Dynamic Sanitary and Phytosanitary Trade Policy

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Abstract

This paper characterizes the optimal use of sanitary and phytosanitary standards to prevent the introduction of harmful pests and diseases through international trade. Because established pest and disease infestations grow and spread over time their introduction has intertemporal consequences. In a dynamic economic model, an efficient trade policy balances the costs of SPS measures against the discounted stream of the costs of control and social damages that are avoided by using SPS measures, where future growth and spread of any established infestation is accounted for. We examine when phytosanitary trade policy makes good economic sense, when it is efficient to provide full protection against pests and diseases, and when restrictive, but not fully protective trade policy is efficient.

1 Introduction

Today, non-native pests and diseases are recognized as one of the leading causes of global environmental change (CBD, 2002). One of the primary pathways for the introduction of pests and diseases is international trade. Public policies that address the negative externalities caused by invasive pests and diseases involve various forms of regulation of imports to prevent entry of new pests and diseases as well as policies for domestic control or eradication of established pests and diseases that were introduced at earlier points in time.

International trade agreements recognize that it is important for individual countries to be able to use sanitary and phytosanitary (SPS) standards to protect themselves from the harmful effects of pests and diseases. The World Trade Organization (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures adopts a fairly broad view of SPS standards as any measure applied to protect human, animal or plant health from pests, diseases, toxins and other contaminants.[1] SPS measures may be implemented through product or process standards, testing, inspection, certification, treatment and quarantine (Annex A, Definition 1). SPS measures reduce the import of pests and disease in two ways. First, production and process standards, inspection and treatment reduce the incidence of pests associated with imported goods. Second, SPS measures raise the marginal cost of imported goods, thereby reducing the volume of imports that have the potential to transmit pests and disease. Because SPS measures restrict trade, the WTO Agreement specifies that "*when establishing or maintaining sanitary or phytosanitary measures to achieve the appropriate level of sanitary or phytosanitary protection, Members shall ensure that such measures are not more trade-restrictive than required to achieve their appropriate level of sanitary or phytosanitary protection, taking into account technical and economic feasibility.*"

[1] The Phytosanitary Agreement of the World Trade Organization (WTO) defines pests as organisms "of economic significance that are either not yet present in an area, or present, but not widely distributed and being officially controlled" (ISPM No. 5).

The key economic question that arises here is, what is the appropriate level of protection? To answer this the WTO Agreement directs countries to "*take into account as relevant economic factors: the potential damage in terms of loss of production or sales in the event of the entry, establishment or spread of a pest or disease; the costs of control or eradication in the territory of the importing Member; and the relative cost-effectiveness of alternative approaches to limiting risks.*" [Article 5 of the WTO Agreement]. This paper examines the economics of SPS measures in this specific context.

Pests and diseases transmitted through trade are specific forms of externalities that cross national borders. A distinctive feature of the negative externalities generated by the invasion of pests and diseases is that, once established in the country, the size of the invasion may grow or spread over time so that the ecological and economic costs to society are essentially dynamic in nature and evolve over time. Further, the true opportunity cost of entry of invasive pests and diseases must take into account the future cost of controlling established invasions in the country through domestic public policy measures. Therefore, as recognized in the articles of the WTO agreement quoted above, it is important to analyze the dynamic costs and benefits of SPS trade restrictions. This requires taking into account the natural growth or spread of pests and diseases over time and the corresponding future cost of control. This paper examines the economics of SPS measures in an explicit dynamic model that captures these important aspects. To the best of our knowledge, this is the first paper in the literature to do so.

The analysis of SPS trade policy in the existing literature is essentially static and extends the static optimal tariff literature in international trade theory to examine the relation between SPS policy and the allocation of resources within an economy open to trade in partial equilibrium or general equilibrium (see Olson (2007) for a survey of this literature). Roberts, Josling and Orden (1999) summarize the typical partial equilibrium framework in which SPS policy: (i) acts like a tariff to raise the marginal cost of imported goods, (ii) protects domestic producers from increased costs associated with pest infestations, and (iii) may provide information that affects domestic demand. Beghin and Bereau (2001) survey different methods that have been applied to study the impact of non-tariff trade barriers on market equilibrium, trade flows and welfare[2]. Margolis, Shogren and Fischer (2005) incorporate an invasive pest externality into the Grossman and Helpman (1994) political economy model of trade. McAusland and Costello (2004) examine a theoretical model of the use of tariffs and inspections to reduce trade induced pest damages. Their analysis focuses on how the optimal tariff and inspection intensity vary with the damage parameter, the infestation rate and the marginal costs of production.[3]

More generally, the analysis of international trade policy in the presence of externalities has received attention in the literature on trade and the environment. However, the focus there is largely on the relationship between trade policy and the comparative advantage of clean and dirty goods production or consumption, and the consequences for the distribution of environmental quality (see, Copeland and Taylor (2003) for an overview). In the most common setting there is a clean good and a dirty good and pollution is a by-product of production or consumption of the dirty good. Pollution damages may be confined to the country in which production or consumption of the dirty good takes place, as in Copeland and Taylor (1994 or 1995a). Alternatively, pollution may jointly affect both exporting and importing countries, as in Baumol and Oates (1988), or it may be a global public good as in Whalley (1991) and Copeland and Taylor (1995b). Pests and disease have two features that distinguish them from the kinds of environmental pollution most frequently examined in this literature. First, the geographic distribution of species and the range of habitats suitable

[2] These include the price wedge method, inventory, survey, and gravity based approaches, risk assessment-based cost-benefit analysis, microeconomics based approaches, and multi-market models.

[3] Case studies that examine the economic impacts of SPS measures typically focus on a single market and pest/disease. Examples include Paarlberg and Lee (1998, foot-and-mouth disease), Calvin and Krissoff (1998, Fuji apples), Glauber and Narrod (2001, US wheat), and Acquaye et.al. (2005, US citrus), and Wilson and Anton (2006, foot-and-mouth disease).

for infestation implies that the generation of pest and disease externalities and the mechanism by which they are transmitted through trade differs from the standard models of pollution generated by the production or consumption of dirty goods. Second, as mentioned earlier, pest and disease externalities are not static pollution problems. They evolve over time and the appropriate trade policy must account for this.

As discussed above, the economics SPS policy is linked to the economics of control. In Olson and Roy (2002, 2008) we examine the optimal domestic control of an established pest and the conditions under which eradication is efficient, and when it is not efficient. The focus is confined to established pest populations. Since it is assumed that there are no introductions, there is no role for trade policy and important questions relating to prevention of invasive pests and diseases and the possibility of re-introduction after eradication are ignored. The framework in this paper allows us to address these issues. The objective is to characterize how optimal trade policy should be formulated in the presence of trade induced externalities that have intertemporal consequences. Intuitively, the benefits of SPS policy can be measured by the discounted stream of the costs of control and social damages that are avoided by using SPS measures to prevent the introduction of invasive pests and diseases. In this paper we provide a rigorous characterization of how an efficient trade policy balances the costs of SPS measures against the benefits. We examine when phytosanitary trade policy makes good economic sense, when it makes sense to use SPS policies that provides maximal protection against pests and diseases, and when restrictive, but not fully protective trade policy is efficient.

2 Preliminaries

Let $y_t \geq 0$ represent the size of the size of domestic pest or disease infestation at the beginning of time t. Depending on the context this could be an existing pest population, the biomass of an invasive species or the area infested by a pest or disease. If $y_t = 0$ then there is no established domestic infestation. Management occurs on two fronts: prevention and/or control. Preventive SPS measures reduce the introduction or entry of pests and diseases from abroad but raise the marginal cost of the imported goods.

Let τ denote the effect of SPS policy on the marginal cost of the imported good, or the tariff rate equivalent of SPS policy. Phytosanitary policy is optimal if $\tau > 0$. The pest introduction that occurs under an SPS measure with marginal cost τ is given by $i(\tau) \geq 0$. The welfare cost of the trade restrictions associated with SPS policy is denoted by $W(\tau) \geq 0$. We make the following assumptions on i and W, where subscripts represent derivatives:

A1. (i) $i : \Re_+ \rightarrow \Re_+$ *is continuous and convex.*

(ii) There exists $\overline{\tau} > 0$ *such that* $i(\tau) > 0$ *for all* $\tau \in [0, \overline{\tau})$ *and* $i(\tau) = 0$ *for all* $\tau \geq \overline{\tau}$.

(iii) $i(\tau)$ *is continuously differentiable and convex with* $i_\tau(\tau) < 0$ *on* $[0, \overline{\tau}]$.[4]

(iv) $W : \Re_+ \rightarrow \Re_+$ *is continuously differentiable and strictly convex on* $\Re_+$ *with* $W_\tau > 0$ *on* $\Re_{++}$.

Our assumptions on $i(\tau)$ imply that more stringent trade measures are more effective at preventing pest and disease introductions, but with diminishing marginal returns. Strict monotonicity of i implies a one-to-one relationship between the choice of τ and pest introductions. Note that $\overline{\tau}$ is the marginal cost of the trade policy that completely prevents pest introductions. We shall refer to $\overline{\tau}$ as *fully protective SPS trade policy.* In situations where the risk of pest and disease introduction through imports cannot be fully eliminated by other means, $\overline{\tau}$ corresponds to a ban on imports due to phytosanitary concerns. However, if the imposition of production and transportation standards as well as treatment requirements can fully eliminate the risk of entry of pest or disease introduction

[4] At $\overline{\tau}$, i_τ refers to the left-side derivative. The assumption of a strict inequality avoids some technical complications but is of no consequence for the analysis.

through trade, a fully protective SPS trade policy may be consistent with positive imports.

Our assumption on W implies that more stringent SPS trade measures increase the current welfare cost absolutely as well as at the margin. Our model allows for a very general interpretation of the welfare cost W that incorporates all static domestic costs of SPS policy and, further, it allows for the consideration of different SPS policies such as treatment of commodities to reduce infestation rates, inspection of commodities, process standards, or tariffs. A typical case is where W represents the change in domestic consumer and producer surplus plus any transfer payments from foreign producers less domestic administrative costs.[5] For example, suppose that SPS policy involves treatment of commodities to reduce pest contamination rates, where the cost of treatment is borne by foreign producers. The domestic welfare cost of this type of SPS policy arises from its effect on the marginal cost of imported goods and is transmitted through changes in the equilibrium price in the domestic market. In this example, W measures the corresponding change in consumer and producer surplus: $W = -\left[\int_{p(\tau)}^{\infty} D(\omega)d\omega - \int_{0}^{p(\tau)} S(\omega)d\omega\right]$, where D and S represent domestic demand and supply and p is the domestic price, assumed to be higher than the world price. The negative sign reflects the fact that W represents the welfare cost of SPS policy. Differentiating yields $\frac{dW}{d\tau} = m(p)\frac{dp}{d\tau}$, where $m(p)$ is the import demand function.

The marginal welfare cost per unit of pest and disease invasion prevented by trade policy is given by:

$$\gamma(\tau) = -\frac{W_\tau(\tau)}{i_\tau(\tau)}.$$

Under the assumptions in $A1$, $\dot{\gamma(\tau)} \geq 0$ and γ is strictly increasing on $[0, \overline{\tau}]$.

In addition to prevention, a variety of control methods can be used to reduce the size of a pest or disease infestation, if and when it becomes established. Let a_t be the reduction in the pest infestation achieved through manual, chemical, biological or other control methods, where $a_t \geq 0$.

[5] The latter includes costs borne by domestic regulatory agencies, such as costs of inspection and monitoring.

In this paper, our main interest is optimal trade policy so it is assumed that there is a constant marginal cost of control, c. The pest infestation at the end of period t is given by $x_t = y_t + i(\tau_t) - a_t$. The infestation grows and spreads over time according to a natural growth function $y_{t+1} = f(x_t)$. The growth function is assumed to satisfy the following properties:

$A2$. $f(0) = 0$, $f(x) > 0$ for all $x > 0$.

$A3$. f is continuous on $\Re_+$ and continuously differentiable on $\Re_{++}$.

$A4$. $f_x(x) > 0$

$A5$. $f_x(0) > 1$.

$A6$. There exists a $k > 0$ such that $f(x + i(0)) < x$ for all $x > k$. Further, the initial pest infestation $y_0 \in [0, k]$.

These assumptions place minimal restrictions on the set of possible growth functions. Assumptions $A2 - A4$ require no explanation. Assumption $A5$ rules out situations where an infestation is not biologically sustainable even if it is not controlled. Assumption $A6$ captures the fact that the growth of any infestation is bounded by climatic, geographical or ecological factors even if nothing is done to manage it.

The intertemporal cost minimization problem given y_0 is:

$$Min \sum_{t=0}^{\infty} \delta^t \left[ca_t + W(\tau_t) + D(x_t)\right] \tag{1}$$

$$\text{subject to:} \qquad \tau_t \geq 0, a_t \geq 0, y_t + i(\tau_t) - a_t \leq x_t, y_{t+1} = f(x_t). \tag{2}$$

The analysis of efficient trade policy is facilitated by decomposing the intertemporal problem into two parts: a static optimization problem where the pest infestation at the end of the period is held fixed, and a dynamic optimization problem over the pest infestation level. We consider these in turn. The static, minimum cost of using trade policy and control to move from an initial infestation of size $y \geq 0$ to an end of period infestation of size $x \in [0, y + i(0)]$ is given by:

$$\begin{aligned} F(y-x) &= \min_{a,\tau}[ca + W(\tau)] \\ \text{s.t. } \tau &\geq 0, a \geq 0, a - i(\tau) \geq y - x. \end{aligned} \tag{3}$$

The convexity of W and i imply that this optimization problem is one that minimizes a convex objective over a convex feasible set. This implies that F is convex and that the first order conditions are necessary and sufficient. The static cost function depends only on the difference between y and x, and not their absolute values. The constraints imply $i(\tau) \geq \max\{0, x - y\}$, which reflects the fact that fully protective trade policy is precluded if the targeted pest infestation at the end of period is larger than the initial infestation. Further, prevention and control are inputs that are used to achieve a reduction in the pest infestation from $y + i(0)$ to x. In the third constraint, the reduction in the pest infestation through prevention and control, $a + (i(0) - i(\tau))$, must be at least as large as $y + i(0) - x$. The efficient combination of prevention and control relies on the least cost means of reducing the pest infestation. If one policy always has lower cost then that policy dominates. Otherwise both policies are utilized and the efficient allocation equalizes their marginal cost.

Proposition 1 *Assume that $x < y + i(0)$. Then (i) $\tau = 0$ if and only if $c \leq \gamma(0)$, (ii) $\tau > 0$ and $c = \gamma(\tau)$ if and only if $c > \gamma(0)$ and $c < \gamma(i^{-1}(\max[0, x - y]))$, (iii) trade policy is fully protective and $i(\tau) = \max[0, x - y]$ if and only if $c \geq \gamma(i^{-1}(\max[0, x - y]))$.*

SPS trade policy is never efficient if $c \leq \gamma(0)$ for then it is always cheaper to reduce an infestation through control. This is not the relevant case if optimal trade policy is the question of interest; hence, the remainder of the paper assumes:

A7. $c > \gamma(0)$.

We now turn to the dynamic optimization problem that balances the costs of phytosanitary policy and control against the intertemporal benefits. A sequence $\{y_t, x_t, a_t, \tau_t\}_{t=0}^{\infty}$ that solves (1) is defined to be an *optimal program* from y_0. It is straight-forward to verify that if (y_t, x_t, a_t, τ_t) solves the dynamic optimization problem then a_t and τ_t are solutions to (3). This allows a convenient, reduced form representation of the dynamic optimization problem in (1).

Lemma 2 *If $\{x_t, y_t, a_t, \tau_t\}$ is an optimal program from $y_0 \geq 0$, then for all t, (a_t, τ_t) solves the minimization problem (3) given $y = y_t$ and $x = x_t$. In addition, F is convex and the functional equation of dynamic programming for (1) can be expressed in reduced form as:*

$$V(y) = min_{0 \leq x \leq y+i(0)} \; F(y - x) + D(x) + \delta V(f(x)), \tag{4}$$

where $V(y)$ is the optimal value function.

It is important to recognize that, in spite of the fact that F is convex, this is a *nonconvex* dynamic optimization problem. Every growth function that satisfies assumptions $A5$ and $A6$ is necessarily nonconvex. As a consequence, the feasible choice set in period t is a nonconvex, set-valued mapping of the pest infestation at the end of period $t-1$. In addition, when f is nonconvex, it is easy to see that the composition of V and f on the right hand side of (4) may be nonconvex. We use techniques from variational analysis to deal with the potential effect of nonconvexities on the solution. One possible complication that arises is that the optimal policy may not be uniquely defined. That is, there may exist more than one selection from the optimal policy that minimizes social cost. In such circumstances we assume:

$A8$. The smallest optimal end of period pest infestation is always chosen.

3 Optimal SPS Policy.

The benefits of phytosanitary policy and control in period t are the reduction in the discounted stream of current and future social costs that can be attributed to the SPS and control policies implemented in period t. Since these policies affect the growth and spread of the infestation in all future periods; the benefits of preventing or reducing a unit of the infestation today include the changes in future damages compounded by the marginal impact of prevention and control on future rates of growth and spread in the pest or disease.

Proposition 3 *If* $\tau_t > 0$ *then* $\gamma(\tau_t) \leq D_x(x_t) + \sum_{i=1}^{\infty} \delta^i D_x(x_{t+i}) \prod_{j=0}^{i-1} f_x(x_{t+j})$ *and* $\gamma(\tau_t) \leq D_x(x_t) + \sum_{i=1}^{T-1} \delta^i D_x(x_{t+i}) \prod_{j=0}^{i-1} f_x(x_{t+j}) + \delta^T c \prod_{j=0}^{T} f_x(x_{t+j})$ *for all* $T = 1, ...\infty$.. *If* $\tau_t > 0$ *and* $\overline{\tau} > \tau_{t+1}$ *then* $\gamma(\tau_t) \leq D_x(x_t) + \delta f_x(x_t)\gamma(\tau_{t+1})$. *If* $\overline{\tau} > \tau_t > 0$, $\overline{\tau} > \tau_{t+1} > 0$ *and* $x_t > 0$ *then* $\gamma(\tau_t) = D_x(x_t) + \delta\gamma(\tau_{t+1}) f_x(x_t)$.

Two conditions are necessary for the use of phytosanitary trade policy. First, the welfare cost per unit of pest prevention must be less than the discounted stream of current and future damages caused by that unit of the pest and its growth. The second necessary condition requires that the cost of trade policy be less than the damages and discounted control costs incurred by waiting to remove the pest and its growth at any point in the future. Proper accounting requires that marginal damages in future periods be multiplied by the compound growth over the intervening periods that results from an increment to the infestation in the current period t. All else equal, the benefits of phytosanitary policy are greater for pests with higher growth rates as these pests have more significant negative consequences in the future.

In many instances SPS policy is designed to prevent the introduction of pests or diseases that are not present domestically. The following corrollary provides necessary conditions for fully protective SPS policy to be efficient when there is no existing infestation.

Corollary 4 *Suppose* $y_t = 0$. *If* $\tau_t = \overline{\tau}$ *then* $\gamma(\overline{\tau}) \leq c$ *and* $\gamma(\overline{\tau}) \leq D_x(0) + \sum_{i=1}^{T-1} (\delta f_x(0))^i D_x(0) + c(\delta f_x(0))^T$ *for all* $T = 1, ...\infty$. *In addition, if* $\delta f_x(0) < 1$ *then* $\gamma(\overline{\tau}) \leq \frac{D_x(0)}{1-\delta f_x(0)}$.

For full protection to be optimal it must be better to prevent the pest from being introduced than to incur the damages and discounted costs of removing it in the future. Note that high discounting can make it more attractive to postpone control until some future date. Futher, the welfare cost of full protection must be less than perpituity value of intrinsic marginal damages compounded at the discounted intrinsic growth rate. If $\delta f_x(0) \geq 1$ this will always be true as the perpituity value of intrinsic marginal damages is infinite.

A characterization of sufficient conditions for SPS policy is complicated by two factors. First, the dynamic optimization problem is potentially nonconvex. Second, the alternatives to prevention are to control today or at any future date. To be efficient SPS policy must dominate this infinite set of alternatives.

Define the minimum rate of growth of infestations larger than y by $g(y) = \min_{x \in [y,k]} f_x(x)$ and note that $g(y) < 1$. A sufficient condition for the use of phytosanitary trade policy is:

Proposition 5 *If* $D_x(y_t + i(0)) \left[1 + \delta f_x(y_t + i(0)) \sum_{j=o}^{\infty} (\delta g(y_t + i(0)))^j \right] > \gamma(0)$ *then* $\tau_t > 0$ *and it is optimal to use phytosanitary trade policy to reduce the introduction of pests.*

The left hand side of the inequality is a lower bound on the discounted current and future marginal damages if no preventive trade measures are taken. Future marginal damages are compounded by the growth that results from allowing the pest or disease to enter through trade. The marginal damage terms increase with the size of the existing infestation, y, and this increases the likelihood that some trade restriction is optimal. On the other hand, nonconvexity in the growth function implies that the natural growth rate, $f_x(y + i(0))$, eventually declines in y and this reduces the incentive to impose some trade restriction as the size of the pest infestation increases. In particular, if the growth function is S-shaped, then an increase in y raises the value of SPS trade policy when y is small, but the the effect may be in the opposite direction when y is sufficiently large.

Next, we examine sufficient conditions for the use of fully protective phytosanitary trade policy.

Proposition 6 *Suppose that* $c \geq \gamma(\overline{\tau})$ *and*

$$D_x(y)\left[1 + \delta[\min_{y \leq z \leq y+i(0)} f_x(z)] \sum_{t=0}^{\infty} (\delta g(y))^t\right] \geq \gamma(\overline{\tau}) \tag{5}$$

Then, fully protective SPS policy is optimal, i.e., $y_t = y$ *implies that* $\tau_t = \overline{\tau}$ *and* $i(\tau_t) = 0$*.*

The term on the left hand side of (5) is a lower bound on the current and future marginal damages from allowing a phytosanitary pest or disease to be introduced through trade. If this exceeds the marginal welfare cost of prohibiting the introduction of such pests then complete prevention of pest or disease introductions through trade is optimal. Note that in many situations a prohibitive level of trade restrictions is effectively a ban on imports.

We now turn our attention to the conditions under which optimal trade restrictions are less than fully protective, i.e., the optimal policy allows for positve entry of pests or diseases.

Proposition 7 *a) Suppose* $c < \gamma(\overline{\tau})$*. Then, the optimal level of trade restriction is always less than fully protective and for all* t*,* $\tau_t \leq \gamma^{-1}(c) < \overline{\tau}$*. b) Assume* $c \geq \gamma(\overline{\tau})$ *and that for some* $\widehat{y} > 0$

$$D_x(\widehat{y}) + \delta\{\max_{0 \leq z \leq \widehat{y}} f_x(z)\}c < \gamma(\overline{\tau}). \tag{6}$$

Then, if $y_t \leq \widehat{y}$*, optimal trade policy is less than fully protective and* $\tau_t < \overline{\tau}$*. Further, if trade policy* *is less than fully protective in period t+1 and if*

$$D_x(\widehat{y}) + \delta\{\max_{0\leq z\leq \widehat{y}} f_x(z)\}\gamma(\overline{\tau}) < \gamma(\overline{\tau}) \tag{7}$$

Then, if $y_t \leq \widehat{y}$*, optimal trade policy is less than fully protective in period t and* $\tau_t < \overline{\tau}$.

The first condition simply says that if control is cheaper than the marginal cost of fully protective trade policy then complete prevention is not an optimal policy. Under the second condition the cost of controlling the pest after introduction and growth is less than the welfare cost of full protection. Hence, full protection is not efficient. The final condition for less than fully protective trade policy involves the trade-off between eliminating the last unit of introductions today and preventing an equivalent introduction in the future, appropriately adjusted for growth in the infestation. It requires the invasion to be slow growing when it is small. It must be the case that the maximum discounted growth rate, $\delta\{\max_{0\leq z\leq \widehat{y}} f_x(z)\}$, is less than one for invasion sizes smaller than $\widehat{y}$. The reason is that future damages are compounded by the discounted growth rate of the invasion. If this is high, then the economics of an imperfectly protective trade policy are less favorable as such a policy will result in higher future social costs. In essence, appropriately adjusted marginal damages must be less than the marginal welfare cost of full protection, in order for fully protective trade policy to be inefficient.

The final result examines the conditions under which it does not make sense to restrict trade in any manner.

Proposition 8 *Assume that the efficient trade policy is always less than fully protective and suppose that for some* $\widehat{y} \geq 0$,

$$D_x(\widehat{y} + i(0)) + \delta[\max_{0\leq z\leq \widehat{y}+i(0)} f_x(z)] \max[c, \gamma(\overline{\tau})] < \gamma(0). \tag{8}$$

Then, then if $y_t \leq \widehat{y}$ it is optimal to impose no trade restriction and $\tau_t = 0$.

The economic interpretation of this is that preventive trade policy is inefficient if the marginal cost of the initial unit of prevention, $\gamma(0)$, exceeds the marginal damages associated with the maximum pest introduction plus the marginal cost of reducing the future pest infestation that results from an introduction by an amount equivalent to an upper bound on its growth. That is, trade restrictions are inefficient if it is less costly to incur the damages from an introduction and deal with the pest infestation in the future. All else equal, it is more likely that no trade restrictions are optimal when the pest infestation grows slowly, when the discount rate is high, or when the marginal costs of preventive trade are high.

In addressing alien species that threaten ecosystems, habitats or species the Convention on Biological Diversity argues that "prevention is generally far more cost-effective and environmentally desirable than measures taken following introduction and establishment of an invasive alien species" (CBD, 2002). Propositions 7 and 8 speak to the circumstances under which this prescription may not always be justified.

4 Conclusion.

Our analysis makes explicit the important roles played by the post-establishment growth rate for a pest or disease and its control cost in determining the optimal degree of SPS trade restrictions. Independent of the ecological and economic damage caused by a pests or disease, optimal trade policy does not need to be restrictive as long as the dynamic domestic cost of control in the post-establishment phase is small enough. Thus, international transfer of technology that makes domestic control of invasive pests and disease more efficient is likely to be reciprocated with reduction in SPS trade barriers. High trade restrictions are also unlikely to be worthwhile if the pests or diseases do not grow fast over time; the latter is likely to be the case when the existing established size of invasion in the economy is sufficiently small or, sufficiently large; this underscores the importance of understanding the state of the existing spread and size of established invasion within the country when deciding on measures to prevent future entry through trade. To the extent that the size of the established invasion size changes over time through a combination of new entry, endogenous domestic control and natural growth, the optimal level of SPS trade restrictions change over time.

5 Technical Appendix.

5.1 Subsidiary Lemmas.

Lemma 9 *Assume A.1-A.6. If* $\{x_t, y_t, a_t, \tau_t\}$ *is an optimal path and* $x_t \geq (\leq)\ x_{t-1}$*, then* $x_{t+1} \geq (\leq)\ x_t$*. Further, if* x_t *is optimal from* y_t *and* x'_t *is optimal from* y'_t *where* $y_t > y'_t$*, then* $x_t \geq x'_t$*.*

Proof. Suppose to the contrary that $x_t \geq x_{t-1}$ and $x_{t+1} < x_t$. From the principle of optimality $V(f(x_{t-1})) = F(f(x_{t-1}) - x_t) + D(x_t) + \delta V(f(x_t)) < F(f(x_{t-1}) - x_{t+1}) + D(x_{t+1}) + \delta V(f(x_{t+1}))$ and $V(f(x_t)) = F(f(x_t) - x_{t+1}) + D(x_{t+1}) + \delta V(f(x_{t+1})) \leq F(f(x_t) - x_t) + D(x_t) + \delta V(f(x_t))$. The first inequality is strict since otherwise x_{t+1} yields the same social cost from $f(x_{t-1})$ as x_t and $A.6$ implies that the home country always chooses the smallest infestation among those that are optimal. Adding the left and right hand sides together and rearranging yields $F(f(x_t) - x_{t+1}) - F(f(x_t) - x_t) < F(f(x_{t-1}) - x_{t+1}) - F(f(x_{t-1}) - x_t)$. Define $z = f(x_t) - x_{t+1}$, $z' = f(x_{t-1}) - x_{t+1}$ and $\varepsilon = x_t - x_{t+1} > 0$. This yields $F(z) - F(z - \varepsilon) < F(z') - F(z' - \varepsilon)$ which contradicts the convexity of F since $z > z'$. The mathematical intuition behind the proof is that F is convex so that $G(x_{t-1}, x_t) = F(f\,(x_{t-1}) - x_t)$ is a submodular function of x_{t-1} and x_t, while $D(x_t)$ and $V(f(x_t))$ are independent of x_{t-1}. Minimizing a submodular function yields a set of minimizers whose greatest lower bound is monotone (Topkis, 1978) so that, under $A.6$, the home country chooses an optimal transition function for x_t that is monotone. The second part of the Lemma follows using exactly the same arguments. To see this simply replace $f(x_{t-1})$ with y_t, $f(x_t)$ with y'_t, and x_{t+1} with x'_t. ■

In the presence of possible non-convexities and corner solutions the value function, V, may not be differentiable. Indeed, the one-sided derivatives of V may not exist. This necessitates the use of subderivatives to characterize the marginal optimality conditions. Since we are dealing with a one state variable problem it is convenient to use the Dini derivatives of V, which exist everywhere. Define the lower, right and left Dini derivatives of V at $y > 0$ by $D_+V(y) = \liminf_{\epsilon\to 0} \frac{V(y+\epsilon)-V(y)}{\epsilon}$ and $D_-V(y) = \liminf_{\epsilon\to 0} \frac{V(y)-V(y-\epsilon)}{\epsilon}$,and the upper, right and left Dini derivatives of V by $D^+V(y) = \limsup_{\epsilon\to 0} \frac{V(y+\epsilon)-V(y)}{\epsilon}$ and $D^-V(y) = \limsup_{\epsilon\to 0} \frac{V(y)-V(y-\epsilon)}{\epsilon}$. Note that the the Dini derivatives can assume the value $+\infty$. The following subsidiary Lemmas characterize the relationship between the Dini derivatives of V and the underlying elements of the model. These lemmas are used in the proofs of the main propositions.

Lemma 10 $D_+V(y) \leq D^+V(y) \leq c$.

Proof. Let (a, τ, x) be optimal from y. Then $(a + \varepsilon, \tau, x)$ is feasible from $y + \varepsilon$ for $\varepsilon > 0$. The principle of optimality implies $V(y + \varepsilon) - V(y) \leq c(a + \varepsilon) + W(\tau) + D(x) + \delta V(f(x)) - [ca + W(\tau) + D(x) + \delta V(f(x))]$. Dividing by $\varepsilon > 0$ and taking the lim sup on both sides completes the proof. ■

Lemma 11 $D_+V(y) \leq D^+V(y) \leq D_x(x) + \delta D^+V(f(x))f_x(x)$.

Proof. Let (a, τ, x) be optimal from y. Then $(a, \tau, x+\varepsilon)$ is feasible from $y+\varepsilon$. The principle of optimality implies $V(y+\varepsilon)-V(y) \leq ca+W(\tau)+D(x+\varepsilon)+\delta V(f(x+\varepsilon))-[ca + W(\tau) + D(x) + \delta V(f(x))]$.

Using the properties of the lim sup, $A4$, and the fact that D and f are differentiable, we have

$$\begin{aligned}
\limsup_{\varepsilon\downarrow 0}\frac{V(y+\varepsilon)-V(y)}{\varepsilon} &\leq \limsup_{\varepsilon\downarrow 0}\frac{D(x+\varepsilon)-D(x)}{\varepsilon} \\
&\quad +\delta\left(\frac{V(f(x+\varepsilon))-V(f(x))}{f(x+\varepsilon)-f(x)}\right)\left(\frac{f(x+\varepsilon)-f(x)}{\varepsilon}\right) \\
&\leq D_x(x)+\delta\left[\limsup_{\varepsilon\downarrow 0}\frac{V(f(x+\varepsilon))-V(f(x))}{f(x+\varepsilon)-f(x)}\right]f_x(x) \\
&= D_x(x)+\delta D^+V(f(x))f_x(x).
\end{aligned}$$

■

Lemma 12 *If $0<\tau\leq\overline{\tau}$ then $\gamma(\tau)\leq D_x(x)+\delta D^+V(f(x))f_x(x)$.*

Proof. First note that it is never optimal to set $\tau>\overline{\tau}$. Let (a,τ,x) be optimal from y. Then $(a,\tau-\varepsilon,x+i(\tau-\varepsilon)-i(\tau))$ is feasible from y for sufficiently small $\varepsilon>0$. By the principle of optimality $ca+W(\tau)+D(x)+\delta V(f(x))-[ca+W(\tau-\varepsilon)+D(x+i(\tau-\varepsilon)-i(\tau))+\delta V(f(x+i(\tau-\varepsilon)-i(\tau)))]\leq 0$. Using $A1(iii)$, $A4$, the differentiability of W,D and f, and the properties of the lim sup we obtain

$$\begin{aligned}
W_\tau(\tau) &= \limsup_{\varepsilon\downarrow 0}\frac{W(\tau)-W(\tau-\varepsilon)}{\varepsilon} \\
&\leq \limsup_{\varepsilon\downarrow 0}\left(\frac{D(x+i(\tau-\varepsilon)-i(\tau))-D(x)}{i(\tau-\varepsilon)-i(\tau)}\right)\left(\frac{i(\tau-\varepsilon)-i(\tau)}{\varepsilon}\right) \\
&\quad +\delta\left(\frac{V(f(x+i(\tau-\varepsilon)-i(\tau)))-V(f(x))}{f(x+i(\tau-\varepsilon)-i(\tau))-f(x)}\right)\left(\frac{f(x+i(\tau-\varepsilon)-i(\tau))-f(x)}{i(\tau-\varepsilon)-i(\tau)}\right)\left(\frac{i(\tau-\varepsilon)-i(\tau)}{\varepsilon}\right) \\
&\leq -D_x(x)i_\tau(\tau)-\delta\left[\limsup_{\varepsilon\downarrow 0}\frac{V(f(x+i(\tau-\varepsilon)-i(\tau)))-V(f(x))}{f(x+i(\tau-\varepsilon)-i(\tau))-f(x)}\right]f_x(x)i_\tau(\tau) \\
&= -\left[D_x(x)+\delta D^+V(f(x))f_x(x)\right]i_\tau(\tau).
\end{aligned}$$

Dividing through by $-i_\tau$ completes the proof. Note that this final step is possible because the variation is to the left of τ and $A1(iii)$ insures that $-i_\tau>0$. ■

Lemma 13 *If $y>0$ and $\tau>0$ then $D^-V(y)\geq D_-V(y)\geq\gamma(\tau)$.*

Proof. Define $\Upsilon(\xi) = i^{-1}(\xi)$ where $d\Upsilon/d\xi = 1/i_\tau$. Let (a, τ, x) be optimal from y and define $i = i(\tau)$. Since $\tau > 0$, $(a, \Upsilon(i + \varepsilon), x)$ is feasible from $y - \varepsilon$ for ε sufficiently small. The principle of optimality implies

$$\begin{aligned}
D_-V(y) &= \liminf_{\varepsilon\downarrow 0} \frac{V(y) - V(y-\varepsilon)}{\varepsilon} \\
&\geq \liminf_{\varepsilon\downarrow 0} \frac{ca + W(\Upsilon(i)) + D(x) + \delta V(f(x)) - [ca + W(\Upsilon(i+\varepsilon)) + D(x) + \delta V(f(x))]}{\varepsilon} \\
&= \liminf_{\varepsilon\downarrow 0} \left(\frac{W(\Upsilon(i)) - W(\Upsilon(i+\varepsilon))}{\Upsilon(i) - \Upsilon(i+\varepsilon)}\right)\left(\frac{\Upsilon(i) - \Upsilon(i+\varepsilon)}{\varepsilon}\right) \\
&= -W_\tau(\tau)/i_\tau(\tau) = \gamma(\tau).
\end{aligned}$$

■

Lemma 14 *If $\tau < \overline{\tau}$ then $D_+V(y) \leq D^+V(y) \leq \gamma(\tau)$.*

Proof. Let (a, τ, x) be optimal from y. Since $\tau < \overline{\tau}$, $(a, \Upsilon(i - \varepsilon), x)$ is feasible from $y + \varepsilon$ for ε sufficiently small. The proof then proceeds in a similar fashion to the proof of Lemma 13. ■

Lemma 15 *If $y > 0$ and $x > 0$ then $D^-V(y) \geq D_-V(y) \geq D_x(x) + \delta D_-V(f(x))f_x(x)$.*

Proof. Let (a, τ, x) be optimal from $y > 0$. Since $x > 0$, $(a, \tau, x - \varepsilon)$ is feasible from $y - \varepsilon$ for suffiently small $\varepsilon > 0$. The principle of optimality implies

$$\begin{aligned}
D_-V(y) &= \liminf_{\varepsilon\downarrow 0} \frac{V(y) - V(y-\varepsilon)}{\varepsilon} \\
&\geq \liminf_{\varepsilon\downarrow 0} \frac{ca + W(\tau) + D(x) + \delta V(f(x)) - [ca + W(\tau)) + D(x-\varepsilon) + \delta V(f(x-\varepsilon))]}{\varepsilon} \\
&= \liminf_{\varepsilon\downarrow 0} \frac{D(x) - D(x-\varepsilon)}{\varepsilon} + \delta\left(\frac{V(f(x)) - V(f(x-\varepsilon))}{f(x) - f(x-\varepsilon)}\right)\left(\frac{f(x) - f(x-\varepsilon)}{\varepsilon}\right) \\
&\geq D_x(x) + \delta D_-V(f(x))f_x(x),
\end{aligned}$$

where the last inequality follows using the properties of the lim inf and the fact that D and f are differentiable. ■

Lemma 16 *If $x > 0$ then $c \geq D_x(x) + \delta D_- V(f(x)) f_x(x)$.*

Proof. Let (a, τ, x) be optimal from y. Since $x > 0$, $(a + \varepsilon, \tau, x - \varepsilon)$ is feasible from y for sufficiently small $\varepsilon > 0$. The principle of optimality implies $ca + W(\tau) + D(x) + \delta V(f(x)) - [c(a + \varepsilon) + W(\tau) + D(x - \varepsilon) + \delta V(f(x - \varepsilon))] \leq 0$. Rearranging and dividing by ε yields

$$\liminf_{\varepsilon \downarrow 0} \frac{D(x) - D(x - \varepsilon)}{\varepsilon} + \delta \left(\frac{V(f(x)) - V(f(x - \varepsilon))}{f(x) - f(x - \varepsilon)} \right) \left(\frac{f(x) - f(x - \varepsilon)}{\varepsilon} \right) \leq c.$$

The result then follows using the properties of the lim inf and the fact that D and f are differentiable.

■

Lemma 17 *If $x > 0$ and $\tau < \overline{\tau}$ then $\gamma(\tau) \geq D_x(x) + \delta D_- V(f(x)) f_x(x)$.*

Proof. Let (a, τ, x) be optimal from y. Since $x > 0$, $(a, \tau + \varepsilon, x - (i(\tau) - i(\tau + \varepsilon)))$ is feasible from y for sufficiently small $\varepsilon > 0$. The principle of optimality implies $ca + W(\tau) + D(x) + \delta V(f(x)) - [ca + W(\tau + \varepsilon) + D(x - (i(\tau) - i(\tau + \varepsilon))) + \delta V(f(x - (i(\tau) - i(\tau + \varepsilon))))] \leq 0$. Rearranging and dividing by ε yields

$$\begin{aligned}
W_\tau(\tau) &= \liminf_{\varepsilon \downarrow 0} \frac{W(\tau + \varepsilon) - W(\tau)}{\varepsilon} \\
&\geq \liminf_{\varepsilon \downarrow 0} \left(\frac{D(x - (i(\tau) - i(\tau + \varepsilon))) - D(x)}{i(\tau) - i(\tau + \varepsilon)} \right) \left(\frac{i(\tau) - i(\tau + \varepsilon)}{\varepsilon} \right) \\
&\quad + \delta \left(\frac{V(f(x - (i(\tau) - i(\tau + \varepsilon)))) - V(f(x))}{f(x + (i(\tau) - i(\tau + \varepsilon))) - f(x)} \right) \left(\frac{f(x + (i(\tau) - i(\tau + \varepsilon))) - f(x)}{i(\tau) - i(\tau + \varepsilon)} \right) \left(\frac{i(\tau) - i(\tau + \varepsilon)}{\varepsilon} \right) \\
&\geq -D_x(x) i_\tau(\tau) - \delta D_- V(f(x)) f_x(x) i_\tau(\tau).
\end{aligned}$$

The last inequality comes from the properties of the lim inf, the fact that $\tau < \overline{\tau}$, and the differentiability of D, f and i. Dividing both sides by $-i_\tau$ completes the proof. ■

Lemma 18 *If $a > 0$ then $c \leq D_x(x) + \delta D^+V(f(x))f_x(x)$.*

Proof. Let (a, τ, x) be optimal from y and suppose that $a > 0$. Then $(a - \varepsilon, \tau, x + \varepsilon)$ is feasible from y for sufficiently small $\varepsilon > 0$. By the principle of optimality $ca + W(\tau) + D(x) + \delta V(f(x)) - [c(a - \varepsilon) + W(\tau) + D(x + \varepsilon) + \delta V(f(x + \varepsilon))] \leq 0$. This implies

$$\begin{aligned} c &\leq \limsup_{\varepsilon \downarrow 0} \frac{D(x+\varepsilon) - D(x)}{\varepsilon} + \delta \left(\frac{V(f(x+\varepsilon)) - V(f(x))}{f(x+\varepsilon) - f(x)} \right) \left(\frac{f(x+\varepsilon) - f(x)}{\varepsilon} \right) \\ &\leq D_x(x) + \delta D^+V(f(x))f_x(x), \end{aligned}$$

where the last inequality follows from the properties of the lim sup and the differentiability of D and f. ■

Lemma 19 *If $y > 0$ and $a > 0$ then $D^-V(y) \geq D_-V(y) \geq c$.*

Proof. Let (a, τ, x) be optimal from $y > 0$ and suppose that $a > 0$. Then $(a - \varepsilon, \tau, x)$ is feasible from $y - \varepsilon$ for sufficiently small $\varepsilon > 0$. By the principle of optimality

$$\begin{aligned} D_-V(y) &= \liminf_{\varepsilon \downarrow 0} \frac{V(y) - V(y - \varepsilon)}{\varepsilon} \\ &\geq \liminf_{\varepsilon \downarrow 0} \frac{ca + W(\tau) + D(x) + \delta V(f(x)) - [c(a - \varepsilon) + W(\tau) + D(x) + \delta V(f(x))]}{\varepsilon} \\ &= c. \end{aligned}$$

■

5.2 Proofs of Propositions.

Proof of Proposition 3. Assume $\tau_t > 0$. Lemma 11 implies that $D^+V(y_{t+1}) \leq D_x(x_{t+1}) + \delta D^+V(y_{t+2})f_x(x_{t+1})$. Shifting time forward and substituting for $D^+V(y_{t+2})$ on the right yields $D^+V(y_{t+1}) \leq D_x(x_{t+1}) + \delta D_x(x_{t+2})f_x(x_{t+1}) + \delta^2 D^+V(y_{t+3})f_x(x_{t+1})f_x(x_{t+2})$. Iterating forward and continuing to substitute for $D^+V(y_{t+i})$ in a similar fashion implies $D^+V(y_{t+1}) = D_x(x_{t+1}) + \sum_{i=1}^{\infty} \delta^i D_x(x_{t+i+1}) \prod_{j=1}^{i} f_x(x_{t+j})$. Since $\tau_t > 0$ Lemma 12 implies $\gamma(\tau) \leq D_x(x) + \delta D^+V(f(x))f_x(x)$. Substituting for $D^+V(f(x_t))$ on the right hand side of this expression gives the first inequality. The second inequality follows from Lemmas 10, 11 and 12 using similar arguments, where for each T, Lemma 10 is used to replace $D^+V(y_T)$ with c.

Next assume that $\overline{\tau} > \tau_{t+1}$ as well as $\tau_t > 0$. Then Lemmas 12 and 14 imply $\gamma(\tau_t) \leq D_x(x_t) + \delta f_x(x_t)\gamma(\tau_{t+1})$. Finally, in addition to the previous assumptions, if $\overline{\tau} > \tau_t$, $\tau_{t+1} > 0$ and $x_t > 0$ then Lemmas 13 and 17 imply $\gamma(\tau_t) \geq D_x(x_t) + \delta\gamma(\tau_{t+1})f_x(x_t)$. Combining this with the previous inequality completes the proof. ■

Proof of Proposition 5. Let (a, τ, x) be optimal from y. We first show that $D_x(y + i(0)) + \delta D_x(y+i(0))f_x(y+i(0)) \sum_{t=0}^{\infty}(\delta g(y+i(0)))^t > \gamma(0)$ implies $x < y+i(0)$. Suppose to the contrary that $x = y+i(0)$, which implies $a = \tau = 0$. Then $y_1 = f(y+i(0)) > y$. The second part of Lemma 9 then implies that $x_1 \geq x$. From the first part of Lemma 9 it then follows that $x_{t+1} \geq x_t \geq x = y+i(0) > 0$ for all t. Since $x > 0$, Lemma 17 implies $\gamma(0) \geq D_x(y + i(0)) + \delta D_-V(f(y + i(0)))f_x(y + i(0))$. Further, Lemma 15 implies that $D_-V(f(x_{t-1})) \geq D_x(x_t) + \delta D_-V(f(x_t))f_x(x_t) \geq D_x(y + i(0)) + \delta g(y + i(0))D_-V(f(x_t))$, for all t, where the last inequality follows from the convexity of D and the definition of $g(y)$. Iterating forward and substituting for $D_-V(f(x_t))$ in the last inequality one obtains $\gamma(0) \geq D_x(y + i(0)) + \delta D_x(y + i(0))f_x(y + i(0)) \sum_{t=0}^{\infty}(\delta g(y + i(0)))^t$, which violates the inequality in the statement of the proposition. Hence, it must be that $x < y+i(0)$, which can only occur if $\tau > 0$ (using Proposition 1 and $A7$). ■

Proof of Proposition 6. It follows from Proposition 1 that a necessary condition for trade policy to be fully protective is $c \geq \gamma(\overline{\tau})$. We show that if (x, a, τ) are optimal from y, then $\tau = \overline{\tau}$. Suppose to the contrary that $\tau < \overline{\tau}$. Then, $c \geq \gamma(\overline{\tau}) > \gamma(\tau)$ so that $a = 0$ by Proposition 1. Therefore, as in the proof of Porposition 5 $x_t \geq y+i(\tau) > 0$ for all t. Since $x > 0$, Lemma 17 implies $\gamma(\tau) \geq D_x(y+$

$i(\tau)) + \delta D_-V(f(y+i(\tau)))f_x(y+i(\tau)) \geq D_x(y) + \delta[\min_{y \leq z \leq y+i(0)} f_x(z)]D_-V(f(y+i(\tau)))$. Further Lemma 15 implies that $D_-V(f(x_{t-1})) \geq D_x(x_t) + \delta D_-V(f(x_t))f_x(x_t) \geq D_x(y) + \delta D_-V(f(x_t))g(y)$ for all t, where the last inequality follows from the convexity of D, the definition of $g(y)$, and the fact that $x_t > y$. Iterating forward, substituting for $D_-V(f(x_t))$ in the inequality above one obtains $\gamma(\overline{\tau}) > \gamma(\tau) \geq D_x(y) + \delta D_x(y)[\min_{y \leq z \leq y+i(0)} f_x(z)] \sum_{t=0}^{\infty} (\delta g(y))^t$, which violates (5). ■

Proof of Proposition 7. Part (a) follows directly from Proposition 1. For part (b),let (x, a, τ) be optimal from $y \leq \widehat{y}$ and suppose to the contrary that $\tau = \overline{\tau}$. Then, $x \leq y$. Since $\overline{\tau} > 0$, lemma 12 holds and $D_x(x) + \delta D^+V(f(x))f_x(x) \geq \gamma(\overline{\tau})$. By lemma 10, $c \geq D^+V(f(x))$. Then, using the convexity of D and the fact that $x \leq \widehat{y}$, these two inequalities imply $D_x(\widehat{y}) + \delta c\{\max_{0 \leq x \leq \widehat{y}} f_x(x)\} \geq D_x(x) + \delta c f_x(x) \geq \gamma(\overline{\tau})$, which contradicts (6). Next, suppose $\tau_t = \overline{\tau}$ and $\tau_{t+1} < \overline{\tau}$. Then Proposition 3 implies $\gamma(\overline{\tau}) \leq D_x(x) + \delta\gamma(\tau_{t+1})f_x(x) \leq D_x(x) + \delta\gamma(\overline{\tau})\{\max_{0 \leq x \leq \widehat{y}} f_x(x)\}$, which contradicts (7).

Proof of Proposition 8. Suppose to the contrary that $\tau_t > 0$. Then Proposition 3 implies $\gamma(0) \leq \gamma(\tau_t) \leq D_x(x) + \delta\gamma(\tau_{t+1})f_x(x) \leq D_x(\widehat{y} + i(0)) + \delta[\max_{0 \leq z \leq \widehat{y}+i(0)} f_x(z)] \max[c, \gamma(\overline{\tau})]$. This contradicts (8). ■

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