Journal of Agricultural and Applied Economics, 39(October 2007):35–46

Border Enforcement and Firm Response in the Management of Invasive Species

Holly A. Ameden, Sean B. Cash, and David Zilberman

This analysis presents a theoretical model of firm response to border enforcement and evaluates both the intended and unintended effects under two enforcement regimes: destruction versus treatment of contaminated shipments. The results indicate that importers may respond to increased inspection by reducing shipments and decreasing due care. In response to increased pest populations, firms may reduce shipments and increase due care, indicating that an enforcement response may not be necessary. The analysis reveals the importance of the nature of the due-care technology, as well as the relationships underlying the probability of detection, in determining the effects of enforcement.

Key Words: border enforcement, environmental regulation, invasive species, trade and environment

JEL Classifications: F18, L51, Q17, Q56, Q58

In the context of international trade, invasive species are a negative externality associated with imported goods. Policies aimed at excluding pests associated with imports include preshipment treatment requirements, varied inspection schemes, treatment at the border, penalties, and import bans or restrictions. To date, these pest exclusion policies have been developed primarily on the basis of 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. In addition to a deterrence effect under which importers respond to increased enforcement with increased due care with respect to pest control, importers may respond in ways that regulators do not intend. For example, importers may respond to the increased costs imposed by inspections by choosing not to bring goods into the country, or they may ship a reduced amount. Moreover, different types of firms are likely to respond to enforcement in different ways, affecting socially optimal enforcement and social welfare.

The present analysis seeks to inform government decision makers concerning border enforcement to address trade-related invasive species risk. We develop a theoretical model of firm response to border enforcement and analyze both the intended and unintended effects of this enforcement. This analysis considers two inspection and enforcement

Holly A. Ameden is a Ph.D. candidate, Department of Agricultural and Resource Economics, University of California, Berkeley, CA. Sean B. Cash is assistant professor, Department of Rural Economy, University of Alberta, Edmonton, Alberta, Canada. David Zilberman is professor, Department of Agricultural and Resource Economics, University of California, Berkeley, CA.

The authors thank two anonymous reviewers of the journal for their useful comments and insights and gratefully acknowledge the support of the Program of Research on the Economics of Invasive Species, Economic Research Service, United States Department of Agriculture.

approaches for imports of a single commodity (i.e., destruction versus treatment of contaminated goods). Interpreting differences in initial pest populations as a proxy for differences between firms, we discuss one way the model can be used to evaluate heterogeneous firms. Although our primary focus is on importer response to enforcement policies, we also examine social welfare effects.

Previous Research

Much of the research on the economics of enforcement has been rooted in the concept that optimal enforcement is simply a matter of balancing the level of fines and probability of detection (Becker) 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. Thus, in the case of environmental enforcement, firms would choose either pollution or output levels.

Malik was among the first to suggest 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. Malik showed that, in contrast to Becker's conclusion that fines should be set arbitrarily high, 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 papers found that 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 (Huang; Kadambe and Segerson; Kambhu; Lee; Oh). Lee concluded that higher emission taxes may not achieve the optimal level of pollution because firms may find it profitable to invest in efforts to evade a pollution tax rather than reduce emissions. Similarly, Oh and Huang found that pollution levels may actually increase in response to higher pollution fees.

In the economics of invasive species literature, research on prevention and control does not address the specifics of border enforcement (Horan et al.; Kim et al.; Olson and Roy). The trade-offs between the costs and benefits of inspection policies in an invasive species context are considered by Batabyal and Beladi, and Moffit, Stranlund, and Field. The work of Batabyal and Beladi presents a queuing theory approach and suggests that less stringent inspections lead to more damages from biological invasions. Moffit, Stranlund, and Field focus on dealing with policy makers' limited knowledge concerning risks and policies that involve achieving threshold levels of risk. Their results could be interpreted to show that high levels of robustness may be achieved with low levels of inspections due to low inspection costs, or with high levels of inspection given low levels of expected losses. In addition, given that expected losses are low and acceptable failure rates are high, high levels of robustness could be achieved with fewer inspections. McAusland and Costello analyze the optimal mix of tariffs (not penalties/fines) and inspection to control invasive species introductions. They find that at high rates of infection, inspections should decrease because as more infected shipments are detected, consumers in the importing country suffer because these shipments are barred from importation. Often, however, infected goods are treated and then allowed entry. This analysis does not evaluate the trade-off between inspections and sanctions or fines, nor does it consider potential avoidance behavior in response to enforcement.

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

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

of regulators (instead of monetary incentives) may result in unintended firm response. Limited theoretical and empirical work exists in the general environmental economics literature that evaluates firm response to monitoring or inspections. To date, both the environmental enforcement and the general economics literature have not considered how changes in border monitoring effort (as opposed to fines and monetary incentives) may result in unintended firm response.

A Model of Importing Firms and Border Enforcement

The basis of our theoretical analysis is a model of importing firm and government inspection agency behavior. Assume there are $i = 1, \ldots, I$ risk-neutral importing firms that handle a specific agricultural product and assume that pest risk increases with i.[2] These firms ship their product through a single port of entry. The model has four stages with different actors at each stage:

- Stage 1: Firms preborder—production, initial pest exposure, treatment, and shipment to border,
- Stage 2: Government inspection agencies—border inspections and enforcement,
- Stage 3: Firms after inspection—shipment to final market,
- Stage 4: Environmental agencies—environmental damage, monitoring, and control.

Stage 1: Firms Preborder

Stage 1 begins after the harvest of a specific agricultural commodity. So postharvest, each firm chooses:

- how many units to ship through the port to the importing country, y_i, and
- point-of-origin treatment effort per unit, e_i.

Each unit of a firm's output has an associated initial pest population, $n_i(0)$. After application of point-of-origin treatment, the pest population per unit is $n_i(1) = n_i(0)g(e_i)$, where $g(e_i)$ is a kill function bounded between 0 and 1, $\partial g(e_i)/\partial e_i < 0$, thus $\partial n_i(1)/\partial e_i < 0$, and all units of output are shipped to the port of entry. Transportation costs from the point of origin for firm i to the port are τ_i. Initial cost of production is $c_i(y_i, e_i)$. Total initial costs are $c_i(y_i, e_i) + \tau_i y_i$.

Stage 2: Government Inspection Agencies

A risk-neutral government representative chooses a per-unit level of inspection to apply to all firms importing a specific agricultural commodity. Associated with this level of inspection is a per-unit cost, w, where w is a measure of inspection intensity. Total inspection costs for the regulator are *Inspection* $= \Sigma_{i=1}^{I} w y_i$.

Government inspection at the port will lead to discovery of $h(n_i(1), w)y_i$ contaminated units of output where $h(n_i(1), w)$ is a fraction between 0 to 1. We assume $0 \leq h(n_i(1), w) \leq 1$, $\partial h(n_i(1), w)/\partial n_i(1) > 0$, $\partial h(n_i(1), w)/\partial w > 0$, and $\partial^2 h(n_i(1), w)/\partial w^2 < 0$. These assumptions suggest that higher investment leads to higher discovery but the marginal productivity of investment is decreasing.

We assume that the number of pests associated with each unit of output is deterministic.[3] The volume of these pests is small in proportion to the size of the shipment and the pests are uniformly distributed through the shipment. Thus detection, or discovery, of these pests is a random variable. The 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

[2] Both firms and the government regulator are assumed to be risk neutral in the present analysis. This is both for tractability and because risk neutrality is a reasonable assumption for regulators and importers in this framework. As Harford argues in his early work on firm behavior and imperfect environmental enforcement, risk-neutral firms should be the most successful over time. For the societal actor, resources are large and psychological effects minor.

[3] Several bodies of literature on pest control, for example, on threshold models, damage control, and predator/prey relationships assume that population size is given (Sexton, Lei, and Zilberman).

shipment is either cleared for entry or not on the basis of 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, so the actual quantity supplied by the ith firm under scenario 1, where scenario is indicated by $j \in \{1, 2\}$, is $s_{ij} = s_{i1} = [1 - h(n_i(1), w)]y_i$. The firm will pay a penalty of $t_1 h(n_i(1), w)y_i$ where $t_j = t_1$ is the penalty per unit of contaminated output under scenario 1. If firms are charged a tariff, ϕ, they pay $\phi[1 - h(n_i(1), w)]y_i$.

Scenario 2: shipments are treated. Under scenario 2, units discovered to be contaminated are treated so that the quantity supplied by the *i*th firm is $s_{i2} = y_i$, total tariffs paid are ϕy_i. The cost of the treatment at the border is x per unit with total cost of treatment equal to $xh(n_i(1), w)y_i$. The firm will also pay a per-unit penalty of t_2. The penalty for the firm in this case will be $t_2 h(n_i(1), w)y_i$. The total enforcement cost for the firm will be $(x + t_2)h(n_i(1), w)y_i$. Treatment may not be completely effective. After treatment, pest populations on the output discovered to be contaminated is $h(n_i(1), w)n_i(1)z(x)$ where $z(x)$ is the scenario 2, stage 2 kill function bounded between 0 and 1, and $\partial z/\partial x < 0$.

Stage 3: Firms After Inspection

The firm's output is shipped to a final market and sold for p, the price of the agricultural commodity in the importing country. The per-unit transportation cost from the port to the final market is γ.

Stage 4: Environmental Agencies

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 the pest population 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 and Response

The model is solved with a nested optimization using backward induction. The government agent first chooses the structure of the enforcement regime; the firms then determine their optimal response functions; the government selects optimal enforcement levels given the reaction functions of the firms; then firms choose their optimal response. Thus, given the structure of the government's enforcement regime, the *i*th firm determines how much to export and how much to treat. The firm is assumed to maximize its expected profit, taking prices as given and given the risk that contaminated produce may be detected. Under scenario 1, output discovered to be contaminated is destroyed; under scenario 2, the contaminated output is treated. The firm's expected profit function under scenario 1 is:

$$(1)\quad \pi_{i1} = \max_{y_i, e_i} [\{(p - \phi - \gamma)(1 - h(n_i(1), w)) - t_1 h(n_i(1), w) - \tau_i\} y_i - c_i(y_i, e_i)]$$

and under Scenario 2:

$$(2)\quad \pi_{i2} = \max_{y_i, e_i} [\{p - (x + t_2)h(n_i(1), w) - \phi - \gamma - \tau_i\} y_i - c_i(y_i, e_i)]$$

The optimal decision rules for each importing firm for scenario 1 are:

$$(3)\quad \frac{\partial \pi_{i1}}{\partial y_i} = 0 \Rightarrow p(1 - h(n_i(1), w)) = (\phi + \gamma)(1 - h(n_i(1), w)) + t_1 h(n_i(1), w) + \tau_i + \frac{\partial c_i}{\partial y_i}$$

and

$$(4)\quad \frac{\partial \pi_{i1}}{\partial e_i} = 0 \Rightarrow (p + t_1)\left(-\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial e_i}\right)y_i = (\phi + \gamma)\left(-\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial e_i}\right)y_i + \frac{\partial c_i}{\partial e_i}$$

and for scenario 2:

$$(5)\quad \frac{\partial \pi_{i2}}{\partial y_i} = 0 \Rightarrow p = (x + t_2)h(n_i(1), w) + \phi + \gamma + \tau_i + \frac{\partial c_i}{\partial y_i}$$

and

$$(6)\quad \frac{\partial \pi_{i2}}{\partial e_i} = 0 \Rightarrow (x + t_2)\left(-\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial e_i}\right)y_i = \frac{\partial c_i}{\partial e_i}$$

Equations (3) and (4) define y_{i1}^* and e_{i1}^*, optimal firm output and point-of-origin treatment under scenario 1. Similarly, Equations (5) and (6) define y_{i2}^* and e_{i2}^* under scenario 2. Solving Equations (3) and (4) for optimal output under scenario 1 and (5) and (6) for scenario 2 gives:

$$(7)\quad y_{i1}^* = \left[(p - \phi - \gamma)(1 - h(n_i(1), w)) - t_1 h(n_i(1), w) - \tau_i - \frac{\partial c_i}{\partial y_i} + \frac{\partial c_i}{\partial e_i}\right] \div \left[(p + t_1 - \phi - \gamma)\left(-\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial e_i}\right)\right]$$

and

$$(8)\quad y_{i2}^* = \left[p - (x + t_2)h(n_i(1), w) - \phi - \gamma - \tau_i - \frac{\partial c_i}{\partial y_i} + \frac{\partial c_i}{\partial e_i}\right] \div \left[(x + t_2)\left(-\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial e_i}\right)\right]$$

Equations (3) through (6) show that at the optimal levels of output and point-of-origin treatment, the marginal benefit of the firm's action will equal its cost. Equation (3) 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 costs of increased output consist of higher production and transportation costs, penalties, and port fees. Equation (4) shows that the marginal benefit of an increase in point-of-origin treatment is reduced discovery and thus increased revenue and decreased penalties, whereas the marginal costs are increased transportation costs from the port to market, and 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 cost of increased output is not only higher production and transportation costs, penalties, and port fees, but also treatment costs. Equations (7) and (8) show that the lower marginal benefit of an additional unit of output under scenario 1 versus scenario 2 translates to lower optimal output under scenario 1 than under scenario 2.

The firm's optimal choices display the following features (see the Appendix).

1. The optimal output chosen by each firm is likely to decrease (increase) under both scenario 1 and scenario 2 as inspection levels, tariffs, and penalties increase (decrease), depending on certain conditions. Behind Proposition 1 is the intuition that increases in inspection levels, tariffs, and penalties are equivalent to a decrease in price received by the firm, reducing the marginal benefit of each unit of output with little or no effect on marginal benefit. In response, firms will reduce the amount of output shipped to the importing country. Even if penalties are not tied to output levels, output levels may decrease in response to higher penalties.

These results have several implications. Policies specifically aimed at influencing due-care decisions have the unintended consequence of affecting output decisions. These supply effects should be accounted for in the design of optimal monitoring regimes. Moreover, while higher enforcement levels reduce the output shipped through legitimate channels, they create incentives for firms with excess supply to avoid this enforcement, whether by misrepresenting their goods or through aggressive smuggling.

Under certain conditions, specifically when both $\partial^2 h/\partial n_i(1)\partial w > 0$ and $\varepsilon = y[(\partial^2 c)/(\partial y \partial e)]/(\partial c/\partial e) < 1$ hold, where $\partial^2 h/\partial n_i(1)\partial w$ indicates how the marginal rate of discovery with respect to inspection changes with pest populations, and ε is the elasticity of the marginal cost of treatment with respect to output, the relationship between inspection and output depends on the relative magnitudes of offsetting effects (see the Appendix). If $\partial^2 h/$

$\partial n_i(1)\partial w > 0$, then each unit of inspection effort becomes more effective as pest populations increase. This effect (which may be zero or negative) would have to be relatively large and positive to push the relationship between output and inspection from negative to positive.

The elasticity of the marginal cost of treatment with respect to output, denoted by $\varepsilon = y[(\partial^2 c)/(\partial y \partial e)]/(\partial c/\partial e)$, provides a boundary for some of our results and warrants closer examination. This elasticity concerns the nature of the pre-entry treatment technology and its relationship to output levels. When ε is greater than unity, the marginal treatment cost with respect to output is greater than the average treatment cost with respect to output. This suggests a strong positive relationship between the cost of treatment and the scale of production. This may be due to a shortage of inputs for the pre-entry treatment technology so that, as output levels and total treatment levels increase, the per-unit cost for additional treatment increases precipitously. When ε is small, the marginal treatment costs with respect to output are 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; thus as output levels increase, the per-unit cost for additional treatment is low. We cannot rule out either situation as infeasible a priori. In fact, this parameter is likely to vary across commodities, and as such, the impact of enforcement policies will vary across commodities because of this parameter. Our analysis indicates that policy makers may want to further evaluate this elasticity to better understand enforcement effectiveness.

2. The optimal output chosen by each firm is likely to decrease (increase) as transportation costs increase (decrease) and commodity price decreases (increases). These are obvious results included for completeness and to show that the economic parameters in our model have the predicted result.

3. The response of firms to changes in inspection, in terms of optimal output and pre-entry treatment, is likely to be greater under scenario 1 than under scenario 2. In other words, the choice of enforcement scenario affects the magnitude of firm response. Under scenario 1, because output that is discovered to be contaminated is destroyed and is not part of total supply, the firm response to increases in inspection intensity is affected by the lost revenue of this destroyed output, in addition to penalties. Under scenario 2, output discovered to be contaminated is treated and remains part of total supply; thus, firm response to changes in inspection stems from increased penalties and treatment costs.

4. The optimal pre-entry treatment chosen by each firm may increase or decrease in response to changes in inspection and penalties, and is likely to decrease (increase) in response to increases (decreases) in tariffs, depending on certain conditions. When the response of the marginal cost of treatment with respect to output is elastic ($\varepsilon > 1$), 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. When the response of the marginal cost of treatment with respect to output is inelastic ($\varepsilon < 1$), however, we obtain an opposite result—namely, that firms' profits will increase with less point-of-origin treatment. Under these conditions, total point-of-origin treatment decreases. Similarly, under most conditions, firms decrease pre-entry treatment in response to higher tariffs.

Thus, in response increases in enforcement, firms do not necessarily increase due care (pre-entry treatment), and may decrease both output and pre-entry treatment. The relative magnitudes of the output and treatment effect will determine the ultimate effect on total pest populations. In other words, total pest levels on output supplied at the border may not necessarily decrease in response to an increase in enforcement. Again, this is an unintended consequence of enforcement.

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 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 and 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.

5. Optimal firm output is likely to decrease (increase) and optimal pre-entry treatment is likely to increase (decrease) as initial pest populations increase (decrease), depending on certain conditions. As with increased inspection intensity, an increase in initial pest populations increases probability of detection. If 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. Under these conditions, firms will respond to an increase in initial pest populations by reducing output and using more preborder treatment, without any government intervention. Thus, depending on the magnitudes of the output and pre-entry treatment response on the part of firms, an increase in border enforcement after pest outbreaks may not be necessary. Moreover, if the government does respond to increased pest populations with stricter enforcement under these conditions, without considering firm response, output and thus supply will be further reduced.

If instead the marginal cost of treatment with respect to output is less than unity, the firm may respond to higher initial pest populations by increasing or reducing output and point-of-origin treatment, depending, in part, on the relative magnitudes of the point-of-origin kill function, $g(e_i)$, and its slope, $\partial g/\partial e_i$. If the kill function is effective, i.e., $g(e_i)$ is relatively small and $\partial g/\partial e_i$ is steep, then firms are likely to respond to increases in inspection intensity by increasing point-of-origin treatment ($\partial e_i/\partial n_i(0) > 0$). So, the response of firms to an increase in initial pest populations depends on the efficiency of their treatment technology. Thus, when regulators get information that pest outbreaks are occurring at the point of origin, they should consider the nature of the treatment technology when deciding whether to respond with increased enforcement.

There are several ways this model can be used to evaluate the role of firm heterogeneity. The following is an example of one simple way to consider the role of firm heterogeneity. It illustrates the kind of findings that are likely to be confirmed with a more rigorous approach. Assume these are $i = 1, \ldots, I$ importing firms that handle a specific agricultural product. Firm heterogeneity comes in the form of different initial pest populations across firm so that $n_i(0)$ increases with i. Firms that have lower initial pest populations, $n_L(0) < n_H(0)$, pose less risk. In this context, the comparative statistics analysis on firm response to changes in $n_i(0)$ serves as an analysis of firm heterogeneity. Assuming for now that $c_i(y_i, e_i)$ and the discovery function $h(n_i(1), w)$ do not vary with i, and that all other parameters are equal between firms, then shipments from low-risk firms are larger, $y_L > y_H$, 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, or they may attempt to circumvent enforcement. Medium-risk firms may reduce exports slightly while low-risk, high-profit-margin firms may not significantly change the levels of output or point-of-origin treatment.

Social Planner's Decision

Ideally, optimal regulation will be determined by maximizing expected social surplus, including domestic consumer surplus and producer surplus, minus environmental damages, inspection costs, and response costs:

$$(9)\quad sw = E[CS + PS - Envir.\,Damages - Inspection - Response].$$

In the case of the United States, the supply of an agricultural good is made up of imported and domestic supply, so the regulation of invasive species affects both the price and production of domestic growers. Stricter regulations would reduce import supply and increase prices and domestic output. The prevailing enforcement scenario will determine the impact of policy tools. Although firm response is likely to be greater under scenario 1 than scenario 2, the policy of destroying contaminated output under scenario 2, as opposed to treatment under scenario 1, will have a more direct impact on consumer and producer surplus through reduced supply. Under both enforcement scenarios, the marginal costs of increased inspection will be the losses in consumer surplus from reduced supply and higher prices, and additional per-unit inspection costs, whereas the marginal benefits of inspection will be the gains to domestic producer surplus from a decrease in import supply and an associated increase in price, reduced damages from lower pest populations, and reduced inspection costs due to lower output levels. The marginal cost of increasing penalties will be the losses in consumer surplus only and the marginal benefits will be an increase in domestic producer surplus and reduced damages. As further analytical work is able to specify functional forms and distributions, and thus rigorously define expected consumer and producer surplus as functions of policy tools, our understanding of the specific nature of these trade-offs will be more complete.

There are real-world considerations that significantly affect social welfare outcomes. First is seasonality. In some seasons, imported goods complement domestic production, supply is ample, prices are low, and optimal enforcement will be higher than when importers are the only suppliers and consumer surplus losses from strict enforcement could be great. In many cases, agricultural imports peak in the winter when conditions for the spread of pests are less favorable and there is little domestic competition. Thus we would expect more lax enforcement in the off-season.

The political economy of invasive species regulations is not necessarily set by social optimizers but is the result of the influence of different parties with varying political clout. Domestic producers and environmental groups push for tougher enforcement while consumers, who are less organized and less likely to effectively advocate for their interests, may lose from these tougher regulations. Furthermore, environmental and agricultural interests may push to emphasize border control over postborder response and eradication, reducing domestic use of chemicals to treat invading pests, even when they are relatively inexpensive and effective. So environmentalism and protectionism may lead to stricter regulation of importers than is socially optimal.

Discussion

The model presented above is simplified in many respects. Notably, it does not account for the many sources of uncertainty, including uncertainty concerning pest populations. Although pest populations vary seasonally, reflecting weather conditions and other factors, agricultural producers and firms shipping their goods are aware of these changes in pest populations and modify their choices accordingly. Similarly, regulators are aware of pest variation and may adjust enforcement to accommodate these changes. Since ports receive materials from different countries and every country has different patterns of seasonal variations in the likelihood of infestation, inspectors are likely to shift their efforts toward the countries that are most problematic at each time of the year. Thus, it is reasonable to assume that pest populations associated with shipment of a particular agricultural good from a specific country is deterministic. Instead of pest populations, probability of detection, which is a random variable in this model, albeit quite simplified, is likely to be the most important source of uncertainty.

Our model is also simplified in that it does not incorporate heterogeneous levels of risk aversion on the part of firms/importers/shippers or the ability of shippers to choose among various ports that may differ in their inspection intensity or competency (''port shopping''). Ameden, Cash, and Zilberman address multiple port locations and find that differences in enforcement may cause some firms to choose ports that are farther away, resulting in higher transportation costs to the firm, so that their shipments are subject to more relaxed enforcement. 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, making it difficult for port officials to track these problem firms.

Despite these limitations, several relevant policy implications can be drawn from the present analysis. This paper is apparently the first to model shipper behavior as a strategic interaction with border enforcement policies to manage invasive species. 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., care), but under certain conditions they may actually respond by *decreasing* care to lower the cost of shipment. Similarly, these same conditions also dictate whether or not firms will increase or decrease the level of care as pest populations at the point of shipment increase. In response to environmental conditions such as increased pest populations, firms may reduce output and increase due care, so a simultaneous increase in enforcement may not be necessary and in fact may be suboptimal. This is a critical consideration for policies that prioritize inspections on the basis of changes in the level of pests in specific exporting countries. Furthermore, some of our results are bounded by conditions that indicate that it is important for policy makers to understand the effect of pest populations on relationships underlying the probability of detection as well as the nature of the due care, or pre-entry treatment technology used by firms, when making changes to enforcement policies.

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 establishment of an invasive species, and the impact on domestic consumers from reduced imports of destroyed goods. Destroying infected shipments is likely to be optimal when response costs or potential damages (or both) 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.

Our social welfare analysis has several implications. The first is the importance of the trade-offs between severity of enforcement and cost of controlling invasions. For those pests that are relatively inexpensive to eradicate, clearly enforcement should be more lax. Thus, the changes and advances in pest control technologies should be a constant input into enforcement decisions. Second is the trade-offs between control and treatment preborder, detection and treatment at the border, and detection and response postborder. Given that most treatment of and response to invasive species involves pesticide use, changes in invasive species policies are likely to shift pesticide use from one country to another. Moreover, changes in environmental policies affecting pesticide use and cost will affect the balance of these optimal invasive species policies.

Finally, the purchasing arrangements for imported goods present issues of interest to policy makers addressing invasive species risk. 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 trade-offs between product quality and invasive species management.

[Received March 2007; Accepted June 2007.]

References

Ameden, H.A., S.B. Cash, and D. Zilberman. "Invasive Species Management: Importers, Border Enforcement, and Risk." Selected paper no. 26411, American Agricultural Economics Association Annual Meeting, 2007.

Batabyal, A.A., and H. Beladi. "International Trade and Biological Invasions: A Queuing Theoretic Analysis of the Prevention Problem." *European Journal of Operational Research* 170(May 2006):758–70.

Becker, G.S. "Crime and Punishment: An Economic Approach." *Journal of Political Economy* 76(May–April 1968):169–217.

Harford, J.D. "Firm Behavior Under Imperfectly Enforceable Pollution Standards and Taxes." *Journal of Environmental Economics and Management* 5(March 1978):26–43.

Horan, R.D., C. Perrings, F. Lupi, and E.H. Bulte. "Biological Pollution Prevention Strategies Under Ignorance: The Case of Invasive Species." *American Journal of Agricultural Economics* 84(December 2002):1303–10.

Huang, C.H. "Effectiveness of Environmental Regulations Under Imperfect Enforcement and the Firm's Avoidance Behavior." *Environmental and Resource Economics* 8(September 1996): 183–204.

Kadambe, S., and K. Segerson. "On the Role of Fines as an Environmental Enforcement Tool." *Journal of Environmental Planning and Management* 41(March 1998):217–26.

Kambhu, J. "Direct Controls and Incentives Systems of Regulation." *Journal of Environmental Economics and Management* 18(March 1990):S72–S85.

Kim, C.S., R.N. Lubowski, J. Lewandrowski, and M.E. Eiswerth. "Prevention or Control: Optimal Government Policies for Invasive Species Management." *Agricultural and Resource Economics Review* 35(April 2006):29–40.

Lee, D.R. "The Economics of Enforcing Pollution Taxation." *Journal of Environmental Economics and Management* 11(June 1984):147–60.

Malik, A. "Avoidance, Screening and Optimum Enforcement." *Rand Journal of Economics* 21(Autumn 1990):341–53.

McAusland, C., and C. Costello. "Avoiding Invasives: Trade-Related Policies for Controlling Unintentional Exotic Species Introductions." *Journal of Environmental Economics and Management* 48(September 2004):954–77.

Moffit, L.J., J.K. Stranlund, and B.C. Field. "Inspections to Avert Terrorism: Robustness Under Severe Uncertainty." Working paper, Dept. of Resour. Econ., University of Massachusetts, Amherst, 2005.

Oh, Y. "Surveillance or Punishment? A Second-Best Theory of Pollution Regulation." *International Economic Journal* 9(Autumn 1995):89–101.

Olson, L.J., and S. Roy. "On Prevention and Control of an Uncertain Biological Invasion." *Review of Agricultural Economics* 27(September 2005):491–97.

Polinsky, A.M., and S. Shavell. "The Optimal Tradeoff between the Probability and Magnitude of Fines." *American Economic Review* 69(December 1979):880–91.

———."Enforcement Costs and the Optimal Magnitude and Probability of Fines." *Journal of Law and Economics* 35(April 1992):133–48.

Sexton, S.E., Z. Lei, and D. Zilberman. "The Economics of Pesticides and Pest Control." *International Journal of Environmental and Resource Economics* 1(2007):271–326.

Appendix

The ith firm's decision problem for Scenario 1 is:

$$\pi_{i1} = \max_{y_i,e_i}[\{(p - \phi - \gamma)\{1 - h[n_i(1),w]\} - t_1 h[n_i(1),w] - \tau_i\}y_i - c_i(y_i,e_i)],$$

and for Scenario 2 is:

$$\pi_{i2} = \max_{y_i,e_i}[\{p - (x + t_2)h[n_i(1),w] - \phi - \gamma - \tau_i\}y_i - c_i(y_i,e_i)].$$

The optimal decision rules for each importing firm under Scenario 1 are:

$$\frac{\partial \pi_{i1}}{\partial y_i} = (p - \phi - \gamma)\{1 - h[n_i(1),w]\} - t_1 h[n_i(1),w] - \tau_i - \frac{\partial c_i}{\partial y_i} = 0,$$

and

$$\frac{\partial \pi_{i1}}{\partial y_i} = (p - \phi - \gamma + t_1)\left[-\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial e_i}\right]y_i - \frac{\partial c_i}{\partial e_i} = 0,$$

and for Scenario 2 are:

$$\frac{\partial \pi_{i2}}{\partial y_i} = p - (x + t)h[n_i(1),w] - \phi - \gamma - \tau_i - \frac{\partial c_i}{\partial y_i} = 0,$$

and

$$\frac{\partial \pi_{i2}}{\partial e_i} = (x + t_2)\left[-\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial e_i}\right]y_i - \frac{\partial c_i}{\partial e_i} = 0.$$

Total differentiation of the necessary conditions for each Scenario $j = \{1, 2\}$ gives:

$$\begin{bmatrix} H_{11} H_{12} \\ H_{21} H_{22} \end{bmatrix} \cdot \begin{bmatrix} dy_i \\ de_i \end{bmatrix} = -A_j \begin{bmatrix} \left(-\frac{\partial h}{\partial w}\right) \\ \left(-\frac{\partial^2 h}{\partial n_i(1)\partial w}\frac{\partial n_i(1)}{\partial e_i}\right)y_i \end{bmatrix} \cdot dw - \begin{bmatrix} -h[n_i(1),w] \\ -\left(\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial e_i}\right)y_i \end{bmatrix} \cdot dt_j$$
$$- [-(j - 2)] \begin{bmatrix} -\{1 - h[n_i(1),w]\} \\ -\left(-\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial e_i}\right)y_i \end{bmatrix} \cdot d\phi - (j - 1)\begin{bmatrix} -1 \\ 0 \end{bmatrix} \cdot d\phi$$
$$- \begin{bmatrix} -1 \\ 0 \end{bmatrix} \cdot d\tau - [-(j-2)] \begin{bmatrix} -\{1 - h[n_i(1),w]\} \\ -\left(-\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial e_i}\right)y_i \end{bmatrix} \cdot d\gamma$$
$$- (j - 1)\begin{bmatrix} -1 \\ 0 \end{bmatrix} \cdot d\gamma - [-(j - 2)] \begin{bmatrix} \{1 - h[n_i(1),w]\} \\ \left(-\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial e_i}\right)y_i \end{bmatrix} \cdot dp$$
$$- (j - 1)\begin{bmatrix} -1 \\ 0 \end{bmatrix} \cdot dp - A_j \begin{bmatrix} \left(-\frac{\partial h}{\partial n_i(1)}\frac{\partial n_i(1)}{\partial n_i(0)}\right) \\ \left(-\frac{\partial h}{\partial n_i(1)}\frac{\partial^2 n_i(1)}{\partial e_i \partial n_i(0)}\right)y_i \end{bmatrix} \cdot dn_i(0),$$

where $A_1 = (p - \phi - \gamma + t_1)$ and $A_2 = (x + t_2)$. Given H is a negative definite matrix and satisfies second order conditions, then $H_{11} < 0$, $|H| > 0$, and thus $H_{22} < 0$. We know $H_{12} = H_{21} = A_j\{-[\partial h/\partial n_i(1)][\partial n_i(1)/\partial e_i]\} - (\partial^2 c_i/\partial y_i \partial e_i)$ which may be positive or negative (zero at the switch point). Setting $(\partial \pi_{ij}/\partial e_i) = H_{12} = 0$, we derive the relationship, $\varepsilon = [y(\partial^2 c/\partial y \partial e)]/(\partial c/\partial e) = 1$, where ε is the elasticity of the marginal cost of treatment with respect to output. If $\varepsilon > 1$, then $H_{12} = H_{21} < 0$, or if $\varepsilon < 1$, then $H_{12} = H_{21} > 0$.

PROPOSITION 1

If $[\partial^2 h/\partial n_i(1)\partial w] = 0$, or if $[\partial^2 h/\partial n_i(1)\partial w] > 0$ and $\varepsilon > 1$ (so that $H_{12} < 0$), for Scenario j, $\partial y_i/\partial w = -(1/|H|)A_j\{(-\partial h/\partial w)H_{22} - [(-\partial^2 h/\partial n_i(1)\partial w)(\partial n_i(1)/\partial e_i)]y_i h_{12}\} < 0$, otherwise, the sign on $\partial y_i/\partial w$ may be positive or negative depending on the relative magnitudes of its elements. If $\varepsilon > 1$, $\partial y_i/\partial t_j = -(1/|H|)\{-h[n_i(1), w]H_{22} - \{-[\partial h/\partial n_i(1)][\partial n_i(1)/\partial e_i)]y_i\}H_{12}\} < 0$. Otherwise $\partial y_i/\partial t_j$ may be positive or negative. Under Scenario 1, if $\varepsilon < 1$, $\partial y_i/\partial \phi = -(1/|H|)\{-\{1 - h[n_i(1), w]\}H_{22} - \{-[-\partial h/\partial n_i(1)][\partial n_i(1)/\partial e_i]y_i\}H_{12}\} < 0$, or if $\varepsilon > 1$ under Scenario 2, $\partial y_i/\partial \phi = -(1/|H|)[(-1)H_{22} - (0)H_{12}] < 0$, otherwise the sign may be positive or negative.

PROPOSITION 2

$\partial y_i/\partial \tau = -(1/|H|)[(-1)H_{22} - (0)H_{12}] < 0$ under all conditions. Under Scenario 1, if $\varepsilon < 1$, $\partial y_i/\partial \gamma = \partial y_i/\partial p = -(1/|H|)\{-\{1 - h[n_i(1), w)]H_{22} - \{-[-\partial h/\partial n_i(1)][\partial n_i(1)/\partial e_i]y_i\}H_{12}\} < 0$, or if $\varepsilon > 1$ under Scenario 2, $\partial y_i/\partial \gamma = -\partial y_i/\partial p = -(1/|H|)[(-1)H_{22} - (0)H_{12}] < 0$, otherwise the signs on $\partial y_i/\partial \gamma$ and $-\partial y_i/\partial p$ may be positive or negative.

PROPOSITION 3

For Scenario j we have $\partial y_i/\partial w = -(1/|H|)A_j\{(-\partial h/\partial w)H_{22} - \{[-\partial^2 h/\partial n_i(1)\partial w][\partial n_i(1)/\partial e_i]\}y_i H_{12}\} > 0$, and either $\partial e_i/\partial w = -(1/|H|)A_j\{\{[-\partial^2 h/\partial n_i(1)\partial w][\partial n_i(1)/\partial e_i]\}y_i H_{11} - (-\partial h/\partial w)H_{21}\} > 0$ or $\partial e_i/\partial w = -(1/|H|)A_j[(0)H_{11} - (-\partial h/\partial w)H_{21}] < 0$, under most conditions. If $A_1 > A_2$, or $(p - \phi - \gamma + t_1) > (x + t_2)$, then our results hold.

PROPOSITION 4

Either $\partial e_i/\partial w = -(1/|H|)A_j\{\{[-\partial^2 h/\partial n_i(1)\partial w][\partial n_i(1)/\partial e_i]\}y_i H_{11} - (-\partial h/\partial w)H_{21}\} > 0$ or $\partial e_i/\partial w = -(1/|H|)A_j[(0)H_{11} - (-\partial h/\partial w)H_{21}] < 0$ unless $\partial^2 h/[\partial n_i(1)\partial w] > 0$ and $\varepsilon < 1$, or $\partial^2 h/[\partial n_i(1)\partial w] < 0$ and $\varepsilon > 1$, and then the sign on $\partial e_i/\partial w$ may be positive or negative. The sign on $\partial e_i/\partial t_j = -(1/|H|)A_j\{\{-\partial h/\partial n_i(1)][\partial n_i(1)/\partial e_i]\}y_i H_{11} - h[n_i(1), w]H_{21}\}$ may be positive or negative.

Under Scenario 1, if $\varepsilon < 1$, $\partial e_i/\partial \phi = -(1/|H|)\{-\{[-\partial h/\partial n_i(1)][\partial n_i(1)/\partial e_i]y_i H_{11} - \{-\{1 - h[n_i(1), w]\}H_{21} < 0$, or if $\varepsilon > 1$ under Scenario 2, $\partial e_i/\partial \phi = -(1/|H|)[(-1)H_{21} - (0)H_{11}] < 0$, otherwise the sign may be positive or negative.

PROPOSITION 5

If $\varepsilon > 1$ for Scenario j, $\partial y_i/\partial n_i(0) = -(1/|H|)A_j\{\{[-\partial h/\partial n_i(1)][\partial n_i(1)/\partial n_i(0)]\}H_{22} - \{[-\partial h/\partial n_i(1)][\partial^2 n_i(1)/\partial e_i \partial n_i(0)]\}y_i H_{22} < 0$, otherwise, the sign on $\partial y_i/\partial n_i(0)$ is either positive or negative.

If $\varepsilon > 1$ for Scenario j, $\partial e_i/\partial n_i(0) = -(1/|H|)A_j\{\{[-\partial h/\partial n_i(1)][\partial^2 n_i(1)/\partial e_i \partial n_i(0)]\}y_i H_{11} - \{[-\partial h/\partial n_i(1)][\partial n_i(1)/\partial n_i(0)]\}H_{21}\} > 0$, otherwise, the sign on $\partial e_i/\partial n_i(0)$ may be positive or negative.