Exotic Pests and Trade: When Is Pest-Free Status Certification Worthwhile?

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Pest-free status certification is desirable if the demand-side impacts (increased export revenue) and supply-side impacts (lower pest damage and decreased ongoing control costs) exceed the compliance monitoring and eradication costs. Thus, eradication may be optimal without certification. Certification is more likely for regions facing costly treatment requirements (bans) or possessing geographic traits that lower monitoring costs and infestation probabilities than for those exporting higher-valued products. Certification benefits producers but hurts consumers. Thus, political feasibility may be greater if domestic consumption is a small share of the market and if the additional tax burden of certification programs is light.

Key Words: exotic pests, invasive species, pest-free area, eradication, sanitary/phytosanitary regulations

The expansion of world trade has fueled growing concern about threats to agriculture and indigenous ecosystems from invasions of exotic pests and diseases. In 1998, for example, more than 52,000 items harboring plant pests and diseases identified as economically detrimental to the U.S. agricultural sector were intercepted in shipments in U.S. ports (U.S. Department of Agriculture 1999). It has been estimated that losses from exotic plant pests in the U.S. agricultural sector due to prevention and control expenses and lost agricultural production are currently over $41 billion annually (U.S. General Accounting Office 1997). The potential cumulative economic loss caused by just six non-indigenous insects has been estimated at $74 billion (Office of Technology Assessment 1993).

One response to the threat of exotic pest invasions is to impose bans, quarantines, or other trade restrictions on all products from a trading partner known to harbor any level of potentially invasive pests or diseases. For example, the

United States refuses to accept imports of beef or cattle from countries known to harbor foot-and-mouth disease or mad cow disease, while Mexico refuses to accept shipments of chickens from Texas whose poultry industry is known to harbor Newcastle disease. Similarly, shipments of citrus fruit from areas known to be infested with the Mediterranean fruit fly must typically undergo expensive fumigation and quarantine prior to importation. Countries sometimes impose restrictions on trade from an entire country when only one region is known to harbor a pest, justifying their actions on the grounds that the exotic species may be introduced through trade and/or transshipments from infested regions. Preventing the introduction of an exotic species can be the least costly method of protecting indigenous ecosystems as well as agricultural producers (Horan et al. 2002, McAusland and Costello 2004). At the same time, threats of species invasions may be no more than fig leaves to legitimize the introduction of phytosanitary and sanitary standards (SPS) whose primary purpose is protection of a domestic industry from international competition, hence the insistence of international trade agreements on the need for scientific transparency (Roberts 1998, 1999).

One possible response of a country (or region within a country) facing such SPS trade barriers is to certify itself as pest-free in order to qualify

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for removal of those trade restrictions.[1] Certification as a pest-free area (PFA) can be expensive, however, since it typically requires undertaking a minimum level of effective, ongoing surveillance, exclusion measures to maintain the area free of pests, and rapid remedial measures to restore pest-free status in the event of (re-)introduction.[2]

This paper presents a comprehensive conceptual framework for evaluating the desirability of PFA status certification. We focus on exporting countries and explicitly consider the demand-side impacts of SPS regulations, in contrast to the bulk of studies to date which concentrate on preventive measures (Horan et al. 2002) or control versus eradication decisions (Myers, Savoie, and van Randen 1998; Dumas and Goodhue 1999; Taylor et al. 1983; Tribble, Mcintosh, and Wetzstein 1999; Olson and Roy 2002, 2003; Eiswerth and Johnson 2002; Acquaye et al. 2005) in countries facing invasions or threats from invasive species.

We begin by considering the optimal choice of control measures (including eradication) in both the short and long run in an exporting country facing costly SPS trade barriers using a model that takes into account revenue losses from those trade barriers as well as production losses from the exotic pests. We then consider the choice of PFA status certification in the long-run equilibrium and derive conditions under which certification is worthwhile. We subsequently discuss conditions under which eradication is worthwhile while certification is not. Finally, we discuss the implications of the analysis for trade policy.

A Model of Pest Control in an Exporting Country

We begin by characterizing the optimal control of a potentially invasive pest in its country of origin. Since the benefit of certification is greater access to world markets, we analyze the case of a region that is a net exporter even when the pest is present. Consumers in this region benefit from consuming the product. Their consumer surplus is $CS(p)$, where p denotes the price of the product. Production is characterized by a restricted profit function, $R(p,v,N) = \max_z \{pf(z,N) - \sum v_j z_j\}$, where $z_1, \ldots, z_J$ are inputs, $v_1, \ldots, v_J$ are the respective prices of those inputs, N is the pest population size, and $f(z, N)$ is the production function. The pest population causes damage, hence (letting subscripts denote derivatives) $R_N \leq 0$. To ensure concavity, we assume $R_{NN} \geq 0$.[3]

Denote the market-clearing price in the domestic market in the absence of trade as p_d such that $CS_p + R_p = 0$. Let p_w denote the world market price and α denote the unit cost of the quarantines and/or treatments required for exports when the pest is known to be present. (Under a complete ban, $\alpha = \infty$.) The assumption that the country or region remains a net exporter when the pest is present implies $p_d < p_w - \alpha < p_w$. (The assumption that quarantine or treatment requirements are prohibitively costly or that a ban has been imposed implies that $p_w - \alpha < p_d < p_w$.)

Figure 1 depicts this situation graphically for an initial pest population N_0. The country remains a net exporter (with exports equal to $q_0 - q_d$) when the quarantine cost is α such that $p_w - \alpha > p_d$. When the quarantine cost is α' such that $p_w - \alpha' < p_d$, however, the country ceases to be a net exporter and consumes q_d'.

The pest can be controlled by undertaking measures x at a unit cost of w. Control measures can include application of chemical pesticides, introduction of biological controls, taking land out of production or other changes in landscape that influence habitat (Brown, Lynch, and Zilberman 2002, Gottwald et al. 2001), adjusting the timing of planting and control, monitoring, etc. The unit cost of control includes both the direct costs for the control measures and the indirect costs via externalities from control measures

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[1] The Sanitary and Phytosanitary Standards (SPS) agreement's Article 6 requires member countries to adapt their sanitary and phytosanitary measures to specific geographic areas rather than national borders, i.e., to recognize that pest- and disease-free regions may exist within countries (Anon. 2005a, Anon. 2005b).

[2] Horan et al. (2002) argue that countries may place excessive weight on low-probability extreme outcomes, leading them to engage in or require excessively precautionary behavior, including more intensive monitoring than seems economically efficient.

[3] We assume that the invasive pest itself does not cause any direct harm to consumers, for example, by damaging ornamental plants, causing illness in pets, or triggering allergic reactions. The model does encompass quality damage in the product in cases where the pest increases the cost and/or reduces output of products that meet acceptable quality standards. It does not, however, consider quality-differentiated grades of the product or pesticide residue issues from ongoing pesticide use. Other indirect costs via externalities from ongoing or eradication control measures are assumed to be included in the unit cost of the control, as noted below.
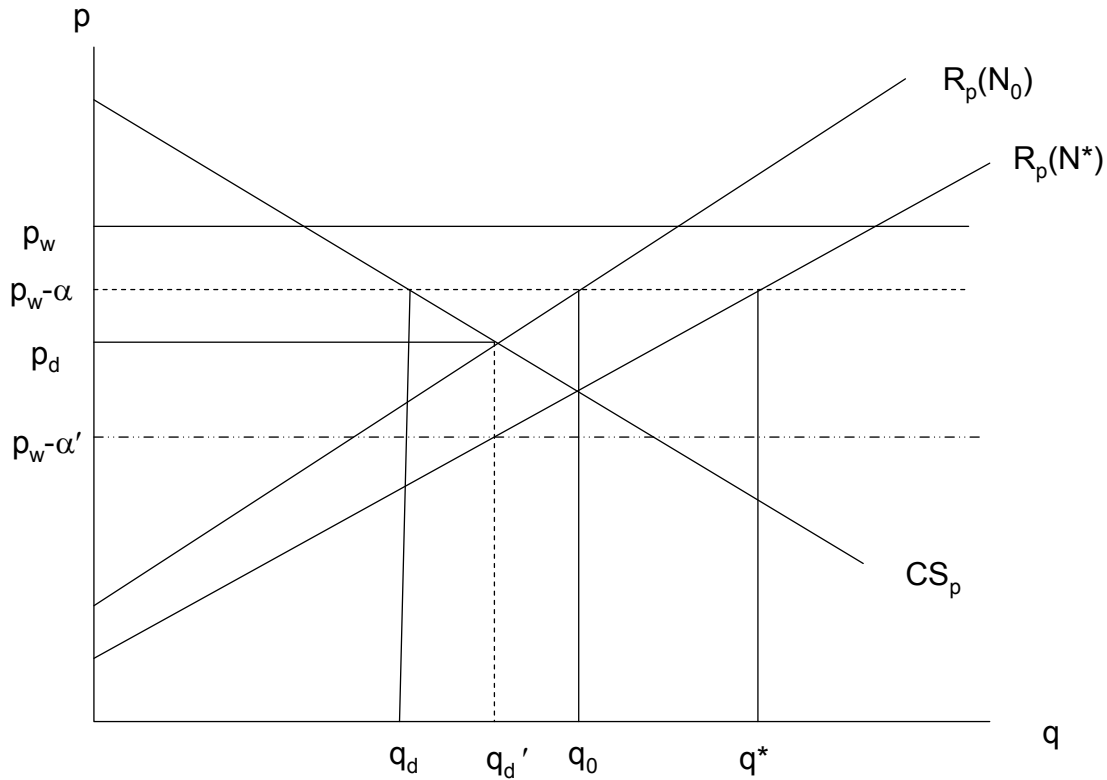
Figure 1. Impacts of Quarantine/Treatment Costs on a Net Exporter

(including losses suffered by consumers and by neighboring growers).[4] Use of these control measures will increase the supply of the product [shift the supply curve to the right from $R_p(N_0)$ to $R_p(N^*)$ in Figure 1] as long as the value of the reduction in damage from the pest population exceeds the cost of control.

We assume that the spread of the pest population in time and space is S-shaped, so that the net natural growth of the pest population (including net migration into the region) is an upside-down U-shaped function $G(N)$, where $G'(N) > (<) 0$ for $N < (>) N^M$. We also assume $G(0) = 0$. Control measures x reduce the pest population by an amount $k(x)$, hence $N' \equiv dN/dt = G(N) - k(x)$. We assume diminishing marginal productivity of pest

control so that $k' \geq 0$, $k'' \leq 0$. We also assume $k(0) = 0$.

We begin by analyzing the transition to a long-run equilibrium level of pest control without certification of PFA status. For simplicity, we consider the case where the country is a net exporter even when $N_0 > 0$.[5] The region decision maker chooses control level x for each period to maximize

$$\int_0^\infty \{CS(p_w - \alpha) + R(p_w - \alpha, v, N) - wx\} e^{-\rho t} dt,$$

subject to the state equation $N' = G(N) - k(x)$ given the initial pest population N_0 and discount rate ρ. The discounted Hamiltonian of this problem is

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[4] Social opposition to aerial spraying of malathion (Dawson et al. 1998) to eradicate the medfly in California and to tree-cutting to eradicate citrus canker in Florida has been politically and financially costly. Eradication campaigns can hurt growers as well, for example, by interfering with integrated pest management protocols utilizing beneficial insects or by killing pollinators.

[5] The cases where the country is not a net exporter at the initial pest population but may become so later on and where it is never a net exporter without PFA status add complications to the analysis without affecting the fundamental results.

$$H = CS(p_w - \alpha) + R(p_w - \alpha, v, N) \\ -wx + \lambda[G(N) - k(w)].$$

The necessary conditions for a maximum include

(1) $$-w - \lambda k'(x) = 0$$

(2) $$[\rho - G'(N)]\lambda - R_N(p_w - \alpha, v, N) = \lambda'$$

(3) $$G(N) - k(x) = N'.$$

Equation (1) is the standard condition that the value of the marginal reduction in the pest population due to use of the control equals the unit cost of control. The shadow price of the pest population λ is negative, since a higher pest population means lower productivity and hence lower social welfare. Use of the control in the short run (i.e., with N and λ fixed) is clearly increasing in the absolute value of that shadow price and decreasing in the unit cost of control. Equation (2) is the standard intertemporal arbitrage condition, while equation (3) is the pest population equation of motion. Since the second-order conditions for sufficiency are satisfied under our assumptions, these conditions are sufficient as well as necessary for a maximum.

Conditions (1)–(3) characterize the long-run equilibrium level of control $x^*(p_w - \alpha, v, \rho, w)$, pest population $N^*(p_w - \alpha, v, \rho, w)$, and pest population shadow price $\lambda^*(p_w - \alpha, v, \rho, w)$ when $\lambda' = N' = 0$. Note that in the long-run equilibrium,

$$\lambda^* = \frac{R_N(p_w - \alpha, v, N^*)}{\rho - G'(N^*)} < 0,$$

the shadow price of the pest population equals the value of the marginal loss in output (yield impact) from the long-run equilibrium pest population N^*, discounted in perpetuity at the discount rate, ρ, adjusted for marginal population growth, as is standard. Under the assumptions maintained here, there is a unique stable long-run equilibrium (see the appendix).

For the purposes of this analysis, we assume that the stable equilibrium population is small, $N^* < N^M$, so that $G' > 0$. In this case, the optimal transition depends on the initial level of infestation when the pest is discovered (see the appendix). If that infestation level exceeds the long-run

equilibrium level, $N_0 > N^*$, it will be optimal to exert control to gradually reduce the pest population to its long-run equilibrium level. The shadow price of the pest will gradually decrease in absolute value, hence use of the control will decrease gradually over time to its long-run equilibrium level as well. If the initial infestation level is less than the long-run equilibrium level, $N_0 < N^*$, it will be optimal to exert less control initially, allowing the pest to grow to its long-run equilibrium level, and to gradually let the level of control increase until reaching its long-run equilibrium level. The shadow price will increase gradually in absolute value as well.

Under these assumptions, the long-run equilibrium is characterized by the following (proofs appear in the appendix):

- PROPOSITION 1. *An increase in the world price of the product,* p_w, *reduces the long-run equilibrium pest population size, the long-run equilibrium level of pest control, and the absolute value of the shadow price of the pest population.*

- PROPOSITION 2. *A higher quarantine cost* α *increases the long-run equilibrium pest population size, the long-run equilibrium level of pest control, and the absolute value of the shadow price of the pest population.*

- PROPOSITION 3. *An increase in the discount rate* ρ *increases the long-run equilibrium pest population size, the long-run equilibrium level of pest control, and the absolute value of the shadow price of the pest population.*

- PROPOSITION 4. *An increase in the unit cost of pest control* w *increases the long-run equilibrium pest population size, the long-run equilibrium level of pest control, and the absolute value of the shadow price of the pest population.*

Intuitively, reducing the pest population from an initial infestation $N_0 > N^*$ involves two benefits for producers: more exports, hence increased revenue, and lower costs, hence increased profit. This is represented by a shift from $R_p(N_0)$ to $R_p(N^*)$ in Figure 1. Consumer welfare is not af-

fected because the price remains $p_w - \alpha$ throughout and the domestic quantity remains unchanged at q_d. The gains in export revenue are greater for products with a higher world price (Proposition 1), making it optimal for countries to incur greater control costs in the short run, so that the level of pest damage is lower in the long run. Less control is needed to maintain the lower level of the pest population once it has been achieved. The gains in export revenue are lower for products facing more restrictive SPS standards (Proposition 2), attenuating the incentive for the country to incur the costs of control in the short run, so that the infestation is allowed to attain a higher long-run equilibrium level. More control is needed to maintain that higher equilibrium infestation once it has been attained. A higher discount rate (Proposition 3) makes future gains less attractive relative to current costs, attenuating the incentive for control in the short run, leading to a greater long-run infestation level and thus equilibrium level of control.

The same logic applies to the case of greater control costs (Proposition 4). Higher control costs reduce the incentive to exert control in the short run, making it economical to allow the infestation to attain a higher long-run equilibrium level. However, more control is needed in the long run to maintain that higher equilibrium population level.

Optimal Certification of Pest-Free Status

To achieve a certified PFA status, the region must engage in a minimum level of surveillance and monitoring activities along the borders of the region and within the agricultural areas as regulated by the international community, in addition to eradicating the pest completely (should any infestation be present). Maintaining pest-free status also requires immediate eradication of any newly introduced pest populations discovered through this monitoring. We assume fixed monitoring and eradication protocols at respective costs of M and $F(w)$, where $F'(w) > 0$. The probability of discovering new pests after attaining PFA status is assumed to be constant at π, so that the expected costs of maintaining PFA status equal $M + \pi F(w)$.

The benefit of certification is the removal of all SPS trade barriers, so that the country can ship to all markets without quarantine and/or treatment and thus receive the full world market price, p_w. The total welfare in that case is

$$CS(p_w) + R(p_w, v, 0) - M - \pi F(w).$$

Certification is optimal if the country's (region's) long-run equilibrium welfare with certification exceeds its long-run equilibrium welfare without certification, i.e., if

$$
\begin{aligned}
(4)\quad \sigma \ &\equiv [CS(p_w) + R(p_w, v, 0) - M - \pi F(w)] \\
&- [CS(p_w - \alpha) + R(p_w - \alpha, v, N^*) - wx^*] > 0.
\end{aligned}
$$

We can rewrite this switching condition as

$$
\begin{aligned}
&[R(p_w, v, 0) - R(p_w - \alpha, v, N^*)] \\
&> [CS(p_w - \alpha) - CS(p_w)] \\
&+ [M + \pi F(w) - wx^*].
\end{aligned}
$$

The left-hand side of the inequality is the increase in producer revenue from the removal of quarantine and/or treatment restrictions on exports (demand-side effects) and from increased yields due to a lower pest population (supply-side effects). The first term on the right-hand side of the inequality is the decrease in the region's consumer welfare due to the increased price (p_w instead of $p_w - \alpha$). The second term on the right-hand side of the inequality is the difference between the pest monitoring and control cost to maintain the PFA status certification compared to pest control costs when N^* may be greater than zero. As illustrated in Figure 2, producers gain the area $a + b + c + d + e + f + g + h + i$ in extra revenue and increased yields (net of control costs). Consumers lose area $a + b$, so the net gain to the region is $c + d + e + f + g + h + i$. If this net gain exceeds the expected cost of maintaining PFA status certification $M + \pi F$, certification will be optimal.

Certification is clearly more likely to be optimal in cases where monitoring costs are lower ($\partial \sigma / \partial M < 0$), eradication costs are lower ($\partial \sigma / \partial F < 0$), and/or re-introductions are less likely ($\partial \sigma / \partial \pi < 0$). As one would expect, it is also more likely to be optimal for products facing higher quarantine and/or treatment costs α. Differentiating the switching function with respect to α gives

$$
\begin{aligned}
\partial \sigma / \partial \alpha \ &= CS_p(p_w - \alpha) + R_p(p_w - \alpha, v, N^*) \\
&- R_N(p_w - \alpha, v, N^*)\frac{\partial N^*}{\partial \alpha} + w\frac{\partial x^*}{\partial \alpha} > 0.
\end{aligned}
$$
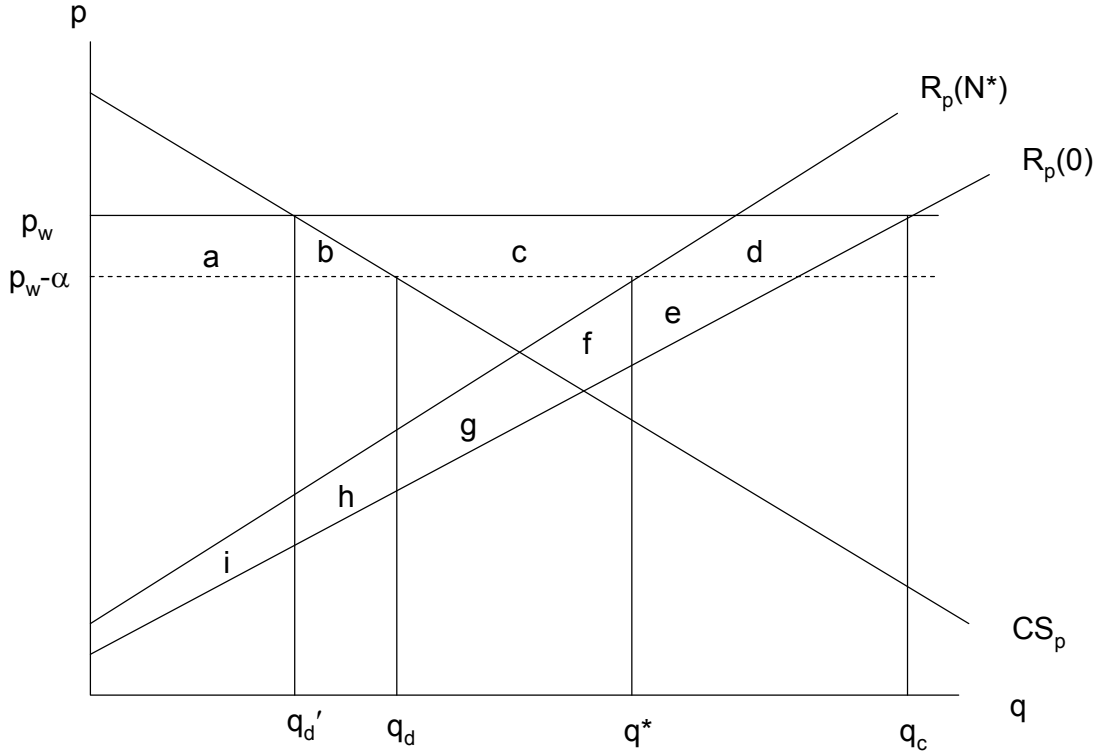
Figure 2. Benefits of Pest-Free Area Status Certification

Standard duality results imply that $R_p + CS_p = (q^* - q_d) > 0$, higher quarantine/treatment costs mean lower exports, which makes certification more attractive. Consumers benefit as the price decreases, but producers lose as the cost of quarantine increases and the price they receive decreases. When the country is a net exporter, producer losses exceed consumer gains. A higher quarantine/treatment cost also means a higher pest population, hence higher equilibrium levels of pest-induced yield damage,

$$-R_N \frac{\partial N^*}{\partial \alpha},$$

and greater pest control expenditures,

$$w \frac{\partial x^*}{\partial \alpha}.$$

As a result, higher quarantine/treatment restriction costs unambiguously increase the gains from certification under our assumptions.

Interestingly, countries facing a higher world market price p_w will not always be more likely to find certification optimal. The effect of a change in the world market price on the switching function is

$$\partial \sigma / \partial p_w = [(q_c - q_d') - (q^* - q_d)]$$
$$-R_N(p_w - \alpha, v, N^*) \frac{\partial N^*}{\partial p_w} + w \frac{\partial x^*}{\partial p_w}.$$

The first term (in square brackets) on the right-hand side of this equation is the increase in net exports from certification. It is positive, since the gains to producers from increased exports always outweigh consumer losses when the country is a net exporter (see Figure 2). But a higher world market price also makes it optimal to drive down the pest infestation to a lower long-run equilibrium level if a country chooses not to certify, reducing any gains from certification. The second term measures this reduction in the value of the productivity gain from certification. The third term is, as before, the reduction in pest control

expenditures due to the decrease in the pest population in the long run. Certification will be less likely for products whenever the net trade impact is smaller than the production cost impact:

$$[(q_c - q_d') - (q^* - q_d)] \quad < R_N(p_w - \alpha, v, N^*)$$
$$\frac{\partial N^*}{\partial p_w} + w \frac{\partial x^*}{\partial p_w}.$$

Alternatively, if the increase in exports due to PFA status certification is greater than the change in cost due to fewer pests and less pest control, the region is more likely to certify.

The effect of higher pest control costs on the desirability of PFA status certification is similarly ambiguous. Differentiating the switching condition gives

$$\frac{\partial \sigma}{\partial w} = -R_N(p_w - \alpha, v, N^*)\frac{\partial N^*}{\partial w}$$
$$+ x^* (\frac{w}{x^*}\frac{\partial x^*}{\partial w} + 1) - \pi \frac{\partial F}{\partial w}.$$

The first and second terms on the right-hand side are positive (Proposition 3): higher pest control costs increase both yield damage and control costs in the non-certified state, making certification more attractive. At the same time, higher control costs make certification more expensive, $\partial F/\partial w > 0$. Certification is optimal when ongoing pest control costs (direct and indirect/external) are higher than the expected cost of ensuring eradication in the event of re-infestation. The latter will be low when the threat of re-infestation π is low, among other things.

Finally, we find that

$$\frac{\partial \sigma}{\partial \rho} = -R_N(p_w - \alpha, v, N^*)\frac{\partial N^*}{\partial \rho} + w \frac{\partial x^*}{\partial \rho} > 0,$$

because a higher discount rate results in a higher pest population and greater control expenditures when the country does not certify. As a result, a higher interest rate makes PFA status unambiguously more desirable.

Eradication without Certification

It is possible that it will be optimal to eradicate the pest infestation in the long run even if certifi-

cation of PFA status is not desirable (i.e., $N^* = 0$). In such cases, the long-run equilibrium level of control is zero as well. The condition for eradication of the pest to be optimal in the long run without certification is thus

$$(4) \qquad -w - \frac{R_N(0)k'(0)}{\rho - G'(0)} \geq 0.$$

[See Olson and Roy (2002, 2003) for the derivation of the equivalent condition when the growth rate of the invasive pest is uncertain.] Condition (4) states that eradication is optimal when the present value of marginal damage avoided by eliminating the very last individual of the invasive species, $-R_N(p_w - \alpha, v, 0)/[\rho - G'(0)]$, exceeds the marginal control cost of eliminating that individual, $w/k'(0)$. Such an outcome is more likely when the control is inexpensive (w is small) or extremely effective at low population levels [$k'(0)$ is large] or when the pest is extremely damaging at even low population levels [$-R_N(0)$ is large].

When condition (4) holds, the condition for certification to be optimal becomes

$$[CS(p_w) + R(p_w, v, 0) - M - \pi F(w)]$$
$$- [CS(p_w - \alpha) + R(p_w - \alpha, v, N^*)] > 0.$$

If monitoring costs M and expected re-eradication costs $\pi F(w)$ are sufficiently large, they may outweigh the net gains from increased exports $[R(p_w, v, 0) - R(p_w - \alpha, v, N^*)] - [CS(p_w - \alpha) - CS(p_w)]$. As a result, eradication without certification may be optimal, i.e., a country may choose to rid itself of a pest infestation completely, both initially and in response to any re-infestation, without undertaking to obtain certification as a PFA. Eradication without certification is more likely to be optimal in cases where the unit cost of pest control is higher [note that $\partial \sigma/\partial w$ is less than zero unambiguously when eradication is optimal since $\partial N^*/\partial w = \partial x^*/\partial w = 0$ as long as condition (4) continues to hold].

Implications for Trade Policy

These results have several implications for policy.

One implication is that PFA certification creates winners and losers even within an exporting

country or region. Producers may gain due to the expansion of the export market and lower equilibrium pest damage and pest control costs. But domestic consumers may well lose because the expansion of the export market increases the price they pay for the product. Thus, the gains from certification will tend to be smaller for products for which domestic consumption accounts for a large share of the market. While producer gains always exceed consumer losses, compensation is unlikely to be paid. Moreover, if the cost of maintaining PFA status is financed from general government revenues, consumers lose as taxpayers as well. These considerations suggest that PFA certification is likely to garner greater political support in larger, richer countries than in smaller, poorer ones, and at the national rather than local level. Thus, for example, California growers may find it easier to convince the U.S. Department of Agriculture to underwrite PFA certification for Mediterranean fruit fly than the State of California.

Our analysis also indicates that geography matters a great deal. Regions or countries that possess physical barriers to invasions are more likely to find PFA certification desirable. Physical barriers reduce the risk of infestation or re-infestation (π). They also lower monitoring costs (M) by reducing the number and variety of entry possibilities. As a result, the costs of attaining and maintaining PFA status should be lower.

As is well known, it is quite possible to use SPS standards as barriers to trade. The preceding analysis suggests that monitoring requirements for PFA certification can be used in a similar manner. Stringent monitoring requirements can make PFA status certification too expensive to be desirable, even in cases where the threat of re-introduction is quite low, where re-eradication costs are low, or when eradication is optimal even without certification. As a result, countries may be able to maintain protection of domestic markets from imports by insisting on monitoring requirements costly enough to deter countries or regions from seeking PFA status certification. In other words, pest surveillance requirements in PFA certification standards are as susceptible to potential abuse as technical barriers to imports. For that reason, scientific transparency can be as important in PFA status certification requirements as in SPS standards.

The preceding analysis also makes it clear that the desirability of PFA status certification is sensitive to technological changes, notably changes in treatment methods and monitoring techniques. New, more effective (and/or less costly) treatment methods make PFA status certification relatively less desirable by reducing the cost of complying with SPS standards for uncertified products. By the same token, removal of more effective, less costly treatment techniques on account of environmental spillovers, occupational hazards, or other negative externalities can make PFA status relatively more desirable. Thus, for instance, the removal of methyl bromide as a fumigant would have enhanced the incentives for states like California to seek certification as a Mediterranean fruit fly free zone (if the harmonization of the Clean Air Act with the Montreal Protocol's exemption for quarantine uses had not ensured its continued use as a fumigant).

The effect of expanding world trade in agricultural commodities on the desirability of PFA status certification is unclear. One would expect greater entry into world markets to reduce the world market price. As shown above, a change in the world market price has an ambiguous effect on the returns to certification. A lower world market price means smaller gains from further expansion of exports subsequent to certification. At the same time, a lower world market price means a higher pest population, hence greater savings from certification in terms of reduced damage and pest control costs.

Conclusion

Threats from invasive exotic pests and diseases are a growing source of concern in importing countries and a source of conflicts over trade policy between importing and exporting countries. Historically, importing countries have imposed restrictions ranging from treatment requirements to bans on imports from regions (and countries containing regions) known to harbor a given invasive species. Recent trade agreements offer exporters an escape hatch: by meeting specific conditions, exporters can certify themselves (or specific regions within themselves) as pest-free areas. Thus, by eradicating any existing infestations and conducting ongoing monitoring to

detect re-infestations and prevent transshipments from infested regions, a country or region can export freely without incurring the costs involved in quarantines or treatments.

This paper presents a conceptual framework for analyzing the desirability of pest-free status certification. In contrast to the bulk of the existing literature, we concentrate on exporters and consider both demand- and supply-side effects of pest control and pest-free status certification. Our model makes explicit the trade-offs involved in certification. On the one hand, certification means increased export revenue, lower pest damage, and lower direct and indirect costs of ongoing pest control. At the same time, compliance with certification requirements is costly. It is thus possible for countries to find it optimal to eradicate an infestation and maintain pest-free status without certifying themselves as pest-free areas. This analysis makes it clear that these certification requirements are as susceptible to abuse as import restrictions purportedly undertaken as protection against exotic pest invasions.

We find that certification is more likely to be desirable for countries facing more costly treatment requirements if they are not certified as pest-free and for countries possessing physical limits to invasions that lower monitoring costs and infestation probabilities. Somewhat surprisingly, though, certification is not always more desirable for higher-valued products: even though revenue increases from the expansion of exports are greater, the cost savings from lower pest populations are smaller. Similarly, higher control costs increase the savings from reductions in damage and ongoing control costs without certification, but increase the expected costs of maintaining pest-free status at the same time. When eradication remains optimal, increases in control costs make certification unambiguously less desirable.

Our analysis also indicates that PFA status certification does not benefit everyone in a region. Consumers in the region are likely to lose from higher prices due to the expansion of export markets. Their losses may be even greater if the costs of certification are defrayed from general tax revenues. Those considerations suggest that certification is more likely to avoid political opposition in countries where domestic consumption is a small share of the market and where the

additional tax burden of certification programs is light.

Our analysis was conducted under a number of simplifications including no uncertainty about the size of introductions and the spread of infestations, no explicit spatial dimension of invasions (and their control), no effects of pest-free status certification on the world market price (the large country case), no effects of the pest on the distribution of product quality grades, and no potential for strategic behavior with regards to quarantine and/or monitoring requirements on the part of importers. Further research in these directions seems likely to be rewarding.

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APPENDIX

Equation (1) implies that x is implicitly a decreasing function of the shadow price λ (with $\partial x/\partial \lambda = -k'/\lambda k''$) and independent of the population size N. We can thus concentrate this problem in the two differential equations (2) and (3). Linearizing these differential equations around an arbitrary equilibrium point, we find that they have eigenvalues

$$\frac{1}{2}\left\{\rho \pm \sqrt{\rho^2 - \frac{4\Omega}{\lambda k''}}\right\},$$

where $\Omega \equiv \lambda k'' G'(\rho - G') + (k')^2(R_{NN} + \lambda G'')$. The equilibrium is a saddle point when $\Omega \leq 0$.

The $\lambda' = 0$ isocline is downward sloping [$d\lambda/dN = (\lambda G'' + R_{NN})/(\rho - G') < 0$], with λ increasing above the isocline and decreasing below it. The $N' = 0$ isocline is U-shaped [$d\lambda/dN = -(k')^2/(\lambda k'' G')$, positive when $N > N^M$], with N increasing above the isocline and decreasing below it. The stability condition $\Omega \leq 0$ implies that the $\lambda' = 0$ isocline is steeper than the $N' = 0$ isocline when both are downward sloping at their intersection point, i.e., for $N^* < N^M$. The phase diagram is thus as illustrated in Figure A.1.
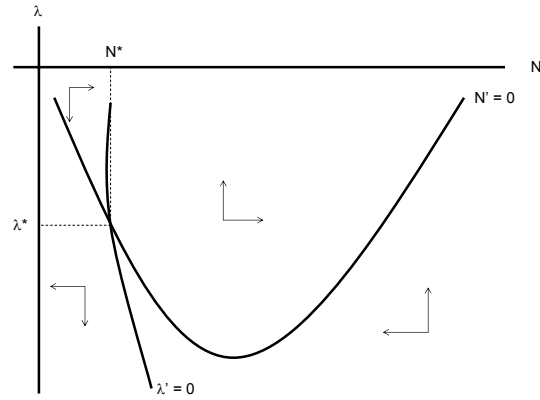
Figure A.1. Phase Plane Analysis of Optimal Invasive Pest Control

The optimal transition in this case involves reductions in N when $N_0 > N^*$ (more control) and increases in N when $N_0 < N^*$ (less control).

Total differentiation of equations (1)–(3) gives

$$\begin{pmatrix} -\lambda k'' & 0 & -k' \\ 0 & -(\lambda G'' + R_{NN}) & \rho - G' \\ -k' & G' & 0 \end{pmatrix}\begin{pmatrix} dx^* \\ dN^* \\ d\lambda^* \end{pmatrix}$$
$$= \begin{pmatrix} 0 \\ R_{Np} \\ 0 \end{pmatrix}(dp_w - d\alpha) + \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}dw + \begin{pmatrix} 0 \\ -\lambda \\ 0 \end{pmatrix}d\rho.$$

The determinant of the Hessian is

$$\Omega \equiv \lambda k'' G'(\rho - G') + (k')^2(R_{NN} + \lambda G'') \leq 0.$$

Applying Cramer's Rule, we find that

$$\frac{\partial x*}{\partial \alpha} = \frac{k'G'R_{Np}}{\Omega} \geq 0$$

$$\frac{\partial N*}{\partial \alpha} = \frac{(k')^2 R_{Np}}{\Omega} \geq 0$$

$$\frac{\partial \lambda*}{\partial \alpha} = -\frac{\lambda k''G'R_{Np}}{\Omega} \leq 0 .$$

$$\frac{\partial x*}{\partial w} = -\frac{G'(\rho - G')}{\Omega} \geq 0$$

$$\frac{\partial N*}{\partial w} = \frac{k'(\rho - G')}{\Omega} \geq 0$$

$$\frac{\partial \lambda*}{\partial w} = \frac{k''(R_{NN} + \lambda G'')}{\Omega} \geq 0 .$$

From standard duality, $R_{Np} = \partial q/\partial N \leq 0$. The derivatives with respect to α and ρ have the same sign as each other and the opposite sign of derivatives with respect to p_w. Because $\lambda* < 0$, an increase in λ means a decrease in absolute value terms. We also get the following: