h(n_i(1), w_k)$, do not vary with i and all other parameters are equal between firms. Shipments from low-risk firms through the single port of entry are larger than those from high-risk firms, $y_L > y_H$, point-of-origin treatment levels may be higher or lower depending on the elasticity of marginal treatment cost with respect to output, $e_L > e_H$ or $e_L < e_H$, and pest populations on shipments at the border may be lower or higher, $n_L(1) < n_H(1)$ or $n_L(1) > n_H(1)$. Firms that are initially very high-risk may choose not to ship at all, selling their output on the domestic market. Medium-risk firms may reduce exports slightly while low-risk, high profit margin firm may not significantly change the levels of output or point-of-origin treatment.

The pest population associated with firm i's output at the end of Stage 2 under Scenario 1 is:

$$n_i^1(2) = (1 - h(n_{ik}(1), w_k))n_{ik}(1)y_{ik},$$

while the total number of pests that enter the country, N, under Scenario 1 is:

$$N^1(2) = \sum_{k=1}^{K}\sum_{i=1}^{I} n_i^1(2) = \sum_{k=1}^{K}\sum_{i=1}^{I}(1 - h(n_{ik}(1), w_k))n_{ik}(1)y_{ik}.$$

Under Scenario 2, at the end of Stage 2, the pest population on undiscovered, untreated output and discovered, treated output is:

$$n_{ik}^2(2) = \left[(1 - h(n_{ik}(1), w_k)) + h(n_{ik}(1), w_k)z(x)\right]n_{ik}(1)y_{ik},$$

while the total number of pests that enter the country is:

$$N^2(2)=\sum_{k=1}^{K}\sum_{i=1}^{I}\left[(1-h(n_{ik}(1),w_k))n_{ik}(1)+h(n_{ik}(1),w_k)n_{ik}(1)z(x)\right]y_{ik}\ .$$

The effect of changes in inspection levels on pest populations under Scenario 1, $N^1(2)(y_{ik}^{1*},e_{ik}^{1*},w_k^{1*},t^{1*};\bullet)$, and under Scenario 2, $N^2(2)(y_{ik}^{2*},e_{ik}^{2*},w_k^{2*},t^{2*};\bullet)$, assuming a single port, $k=1$, are defined by:

(7) $$\partial N^1/\partial w_k=\sum_{i=1}^{I}\left\{\begin{array}{l}(1-h(n_{ik}(1),w_k))n_{ik}(1)\,\partial y_{ik}/\partial w_k+(1-h(n_{ik}(1),w_k))\,\partial n_{ik}(1)/\partial w_k\ y_{ik}\\ +\left(-\partial h/\partial n_{ik}(1)\ \partial n_{ik}(1)/\partial w_k-\partial h/\partial w\right)n_{ik}(1)y_{ik}\end{array}\right\}$$, and

(8) $$\partial N^2/\partial w_k=\sum_{i=1}^{I}\left\{\begin{array}{l}\left[(1-h(n_{ik}(1),w_k))+h(n_{ik}(1),w_k)z(x)\right]n_{ik}(1)\,\partial y_{ik}/\partial w_k+\\ \left[(1-h(n_{ik}(1),w_k))+h(n_{ik}(1),w_k)z(x)\right]\partial n_{ik}(1)/\partial w_k\ y_{ik}+\\ \left(-\partial h/\partial n_{ik}(1)\ \partial n_{ik}(1)/\partial w_k-\partial h/\partial w_k\right)\left(1-z(x)\right)n_{ik}(1)y_{ik}\end{array}\right\}.$$

These results lead to the following.

> Proposition 6a: Stage 2 pest populations unambiguously decrease with an increase in inspection intensity under Scenario 1 and 2 ($\partial N^1/\partial w_k<0$, $\partial N^2/\partial w_k<0$) if Condition 2 holds and $\left(\partial h/\partial n_{ik}(1)\ \partial n_{ik}(1)/\partial w_k<\partial h/\partial w_k\right)$.
>
> Proposition 6b: The relationship between inspection intensity and Stage 2 pest population depends on the relative magnitudes of the output effect ($\partial y_{ik}/\partial w_k<0$), a treatment effect ($\partial e_{ik}/\partial w_k<0$), and a discovery function effect$\left(-\partial h/\partial n_{ik}(1)\ \partial n_{ik}(1)/\partial w_k-\partial h/\partial w_k\ ?\,0\right)$.

The result in Proposition 6a is due to the negative relationship between output and inspection intensity, $\partial y_{ik} / \partial w_k < 0$ (higher inspection levels result in lower output which in turn means a reduced pest population), and positive relationship between point-of-origin treatment and inspection, $\partial e_{ik} / \partial w_k > 0$, if $\varepsilon > 1$ (note $\partial n_{ik}(1) / \partial w_k = \partial n_{ik}(1) / \partial e_{ik} \; \partial e_{ik} / \partial w_k > 0$). Proposition 6b follows from equations (7) and (8).

Two Ports-of-Entry

If we now assume there are two ports from which firms may choose, Port A and Port B, firms will determine optimal output and pre-entry treatment for each port and then choose the profit-maximizing port. If it is initially optimal for firm i to ship through Port A, then it must be the case that $\pi_{iA} > \pi_{iB}$, or $\pi_{iA} - \pi_{iB} \geq 0$, where π_{iA} and π_{iB} are the optimized profits for firm i at Port A and Port B. If regulator decisions or economic conditions change such that $\pi_{iA} - \pi_{iB} < 0$, then firm i will switch to Port B. Note that while profits at the optimal port for firm i must be higher than optimal profits at all other ports, output level at the optimal port may not necessarily be higher depending on the cost structures at the other ports. The difference between optimized profit at Port A and Port B under Scenario 1 is:

$$\begin{aligned} \pi_{iA}^1 - \pi_{iB}^1 &= (p - j - l_k)\left[(1 - h(n_{iA}(1), w_A))y_{iA} - (1 - h(n_{iB}(1), w_B))y_{iB}\right] - t^1 h(n_{iA}(1), w_A)y_{iA} \\ &\quad + t^1(h(n_{iB}(1), w_B))y_{iB} - \tau_{iA}y_{iA} + \tau_{iB}y_{iB} - c_i(y_{iA}, e_{iA}) + c_i(y_{iB}, e_{iB}) > 0 \end{aligned} \tag{9}$$

As increases occur in either inspection at Port A, transportation cost to Port A, or transportation cost from Port A to the market, profit at Port A decreases while profit at Port B is unaffected and the difference between optimized profits for Port A and Port B declines. If market price is port-specific, then a decline in price at Port A would also decrease the profit differential.

Proposition 7a: An increase in any port-specific cost or decrease in port-specific revenue will make firms more likely to switch away from the particular port.

A change in initial pest populations will affect optimal profit at both Port A and Port B through the respective discovery functions as follows:

$$\begin{aligned}(10)\qquad \partial(\pi_{iA}-\pi_{iB})/\partial n_i(0) &= (p-j+t^1-l_A)\left[-\partial h/\partial n_{iA}(1)\;\partial n_{iA}/\partial n_i(0)\, y_{iA}\right]\\ &\quad +(p-j+t^1-l_B)\left[\partial h/\partial n_{iB}(1)\;\partial n_{iB}/\partial n_i(0)\, y_{iB}\right]\end{aligned}$$

The effect of a change in initial pest populations will depend on relative magnitudes of $\partial h/\partial n_{iA}(1)\;\partial n_{iA}/\partial n_i(0)$ and $\partial h/\partial n_{iB}(1)\;\partial n_{iB}/\partial n_i(0)$, where $\partial n_{iA}/\partial n_i(0) = g(e_{iA})$, and $\partial n_{iB}/\partial n_i(0) = g(e_{iB})$. If $\partial h/\partial n_{iA}(1)$ is steep (as initial pest populations increase, inspections become significantly more effective) and $\partial h/\partial n_{iB}(1)$ is not, then firms are more likely to switch to Port B. Alternatively, if the kill (survival) function at Port A, $g(e_{iA})$, is much greater than that at Port B, $g(e_{iB})$, though this seems unlikely, firms may switch to Port B. Note that under Scenario 2 we have:

$$\begin{aligned}(11)\qquad \partial(\pi_{iA}-\pi_{iB})/\partial n_i(0) &= (x+t^2)\left[-\partial h/\partial n_{iA}(1)\;\partial n_{iA}/\partial n_i(0)\, y_{iA}\right]\\ &\quad +(x+t^2)\left[\partial h/\partial n_{iB}(1)\;\partial n_{iB}/\partial n_i(0)\, y_{iB}\right].\end{aligned}$$

Proposition 7b: Under Scenario 1 and Scenario 2, a change in initial pest populations, $n_i(0)$, for firm i may cause that firm to switch ports depending on the relative magnitudes of $\partial h/\partial n_{iA}(1)\;\partial n_{iA}/\partial n_i(0)$ and $\partial h/\partial n_{iB}(1)\;\partial n_{iB}/\partial n_i(0)$.

Regulators may choose to increase inspection intensity uniformly across all ports, reducing profit at all ports. This change affects the profit differential under Scenario 1 as follows:

$$(12)\quad \partial(\pi_{iA}-\pi_{iB})\big/\partial w = (p-j+t^1-l_A)\left(-\partial h(n_{iA}(1),w)\big/\partial w\right)y_{iA} + (p-j+t^1-l_B)\left(\partial h(n_{iA}(1),w)\big/\partial w\right)y_{iB}.$$

Note that under Scenario 2, $(p-j+t^1-l_A)$ and $(p-j+t^1-l_B)$ in this equation would be replaced with $(x+t^2)$. If the slope of the discovery function with respect to inspection intensity for Port A is steep so that profit for Port A is reduced significantly by an increase in inspection while the slope for Port B is shallow, firms may switch to Port B.

Proposition 7c: Under Scenario 1 and Scenario 2, firms may respond to a uniform increase in inspection intensity by switching ports depending on the relative magnitudes of $\partial h(n_{iA}(1),w)\big/\partial w$ and $\partial h(n_{iB}(1),w)\big/\partial w$.

As with the single port case, different types of firms will make different port choices. For example, high-risk firms with high initial pest populations are more likely to prefer ports with lower inspection intensities. Moreover, different firms have different responses to changes in enforcement. Thus, as inspection intensity increases at a particular port, firms that ship through that port are likely to separate into three groups: high-risk firms that choose not to export at all; others that will switch to a lower enforcement port, perhaps located farther from the source of the commodity or market; and low-risk firms that though they ship lower quantities, continue to ship through the now more rigorous port with lower transportation costs. The specifics of these separating equilibria are crucial to evaluate in order to fully understand the role and implications of firm heterogeneity for enforcement policy in a multiple-port setting.

Port-specific attributes that can affect the effectiveness of inspection or make discovery more difficult (such as congestion or port size), or alternatively, importers that take illicit action to deter successful inspection, may play a significant role in determining pest risk. The model can be expanded to include the difficulty of discovery at the *k*th location as ψ_k, defining a type of port heterogeneity. Essentially, this means that the slope of the discovery function with respect to inspection at one port does not equal that at another, or $\partial h / \partial w_1 \neq \partial h / \partial w_2$. A port with high ψ_k may have a higher level of w_k, but the discovery rate may be less than at other ports, so higher risk firms may still choose this port. Factors affecting difficulty of discovery are also crucial to specify and evaluate.

Social Planner's Decision

We define domestic social welfare as the sum of expected domestic consumer surplus and producer surplus minus environmental damages, inspection costs, and response costs:

$$sw = ExpCS + PS_D - Envir.Damages - Inspection - Response .$$

Environmental damages and response costs are random variables under both scenarios. The social planner chooses penalties, inspection levels, and post-border response for each enforcement scenario:

$$\max sw(y_{ik}^*, e_{ik}^*, p^*; \bullet) = \max_{w_k, t, R} \left[\int_0^{S_T(p^*)} [D(p) - p^*] ds + \int_0^{S_D(p^*)} [p^* - S_D(p)] ds - V(N, R) - \sum_{k=1}^{K} \sum_{i=1}^{I} w_k y_{ik} - R \right]$$

assuming under Scenario 1, $sw = sw^1(y_{ik}^{1*}, e_{ik}^{1*}, p^{1*}; \bullet)$ where p^{1*} defines $S_D^1(p^{1*})$ and S_F^{1*}. Similarly, under Scenario 2, $sw = sw^2(y_{ik}^{2*}, e_{ik}^{2*}, p^{2*}; \bullet)$. Expected total supply is $S^T(p^*)$. We assume well-behaved functions. The social planner then chooses the optimal enforcement scenario:

$$\max SW = \underset{\substack{enforcement\\scenario}}{MAX} \left\{ sw^1, sw^2 \right\}.$$

The following conditions define optimal levels of inspection, penalties and response under both Scenarios (w_k^{1*}, t^{1*}, R^{1*} under Scenario 1 and w_k^{2*}, t^{2*}, R^{2*} under Scenario 2):

(15) $\partial sw / \partial w_k = 0 \Rightarrow$

$$\int_0^{S_T(p^*)} \left(\partial[D(p) - p^*] / \partial w_k \right) ds + \left[D(S_T(p^*)) - p^* \right] \partial S_T(p^*) / \partial w_k$$
$$+ \int_0^{S_D(p^*)} \left(\partial[p^* - S(p)] / \partial w_k \right) ds + \left[p^* - S(S_D(p^*)) \right] \partial S_D(p^*) / \partial w_k$$
$$- \partial V / \partial N \, \partial N / \partial w_k - y_{ik} \quad \forall k,$$

(16) $\partial sw / \partial t = 0 \Rightarrow$

$$\int_0^{S_T(p^*)} \left(\partial[D(p) - p^*] / \partial t \right) ds + \left[D(S_T(p^*)) - p^* \right] \partial S_T(p^*) / \partial t$$
$$+ \int_0^{S_D(p^*)} \left(\partial[p^* - S_D(p)] / \partial t \right) ds + \left[p^* - S_D(S_D(p^*)) \right] \partial S_D(p^*) / \partial t - \partial V / \partial N \, \partial N / \partial t$$

, and

(17) $\partial sw / \partial R = 0 \Rightarrow \partial V / \partial R = -1$.

Equation (15) shows that at the optimal level of inspection for a particular port, the marginal costs of inspection will equal its benefits. The marginal costs of inspection are the losses in consumer surplus from reduced supply and higher prices, plus additional per unit inspection costs, while the marginal benefits of inspection are the gains to domestic producer surplus from a decrease in import supply and an associated increase in price, reduced damages from reduced pest populations, and reduced inspection costs due to lower output levels. Equation (16) shows that the marginal costs of increasing penalties are the losses in consumer surplus only, and the marginal benefits are an increase in domestic producer surplus and reduced damages. Equation (17) shows that an additional dollar spent on response to pest damages should equal its marginal benefit.

Discussion

Several policy-relevant implications can be drawn from the present analysis. As noted above, increased enforcement (in the form of higher inspection intensity) will not necessarily result in reduced pest risk. Importers may respond to increased inspection intensity by lowering shipment amounts and increasing point-of-origin treatment (i.e., due care), but under certain situations they may actually respond by *decreasing* care in order to lower the cost of shipment. Similarly, these same conditions also dictate whether or not the level of care will increase or decrease with the level of the pest population at the point of shipment. This is an important point for inspectors who may seek to prioritize inspections on the basis of the level of pests in the exporting country.

Firms consider the tradeoffs associated with the costs and benefits associated with location – i.e., inspection intensity versus transportation costs to port-of-entry and final market. Different types of firms will weigh these tradeoffs differently. The present analysis implies that high-risk firms are likely to select ports that are perceived to be low-enforcement ports, perhaps forfeiting distance, while low-risk firms are likely to value transportation cost savings versus avoiding enforcement. High-risk firms may choose low-enforcement ports rather than costly point-of-origin treatment.

Another key element of this analysis is that regulators can choose between destroying and treating infested shipments. The preferred option will depend on the cost of responsive treatment, the magnitude of damages that may result from an invasive species becoming established, and the impact on domestic consumers from reduced imports of destroyed goods. Destroying infected shipments is likely to be optimal when response costs and/or potential damages are high, and when the impact on domestic consumers is low. In the reverse situation, treatment at the ports may be preferred. As described above, the relative impacts of tariffs and penalties on shipper behavior are also likely to differ under destruction versus treatment regimes.

The model presented above is simplified in many respects. Notably, it does not incorporate heterogeneous levels of risk aversion on the part of firms/importers/shippers or the dynamics that may arise when multiple importing countries have different inspection regimes. The model also does not incorporate the potential ability of inspectors to target known bad actors by incorporating learning over time. This latter omission is not actually as salient as it may first appear, however, as many shippers actually do take steps to avoid bad reputations by changing their stated identities, and it is very difficult for port officials to track these bad actors over time.

Other interesting issues arise when more consideration is given to the purchasing arrangements for imported goods. Many shippers operate under contract to buyers in the importing country. These buyers may impose penalties if produce is not delivered on time. In some cases, pricing may be determined by monopsonistic or oligopsonistic behavior on the part of these buyers. Large shippers may choose to invest in their own treatment equipment, which gives them a new source of market power over fringe firms. To consider these issues more fully, it would be appropriate to model inspection as a nested process: first in the field, then by shippers, then by government, and finally by commercial buyers. Although some of these inspection levels would be more focused on product quality than on the presence of invasives, such considerations would give rise to the possibility of both synergies and tradeoffs between product quality and invasive species management.

It is also worth acknowledging that inspections can be very costly, and liability schemes can provide alternative enforcement mechanisms. Millock, Xabadia and Zilberman (2006) suggest mechanisms to induce payment for monitoring by the regulated community. Importers can either pay for high quality inspection, or be subjected to a less rigorous inspection but pay higher fixed fees based on estimated damage. While their framework is general and addresses generic externality problems under uncertainty, it provides a foundation for combining monitoring schemes and pricing strategies for invasive species control.

This article is part of a larger project integrating import and economic data with spatial models of invasive species damages. This model provides the foundation for an agent-based model and simulation analysis which allows us to evaluate specific inspection and enforcement schemes given heterogeneous agents and to examine the potential role of collective liability schemes. Issues to address in this analysis are how to model pest populations process, whether firms know about contamination or not, and how important are different assumptions concerning risk.

Finally, this analysis leads to further policy questions: How should government decision makers allocate inspection effort and structure penalties across different types of ports, given firm response to enforcement? What are the options for firm-specific enforcement? How quickly can regulators assimilate and utilize new information? How do decisions by agricultural buyers drive the behavior of importing firms? What are the effects of nested inspections (at country of origin, Federal border inspections, State inspections)? These questions have implications not only for invasive species management, but also for food safety and bioterrorism concerns.

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Figure 1.

Model of Pest Population and Movement, Importing Firm Decisions, Border Enforcement, and Environmental Damages