Policy and Risk Processes of Trade-Related Biological Invasions

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Abstract

This report summarizes the methodologies, results and empirical insights of ERS-funded research on trade-related nonindigenous species (NIS) introduction risk. Costello and McAusland (2004) is the first attempt in the economics literature to establish theoretical relationships between trade, trade policy (in the form of tariffs), and NIS-related damage, accounting for the dependence of land-use decisions on tariff rates. McAusland and Costello (2004), extending the policy choice set, characterize the optimal mix of tariffs and inspections and show how the balance depends on trading partner attributes, such as the infection rate of shipments and the marginal NIS damage level. The theory of trade-driven introductions is extended in Costello et al. (2007), where novel trade and NIS discovery data sets are used to gain an empirical understanding of dynamic invasion risk. Results support the hypothesis that cumulative introductions from some regions are a concave function of cumulative trade. Overall, this collection of research on trade-related NIS introductions highlights the welfare and biological implications of both broad and differentiated policy instruments, and the challenge of empirically supporting the latter.

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Table of Contents

List of Figures and Tables

Figures:

Tables:

Introduction

Economists have only begun to address trade-related nonindigenous species (NIS) risk and policy response in recent years. The purpose of this research report is to summarize the results of our ERS funded research through the PREISM program. “Controlling Exotic Species Introductions: Trade Related Policies and Exposure” focused on trade policy for reducing NIS introductions and subsequent damage. This is distinct from, but complementary to, a significantly larger literature on post-introduction NIS policy. Mathematical and computational details of the funded research can be found in three published manuscripts:

1. Costello, C. and C. McAusland. “Protectionism, Trade and Measures of Damage from Exotic Species Introductions,” *American Journal of Agricultural Economics*, 85(4), 964-975, 2004.

2. McAusland, C. and C. Costello. “Avoiding Invasives: Trade Related Policies for Controlling Unintentional Exotic Species Introductions.” *Journal of Environmental Economics and Management*, 48, 954-977, 2004.

3. Costello, C., M. Springborn, C. McAusland, and A. Solow. “Unintended Biological Invasions: Does Risk Vary by Trading Partner?” *Journal of Environmental Economics and Management*, 54(3), 262-276, 2007.

The first publication was in progress when the grant was awarded and sets the stage for more detailed policy analysis (McAusland and Costello, 2004) and empirical analysis (Costello et al. 2007).

Costello and McAusland (2003) and McAusland and Costello (2004) are two of the first attempts to explore the implications of bringing trade policy to bear on the NIS introduction problem. Extending the theory of the process of trade-driven introductions, in Costello et al. (2007), we utilize novel trade and NIS discovery data sets to gain an empirical understanding of dynamic invasion risk. Below we will summarize the methodologies and key results of these contributions, communicating the essential theoretical and empirical insights. An organizing principle throughout is that the risk of unintentional, trade-related NIS introductions is an externality, or an unpriced cost of economic activity, to be estimated empirically and mitigated through policy design.

One of the simplest ways to address an externality associated with economic activity, such as NIS introduction risk, is to impose a tariff on imports equal to the expected damage. However, this simple approach is complicated by multisector and multicountry commodities trade as well as NIS introduction and growth processes. Costello and McAusland (2003) is the first attempt in the economics literature to establish theoretical relationships between trade, trade policy (in the form of tariffs), and invasives-related damage, accounting for the dependence of land-use decisions on tariff rates. Intuitively, then, while higher tariffs impose costs on an economy, they should reduce trade flows and thus, reduce NIS introductions and damage. But under what conditions could higher tariffs lead to more NIS damage? A simple trade model is combined with a model of stochastic NIS introductions to demonstrate that, for certain trading partner attributes, an increase in the tariff can increase certain types of damage. Trade theory illuminates the mechanism of this surprising result--changes in the mix of agricultural and manufacturing output alter a country's vulnerability to invasion damage. The model is also used to demonstrate that, while crop damage estimates may be the most readily available measure of invasion damage, ignoring or discounting ecological damages could lead analysts to mispredict whether damage will rise or fall as a result of a particular trade policy alternative.

Of course a tariff is not the only pre-invasion policy instrument available – port inspections have been widely used for years to weed out infected shipments. One might expect the optimal tariff to depend on inspections intensity, and vice versa. To what degree are inspections and tariffs complementary or substitutable? McAusland and Costello (2004) characterize the optimal mix of tariffs and inspections, including how the balance depends on trading partner attributes, such as the infection rate of shipments and marginal NIS damage level. A key result is that there exists a rate of infection beyond which the optimal level of inspections declines to zero, ultimately leaving a tariff as the sole relevant instrument. Several extensions to the model are examined: multiple trading partners, allowing for the exporter to exert costly control over infectiousness of their goods, incorporating growth dynamics of the NIS population and, finally, the use of discriminating, infection rate contingent policies at the firm level.

Taxes designed to internalize externalities and discriminatory policies, in particular, motivate the empirical task of identifying the expected marginal damage (from NIS) of a unit of imports and determining whether it varies significantly by trading partner. The marginal damage depends on estimating two components – the marginal invasion rate and the marginal cost of the next invader. We tackle the former question in Costello et al. (2007) by extending a semi-structural model of trade-driven NIS introductions. Parameters of the model are estimated in an empirical application of global trade imported into the San Francisco Bay, using over a century of import and NIS discovery data differentiated by the source region.

Results support the hypothesis that cumulative introductions are a concave function of cumulative trade (i.e. the marginal invasion rate per unit of trade declines over cumulative trade). However, after controlling for trade levels, there exists a countervailing time trend effect. Nontrade intertemporal factors, such as advances in shipping technology or the vulnerability of the ecosystem to invasion, inflate the invasion rate over time. As a result, the overall NIS risk is attenuating for some regions, but not all. Combining the parameter estimates with trade forecasts shows that achieving invasion reductions through simple trade volume restrictions is not likely to pass a rigorous cost-benefit test. While the focus here is on aquatic invaders, enabling us to link a specific pool of NIS to a specific trade pathway, the general intuition and methodology is transferable to the broader body of trade-related invasions.

The remainder of this manuscript summarizes the key questions, methods, and findings of each of these published papers. Our focus is on gleaning policy relevant conclusions from this body of work related to the design of economic instruments for managing nonindigenous species introduction and damage. Because of its empirical focus (deriving and implementing a new empirical test), we devote more than proportional space to describing the third contribution.

Protectionism, Trade, and Measures of Damage from Exotic Species Introductions

In what cases can import tariffs, imposed to control damage from NIS, backfire such that damage actually increases? When does freer trade (reduced tariffs) actually lead to less NIS damage? Costello and McAusland (2003) integrates a two-sector model of trade with a model of unintentional, stochastic NIS introductions to generate theoretical insight into these questions. While protective tariffs are one of the most basic trade policy tools available, they have important domestic price distortion effects that can sometimes lead to unintended policy outcomes. To develop basic insight, the model is constructed as simply as possible with extensions discussed afterward.

The purpose of the model of NIS introductions is to specify how changes in the rate of shipping affect the rate of introduction and total damage. Adopting a common model for stochastic arrivals, the waiting time between introductions is a random variable assumed to be exponentially distributed. The mean waiting time is then assumed to be a decreasing function of the rate of imports. Thus, as imports increase, the mean waiting time between introductions falls and the expected number of introductions increases. The two trading countries in the model are referred to as "Home" and "Foreign". Home is a small open economy, which means that its actions do not affect world commodity prices. Production of both manufactures and agricultural goods exhibits constant returns to scale. Finally, we assume that, when the (tariff inclusive) price of a commodity goes up, consumption decreases and production increases. The first proposition then is not surprising: starting from an initial tariff of zero, increasing the tariff rate (decreases the volume of imports which) decreases the rate of successful exotic species introductions to home.

What is the effect of increasing the tariff rate on risk and ultimate damage from NIS introductions? To address this question, we first assume that there is a fixed probability that an introduction leads to successful establishment. Then there may be **K** different types of damage from an established NIS, including, but not limited to, damage to native habitats and crops. The distribution of any damage type depends on the amount of agricultural production in Home (e.g. for a given population of NIS, crop damage will increase in agricultural production). Total damage from an introduction is the sum of the expected present discounted value of all **K** types of damage.

The change in expected type-**k** damage due to a change in the tariff depends crucially on: (1) the elasticity of the introduction rate with respect to imports – which we know is positive; (2) the elasticity of production with respect to prices – which we know is positive; and (3) the elasticity of expected type-**k** damage to the level of agricultural production. The third term is where the interesting action lies, determining whether the sign of the net change is positive or negative. For some types of damage, such as to crops, the economic toll of an introduction will be increasing in the amount of agricultural production – these are termed "Augmented" damages. "Diminished" damages are those which are decreasing in the amount of agricultural production. "Neutral" damage levels are insensitive to agricultural production. Table 1 summarizes the sign of the change in expected type-**k** damage due to a tariff increase, which depends on the category of the damage and whether Home is an importer or exporter of agricultural goods.

Table 1--Summary of the sign of the change in damage of each type due to a tariff increase

	Categories of damage		
	Augmented	Neutral	Diminished
Importer of agricultural goods	ambiguous	--	--
Exporter of agricultural goods	--	--	ambiguous

Note: Sign of the change in expected type-**k** damage through some finite future time in Home due to an increase in the tariff for different categories of damage differentiated by the dependence on the level of agricultural production.

In most cases, the increased tariff acts as expected: it suppresses damage. However, there are two cases in which the sign of the change in damage from a tariff increase is ambiguous and depends on further conditions. The first such case is when Home imports agricultural goods and damages are "augmented" (e.g. crop weeds); the second case is when Home imports manufactures and damages are "diminished."

When Home imports agricultural goods, a tariff induces greater agricultural production. This means there are more crops, for example, available for damage from NIS, and so expected "augmented" damages per introduced exotic rise. In short, agricultural protectionism increases the expected "augmented" damage per introduced exotic. As noted above, protectionism of any type reduces the platform for invasions, hence the ambiguity. Which effect dominates depends on the relative sensitivity of import demand and production, which in turn depend on domestic demand and supply elasticities. Because demand for agricultural goods is relatively price inelastic in high-income countries, the augmented damages response is more likely to dominate the platform response in higher-income countries. Similarly, the platform response is likely to be small when domestic agricultural output is price elastic, as in countries with nonrestrictive planting and land use policies.

Examples of "diminished" type damages are less common, but not implausible. Consider the following. In many countries, agriculture expansion occurs through the extensive margin, i.e. clearing previously untouched land. A tariff on manufacturing output will draw capital and labor out of agriculture, thereby reducing the rate of habitat loss. This means that some species that would have been driven to extinction via agriculture-driven habitat loss may instead survive as a result of protectionism, only to be threatened by NIS competition. When NIS damages are measured according to their threat to endangered species, then a tariff on manufacturing imports could potentially lead to increased estimates of ecological damage, even if the overall introduction rate falls. Admittedly this is a perverse example: a tariff on manufactures raises NIS damage only because protectionism keeps alive a susceptible species in the first place. Again, whether the damage response dominates the platform response to a tariff depends on production and demand elasticities, and is more likely when agricultural demand is price inelastic as in high-income countries.

The tension in the effects above stem from the idea that crop (augmented) and ecological (diminished) damage may move in opposite directions due to changes in trade policy (tariff). Because crop damage is more easily quantified, it typically serves as an indicator of the severity of the NIS problem. However, given the argument above, crop damage alone is a poor proxy since, in isolation, it may mispredict the sign of the change in damage from a particular policy.

Several factors left out of the stylized model above are interesting points of discussion and motivate the next two papers, McAusland and Costello (2004) and Costello et al. (2007), in this synthesis. Excluded is the possibility that farmers might exhibit averting behavior such as observed in the United States when land was switched from wheat to corn in response to the Russian Wheat Aphid. If farmers faced undistorted (world) prices, such a strategy would reduce the magnitude, but not the sign of crop damages. However, if there are pre-existing price distortions, such as water subsidies encouraging water-intensive crops, the effect would depend on the particular distortion. Also set aside here is the possibility that the invasion rate might be sensitive to the cumulative invasion history. If introductions fill an ecological niche, then subsequent invaders are redundant and the introduction rate may taper off over time. Conversely, introductions may be complementary, augmenting the introduction rate over time. Which effect is observed is an empirical question which will be considered in Costello et al. (2007). Deriving theoretical results under this extension to the current model makes it intractable. However, intuitive argument suggests that, while the size of some effects might shift, the qualitative results would still stand.

A final observation is that in addition to tariffs, there are multiple policy instruments for either invasion prevention or post-introduction management. Management options include eradication and control of NIS populations. Control can be easily incorporated into the model by modifying the interpretation of the damage random variable to include control costs. If eradication is an option, then the damage would be incurred repeatedly each time a NIS is reintroduced. A common second instrument for prevention is border monitoring or inspection of imported goods. Because monitoring policies interact with tariffs in complex ways, identifying the optimal mixture is the subject of the paper discussed next.

Avoiding Invasives: Trade Related Policies for Controlling Unintentional Exotic Species Introduction

What is the optimal mix of tariffs and inspection intensity which balances minimizing NIS damage with maximizing consumer surplus from imported goods? Under what circumstance does optimal inspection intensity fall as the infectiousness of the goods increases? When faced with multiple trading partners, can these NIS prevention policies be designed to select the best partner in terms of maximizing the net benefits of trade? In McAusland and Costello (2004), we use a simplified model of contaminated goods trade to explore questions of complementarity and substitutability of invasion prevention instruments.

To begin, Home imports goods from a single trading partner, Foreign. A fixed proportion (**q**) of shipments is infected with an NIS which causes a known and constant level of damage (**d**) per infected shipment accepted for consumption. Nonessential dynamics of trade policy are set aside for simplicity. Thus, perfect competition in Foreign's export sector means there are no Foreign rents for Home to worry about extracting. The marginal cost of export production (**c**) is fixed. Home demand is assumed to be decreasing in the price of goods, which is simply equal to the marginal cost of production plus the tariff divided by the proportion of goods accepted (which maintains zero rents for Foreign firms).

Home's objective is to select inspections intensity (**I**) and tariff rate (**T**) to maximize social welfare in Home, which is a combination of consumer surplus from trade, tariff revenue, inspections cost, and NIS damage. Inspection effort translates into selecting the fraction of infected goods that are intercepted. It is assumed that shipments found to be infested with an NIS are simply discarded or destroyed. Inspection effort incurs a constant marginal cost. Each marginal increase in the fraction of interceptions requires a greater amount of effort (i.e. the fraction intercepted is increasing and concave in **I**).

In addition to costly inspections effort, there is another important opportunity cost associated with inspections. Discarded shipments cannot be consumed, reducing consumer surplus. Additionally, since the quantity of imports demanded in Home is downward sloping in the supply, constricting the supply (through interceptions) causes the price to rise and surplus to fall on inframarginal imports.

Let **I*** and **T*** represent the optimal levels for the policy instruments (port inspections and import tariff), which will depend on the three attributes of Foreign: **q, d**, and **c** (infection rate, marginal damage, and marginal production cost). Given some level of **I,** the optimal tariff (**T***) equals the expected marginal damage from nonintercepted infestations plus the marginal cost of inspecting a shipment. A closed form expression for **I*** is not available, but an analysis of the response of optimal policies to changes in the parameters (comparative statics) highlights a rich environment of instrument tradeoffs.

Table 2 summarizes the results of McAusland and Costello (2004) which appear in Propositions 2-5 in the paper. Many of these are straightforward, intuitive and will not be discussed in depth: **I*** tends to increase in **d** and **T*** tends to increase in **q**. Two results of particular interest are underlined in the table. First, it turns out that the optimal monitoring intensity is, after a point, decreasing in the infection rate until at some limit no monitoring is desired. It is straightforward to see why optimal monitoring is eventually zero as the infection rate increases. If we suppose all shipments are infested (**q** = 1), then monitoring adds no value. The tariff is set equal to the marginal damage and all goods are accepted or the marginal damage is so high that the tariff chokes off all demand and no imports are received.

More generally, the single-peaked, concave shape of **I*(q)** stems from the way in which the benefit and opportunity costs of I respond to the level of **q**. As the infection rate rises, benefits (averted damages) from a given level of monitoring increase. However, increasing **q** elevates the opportunity cost of lost consumer surplus – interceptions constrict supply which drives the price up and consumer surplus down. Eventually, the latter effect dominates and **I*** falls.

Table 2--Summary of results from McAusland and Costello (2004)

	Attributes of Foreign		
Home's policy or welfare	Infection rate, **q**	Per unit damage, **d**	Marginal production cost, **c**
Import goods monitoring intensity, **I**	Inspect the most for intermediate levels of **q**. Inspect zero for sufficiently high **q**.[2]	Larger **d** lead to more inspections. An increase in **d** expands the range of **q** over which **I*** is positive[4]	Larger **c** leads to more inspections. An increase in **c** expands the range of **q** over which **I*** is positive[5]
Home's import tariff, **T**	**T*** tends to increase in **q**[3]	**T*** may be increasing or decreasing in **d**[4]	**T*** is (weakly) increasing in **c**[5]
Home's welfare, **W**	**W** declines with an increase in each Foreign attribute **q**, **d**, and **c**		

Notes: Policy and welfare implications for a single importer (Home) over changes in the attributes of the single exporter (Foreign). A star indicates the policy level is optimized. Superscript numbers indicate the corresponding proposition number from McAusland and Costello (2004).

The second key result from the single-trading partner model is that there are nontrivial situations in which the optimal tariff should decrease as the level of damage increases. Two main drivers for this result are a compensating increase in monitoring and an incentive to boost trade. The results in Table 2 demonstrate that when damage rises, so does the optimal level of monitoring. Interceptions increase and consumer surplus takes a hit from lower consumption. Under a range of nontrivial parameterizations, the optimal tariff falls as **d** increases to boost imports – while elevated trade provides a broader platform for invasions, there is a net welfare gain from augmented consumer surplus.

The above results have direct implications for how multiple trade partners serving unconnected Home markets should be treated. But what about when Home faces multiple trade partners meaning to supply the same market, but have differing cost and NIS risk parameters? Can Home set country specific trading policy such that trade occurs with the partner offering the largest welfare gain from trade? The answer is yes. Setting **T*** and **I*** for each partner according to the same optimality conditions for the single trading partner case leads to the automatic exclusion of all suboptimal trading partners. The optimal trading partner turns out to be the one for which the market price is (inclusive of policy effects) lowest. Other potential suppliers drop out because profits are negative at this market price. Note that the optimal partner is not necessarily the one with the best NIS risk profile. The tradeoff between introduction risk and consumer surplus is again at play, providing situations in which elevated risk is compensated for by a lower consumer price. In reality, we know that trading policy is constrained, in part, by institutional relationships such as membership in the World Trade Organization. If Home is only allowed to discriminate with its tariff, then it can still select its optimal trading partner. However, if only the monitoring intensity is partner specific, it must choose either a suboptimal trading partner or suboptimal instrument levels.

Model Extensions

So far the behavior of foreign firms and NIS population biology have been set aside for simplicity. Realistically, foreign firms can be expected to observe and then react to policy set by Home. Suppose foreign firms have the opportunity to exert costly control over the infectiousness (**q**) of their goods. Under what conditions will policy maximize the joint welfare of both importers and exporters? It turns out that the crucial element is whether or not Home is able to set **q-**contingent policies at the firm level.

If Home sets industry-wide levels of **T** and **I**, precleaning is too low and instrument levels are too high, regardless of whether the instrument levels are set before or after foreign firms produce the goods for export. Under industry-wide policy, individual firms are not compensated (via lower **T** and **I**) for costly reductions in the infectiousness of their goods. Instead, firms set precleaning based only on concerns of getting enough of their exports through inspections. Recognizing that this will occur, Home chooses a high monitoring intensity and a tariff above the standard level. However, if instead Home offers q-contingent policies at the firm level, foreign firms internalize the benefits to Home of reduced infectiousness. Because precleaning now occurs at the joint-welfare maximizing level, Home no longer needs to manipulate **T** and **I**, which are now set to the same effect.

In addition to the dynamics of firm and Home decisions, growth of a NIS population is another potentially important temporal element. The model is extended to allow for an initial population of the invading species, which is taken as given. Additional successful invaders are added in the first period and damage accrues from the combined total. Between the first and second periods, growth in the population occurs and damage is once again realized from the augmented total. This dynamic problem is equivalent to the static problem with an additional nonlinear damage term. Because this effectively scales up the damage term **d,** results mimic those of the basic model under an increase in the parameter **d**: while **I*** becomes unambiguously more stringent, **T*** may rise or fall depending on parameter values.

The model extensions discussed above highlight important empirical questions. If **q-**contingent policies maximize joint-welfare, how can **q** be estimated? Costello and McAusland (2003) discuss the possibility that **q** is not constant over time. Economic theory and biology suggest competing reasons why **q** might be getting worse or better. What are the observable trends in **q** and are there differences between trading regions? These concerns motivate the final work in this synthesis.

Unintended Biological Invasions: Does Risk Vary by Trading Partner?

The introduction rate of NIS per unit of imported goods is expected to vary between partners for two important reasons. First, the number of organisms that can potentially be introduced will vary with source region. In part, this simply reflects differences between source regions in the size of the species pool. However, it also reflects differences in the probability that a species introduction will be successful. This latter probability will depend, in part, on the environmental similarity between the source region and the destination. Second, as cumulative shipping traffic from a given source increases over time, introductions will occur, the remaining pool of introducible species will be depleted, and the rate of new introductions will decline. In short, invasion risk will likely decrease in cumulative import volume and vary according to the region from which imported goods originate. Whether this theoretical prediction is borne out in reality is an empirical question of central importance for the design of pre-invasion policy for NIS.

A major challenge in empirically estimating the link between trade and NIS introductions is identifying a specific pool of NIS resulting from a particular time series of trade. While all unintentional, trade-related NIS introductions in the United States could be tied to the whole of U.S. import history, broad brush insights from this exercise would be unable to pick up nuances such as changes in introduction dynamics over the cumulative trade history with a particular region. Because NIS risk to agriculture is a key policy concern, a desirable focus would be the link between trade and terrestrial pests. However, due to the post-introduction ability of such invaders to spread both naturally and via ground transportation, the direct link to the port of entry and the relevant trade pathway is lost.

Biological invaders into the San Francisco Bay provide a much cleaner link between trade and NIS introductions and are particularly amenable to this region specific empirical analysis. Because these aquatic NIS are unlikely to spread over large distances on land, the links between introductions and economic activity are less noisy. Additionally, due to the work of biologists (Cohen and Carlton, 1995) useful information on the method of introduction, the year of discovery, and the source region of each invading species is available for the San Francisco Bay and estuary. An issue with replicating this methodology is that the forensic work may not be available with which to link trade with species introductions. In Costello et al. (2007), we take advantage of this discovery record of NIS (as established in the environment) in conjunction with newly compiled shipping data to estimate the marginal introduction rates for different source regions. The import data set is assembled from four different published sources, each based on United States Department of Commerce, Bureau of the Census records. For a detailed description of trade data sources, see Costello et al. (2007), Appendix A.

We develop a semistructural model of introductions, which takes into consideration the role played by cumulative import volumes and biogeography of an importer's trade partners. A key empirical and methodological challenge is disentangling NIS introductions and discoveries of those introductions. As Costello and Solow (2003) argue, the discovery record is a poor proxy for actual introductions because it reflects a combination of both the introduction and discovery process. While the former depends on trade patterns, the latter depends on a variety of endogenous factors, not least of which is effort allocated to detecting established NIS in the host region.

We model the number of NIS introductions per unit of imports in a given year as a Poisson random variable. The mean of this distribution, equivalent to the expected marginal introduction rate (MIR), is composed of a baseline introduction rate (**b**) which may attenuate or grow over either cumulative imports (at rate **g** per million tons) and time (at rate **w** per year). We assume that once a NIS arrives, there is a constant annual discovery probability (**p**) – thus the post-introduction waiting time to discovery is geometrically distributed. Maximum likelihood estimation is used to establish the parameters of the model based on import and NIS discovery records from 1856 through 1994, all by region of origin.

Over the 142-year period of study, 232 NIS were discovered in San Francisco harbor, for an average of 1.6 discoveries per year. Of these 232 species, 78 are thought to have arrived by some vector other than ocean vessel and are excluded from our analysis. This includes intentional or accidental release by individuals and government agencies. The remaining NIS are characterized as having arrived “possibly by ocean vessel” (in ballast water or in a ship’s seawater system, in solid ballast, in ship fouling or boring, and unknown).

Ideally, we would estimate the trade-introduction relationship between an ecologically distinct source and host. However, because of limitations in specifying the home territory of each NIS, we aggregate records over seven global regions. Unfortunately, we will lose some additional observations in this process. Table 3 presents the number of NIS discoveries and cumulative imports by region of origin. Of the 154 species believed to have entered San Francisco Bay via shipping traffic,

Table 3--NIS discoveries and cumulative imports by region

Region		NIS	Cumulative Imports (to 1994) (Million tons)
Atlantic/Mediterranean	(ATM)	74	62
West Pacific	(WPC)	43	202
Indian Ocean	(ION)	3	75
Southeast Atlantic	(SEA)	1	2
Southeast Pacific	(SEP)	1	10
Northeast Pacific	(NEP)	0	77
Southwest Atlantic	(SWA)	0	5
Unknown	(UNK)	32	2

Note: NIS data are summarized from Cohen and Carlton (1995). Import data is assembled from United States Department of Commerce records.

27 have unknown native regions, and 5 lack a description of origin of appropriate precision to assign to a single region. Thus, in our disaggregated pool, we exclude these 32 additional species, leaving 122 species upon which to conduct our region-by-region analysis.

In Figure 1 we plot cumulative discoveries against time; discovered NIS that were not introduced by vessel are included for comparison. Diagrams such as Figure 1 have led many researchers to conclude that NIS introductions are increasing at an increasing rate. This conclusion may be oversimplified because the platform for introductions (trade) is ignored and the data reflect discoveries, not introductions. If we instead plot discoveries versus cumulative imports --see Figure 2 --we see that the relationship between shipping volume and new discoveries is not necessarily convex. These simple two-dimensional plots conflate the effects of cumulative shipping and time.

Figure 1--Cumulative NIS discoveries in San Francisco Bay over time and by vector for ocean vessel and other

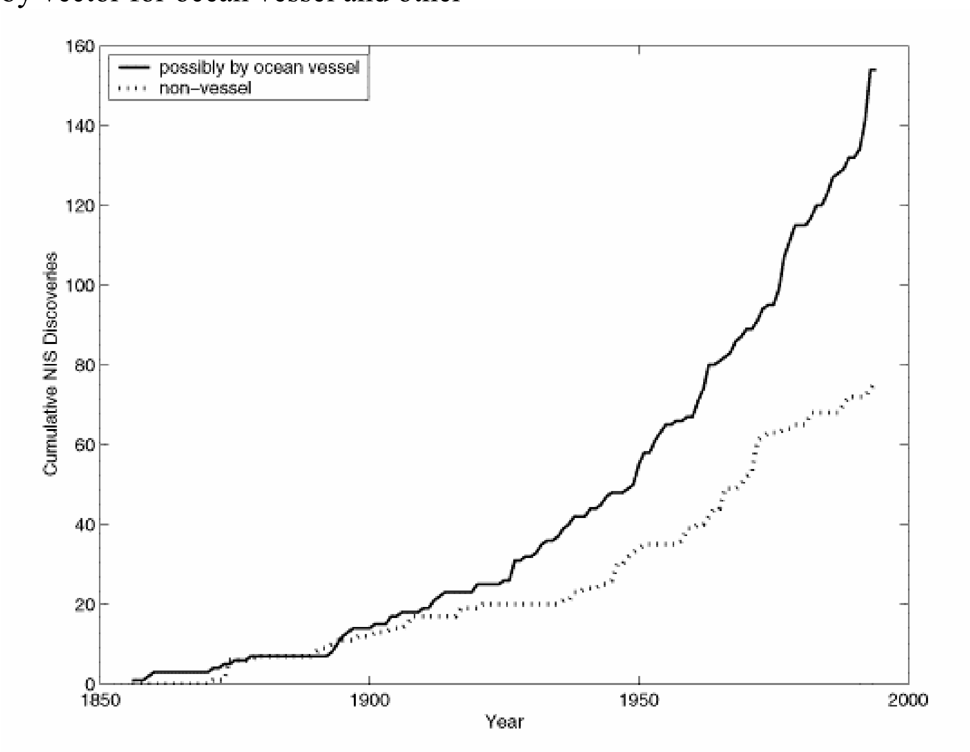
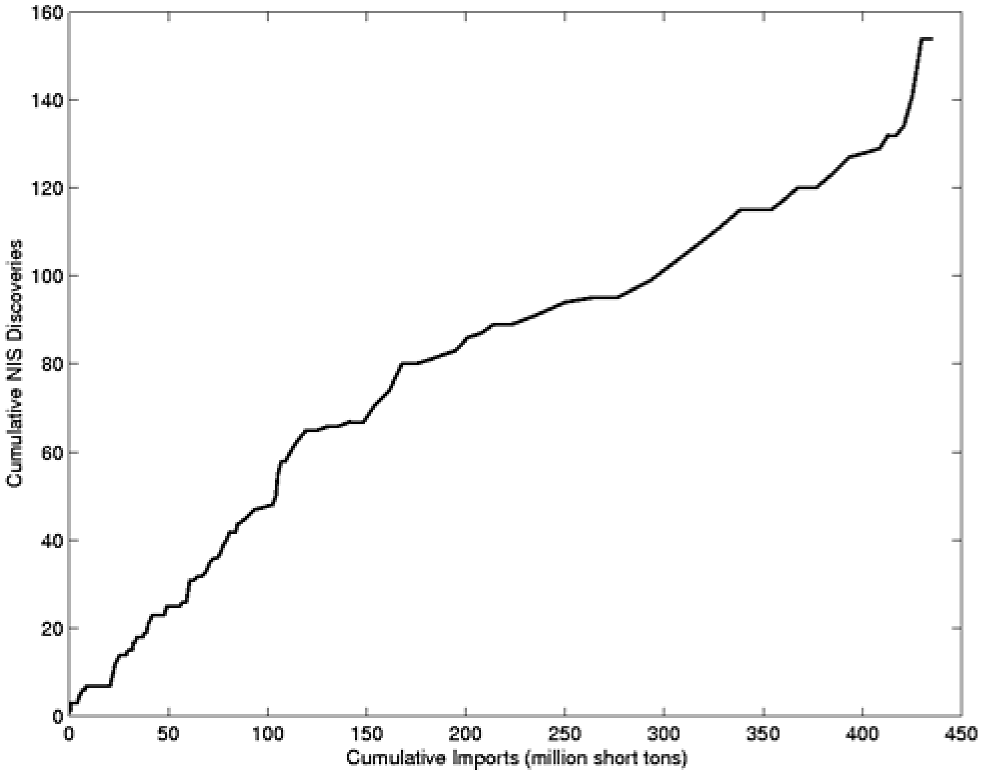


Figure 2—Cumulative NIS discoveries versus cumulative imports



Given our conceptual model, we estimate a separate b_i (baseline invasion rate) and g_i (attenuation over shipping history) for each region i, but assume that time-based attenuation (w) and discovery probability (p) parameters are shared. We limit the analysis here to the three regions, Atlantic/Mediterranean (ATM), West Pacific (WPC), and Indian Ocean (ION), with more than one NIS discovery between 1856 and 1994. Although only three NIS have been discovered from ION, the zeros in the data (i.e. years with no discoveries) contain significant information upon which to draw inference.

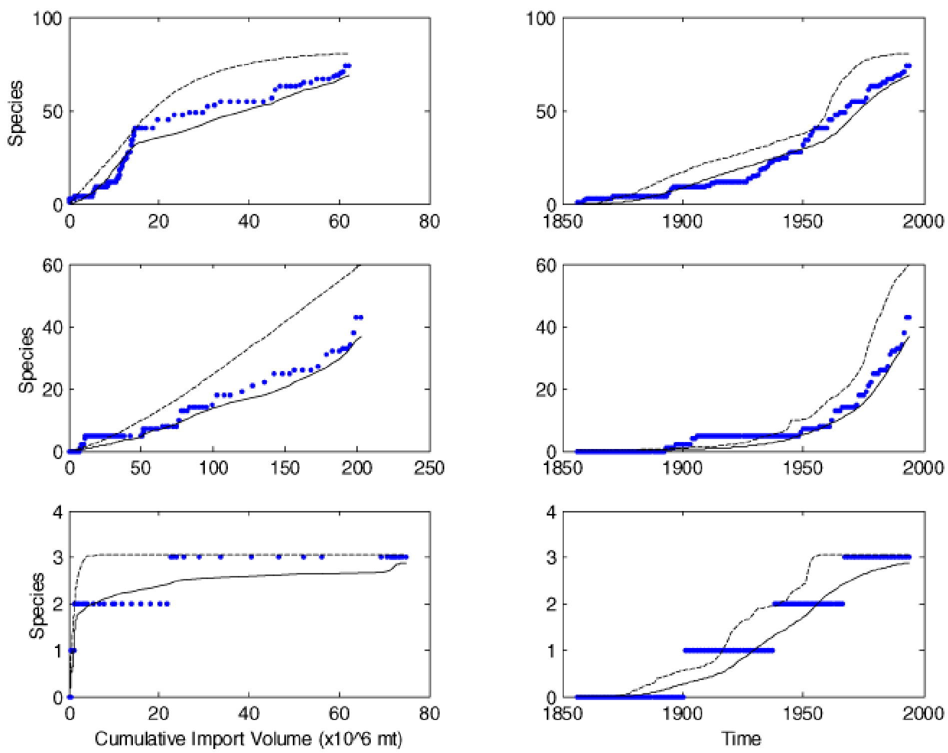
Our estimate of the discovery parameter is $\hat{p} = 0.048$, implying a median introduction-to-discovery lag of about 13 years (calculated as the median of a geometric random variable) and that 90 percent of species are discovered between 1 and 60 years after introduction. The introduction process parameter estimates are given in Table 4. From the perspective of NIS introductions, an important characteristic of a trade partner is its inherent capacity to supply NIS to San Francisco. At the beginning of a trade relationship, how infectious is trade from ATM, for example? Since the estimate of b_{ATM}, the baseline MIR_{ATM} in 1856, is 2.3, we would expect an average of 2.3 introductions in the first million tons of trade from ATM. Using the likelihood ratio test, we reject the hypothesis that $\hat{b}_{ATM} = \hat{b}_{WPC}$, but fail to reject that $\hat{b}_{ION}$ is equal to either at the 10 percent level. Considering only estimates of b, it is tempting to think that ATM is the most risky trade partner, followed closely by ION, and that WPC is a nearly riskless trade partner. That intuition would only be correct in the absence of attenuation of NIS introductions. In other words, that interpretation would only have been correct at the beginning of the shipping history, in the mid-1850s. Intuitively, we would expect that the more trade "experience" a country has with its partner, the less likely it is that new species will be introduced (and so **g** < 0). We estimate that MIR_{ATM} attenuates over cumulative shipping from ATM at rate of 8 percent ($\hat{g}_{ATM}$ =-0.08). Our estimate of $\boldsymbol{g}_{WPC}$ is the only parameter estimate not significant at the 10 percent level. Below we will discuss the implications of this lack of attenuation for WPC for its contemporary and future MIR.

Table 4--Parameter estimates for the import-introduction-discovery model from Costello et al. (2007).

Region		$\hat{b}$	$\hat{g}$	$\hat{w}$
Atlantic/Mediterranean	(ATM)	2.3 (1.3, 4.0)	-0.08 (-0.15,-0.04)	
West Pacific	(WPC)	0.07 (0.02, 0.21)	-0.002 (-0.01,0.006)	0.015 (0.001,0.03)
Indian Ocean	(ION)	1.3 (0.1, 7.5)	-1.06 (-3.45,-0.18)	

Notes: Unrestricted estimates of the base rate of introduction (**b**) and attenuation (**g** and **w**) parameters. The time parameter **w** is common to all regions. Likelihood ratio 90 percent confidence intervals are in parentheses.

Figure 3--Cumulative discoveries (dots), fitted discoveries (solid), and fitted introductions (dashed) over the period 1856 to 1994. Top row is for ATM, middle row is for WPC, and bottom row is for ION.



Aside from shipping, how do other dynamic ecological and technical factors impact the introduction risk? Given improvements in shipping speed we might expect **w** > 0. The same sign could also be driven by increasing vulnerability of the ecosystem over time from environmental stress. Our point estimate is $\hat{w} = 0.015$, which corresponds to a time rate of increase in invasions of 1.5 percent, *ceteris paribus*. This finding suggests that a single unit of shipping could deliver about eight times more introductions in 1994 (the end of the data record) than in 1856 (the beginning of the data record).

Under our introduction model, we derive both the fitted cumulative discovery record and the cumulative introduction record over the period 1856 to 1994 for the three source regions of interest. These calculations are plotted in Figure 4 which is organized as follows. The three rows correspond to regions ATM, WPC, and ION respectively. The left plot in each row shows the cumulative number of NIS against import volume, and the right plot in each row does so with time on the horizontal axis. Each row provides the observed cumulative discoveries (dots), fitted discoveries (solid lines) and fitted introductions (dashed lines). The vertical distance between the fitted introductions and discoveries at any point provides an estimate of the number of undiscovered IS. We estimate that about seven yet undiscovered species from the ATM region were present in San Francisco Bay as of 1994. About 17 such species exist from WPC and none from ION.

Given the countermanding effects of cumulative imports and time on the MIR, has regional risk increased or decreased since trading began? Applying parameter estimates from Table 4 yields MIR estimates of 0.11 (ATM), 0.38 (WPC), and 0 (ION), indicating that risk from WPC has increased while the others have fallen. Thus, in contrast to ATM and ION, any attenuation in the MIR over cumulative imports was not strong enough to counteract the effect of increasing risk over time.

Projections and a Cost/Benefit Consideration of Trade Restrictions

What do these dynamics imply for anticipated invasion risk by trade region? To predict future shipborne NIS introductions into San Francisco Bay by region of origin, we use forecasts of future imports to this district through the year 2020 from Haveman and Hummels (1994).

Combining these trade projections with our introductions model, we are in a position to predict the number of new introductions from 1995 to 2020. Table 5 provides the estimates of the projected trade volume and the estimated number of new NIS introductions from each region over the same period. Focusing attention on the MIRs of the three regions, it is clear that WPC and ATM are the most risky (though statistically indistinguishable) and ION is no risk at all. But if we are interested primarily in predicting the number of new NIS before 2020, we must account for the projected trade volume, which is substantially higher in WPC than in ATM. Once trade volumes are factored in, the predicted number of new NIS is much larger from WPC (52 new species) than from either of the other two regions (1.4 from ATM and 0 from ION). Trade with ION is projected to be the highest of the three regions (182 million short tons), but because the marginal risk is so low, our results suggest no new introductions from this substantial trade volume.

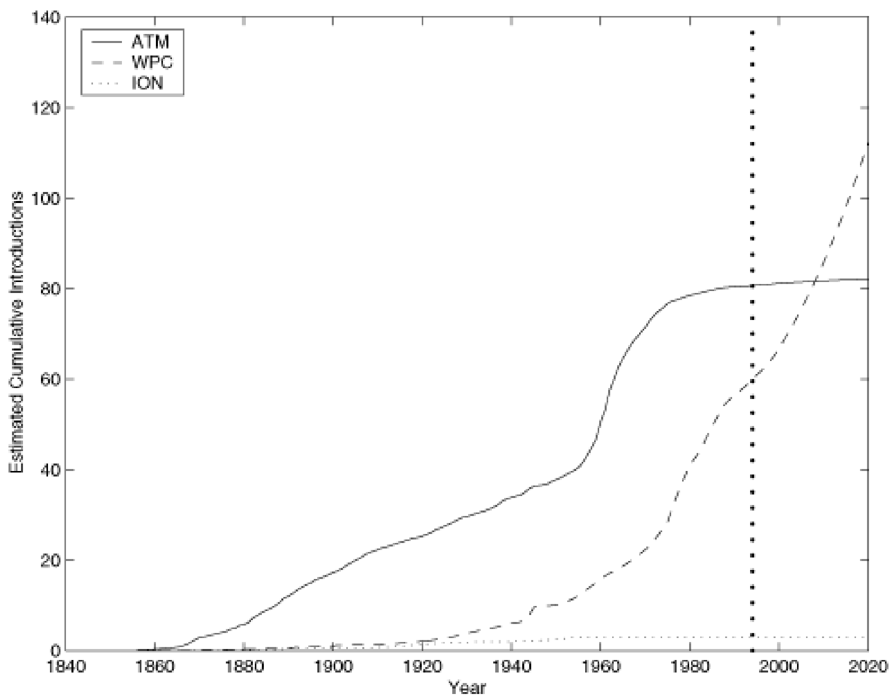
Table 4--Parameter estimates for the import-introduction-discovery model from Costello et al. (2007).

Region		$\hat{b}$	$\hat{g}$	$\hat{w}$
Atlantic/Mediterranean	(ATM)	2.3 (1.3, 4.0)	-0.08 (-0.15,-0.04)	
West Pacific	(WPC)	0.07 (0.02, 0.21)	-0.002 (-0.01,0.006)	0.015 (0.001,0.03)
Indian Ocean	(ION)	1.3 (0.1, 7.5)	-1.06 (-3.45,-0.18)	

Notes: Unrestricted estimates of the base rate of introduction (**b**) and attenuation (**g** and **w**) parameters. The time parameter **w** is common to all regions. Likelihood ratio 90 percent confidence intervals are in parentheses.

Accompanying Table 4, which presents the predicted number of new NIS introductions by 2020, Figure 4 shows the estimated cumulative number of introductions over both the data record (1856-1994) and the forecast time period (1995-2020). Consistent with the forecast estimates in Table 4, the slope of the NIS introduction process is flat for ION, relatively flat for ATM, and relatively steep for WPC.

Figure 4: Estimated NIS introductions. Data record (1856-1994) separated from forecast time period (1995-2020) by vertical dotted line from Costello et al. (2007).



To understand MIR in economic terms, we need to weigh the costs of additional shipborne NIS against the benefits of trade. Suppose the United States used trade restrictions in 2020 to reduce by one the expected number of NIS originating from each region. Our model and associated parameter estimates allow us to calculate the required reduction in trade for each region. These reductions in trade contain an associated loss in consumer surplus, but have benefits from reduced NIS damage. Admittedly, curtailing imports is one of the crudest possible methods for stemming NIS introductions; we have no intention of promoting coarse trade restrictions as a solution. Rather, we offer this thought experiment simply to put the risks from future NIS into an economic context.

Lost surplus from a trade restriction, or deadweight loss (DWL), is calculated using a standard formula for the excess burden of a trade restriction and an empirical estimate for the price elasticity of demand from the literature. Benefits are tabulated by integrating the annual reduction in mean introductions multiplied by some constant annual damage **d** from an average NIS.

We consider an import/NIS reduction program in which import volumes are reduced by a constant percentage each year. We perform this exercise for ATM and WPC only, since we expect no new NIS from ION. We find that reducing expected NIS in 2020 from each region by one would require reducing ATM imports by 90 percent and WPC imports by just 2 percent. This stark contrast occurs because the MIR from ATM is very low, as are projected future imports. The opposite is true for WPC; it has a high MIR and very high projected future trade volume.

Discounting annual DWL using a 5 percent discount rate and 1995 as the base year, our calculations indicate that the total discounted DWLs from using import restrictions to reduce expected 2020 NIS from ATM and WPC are $9.5 billion and $44 million, respectively. In order for the costs and benefits of restrictions on ATM imports to balance, annual damages from the (prevented) introduction would have to be about $1 billion per year; for WPC, annual damages per NIS would have to equal around $8.33 million.

How do these figures compare to costs from current NIS present in the United States? Three of the most expensive aquatic NIS to have invaded the United States to date are Asian clams, zebra mussels, and Teredo navalis, a shipworm. The annual costs from these NIS have been estimated at $1 billion (Pimentel et al., 2005), $700 million (U.S. ACE, 2002) and $205 million, respectively
(Cohen and Carlton, 1995).

If policy makers knew the NIS prevented via trade restrictions would have damages of the same magnitude as any of these three aquatic invaders, then import restrictions on WPC imports would indeed pass the cost-benefit test; for ATM, the deadweight loss of restricting imports is slightly higher than the benefit of avoiding an invasive as damaging as the most costly to date (Asian clams). However, these examples are drawn from the most costly end of the NIS spectrum. The damages avoided by preventing a randomly drawn future NIS are likely much smaller, though no comprehensive analysis exists to provide this number. One very rough estimate of the cost of a typical NIS is total annual U.S. damages from invasives averaged over all NIS in the United States. Pimentel et al. (2005, p. 282) report that there are over 50,000 NIS present in the United States, imposing a total of $120 billion in damages and control costs per year. Thus, a rough estimate of **d** is $2.4 million, which falls far short of the $1 billion figure for ATM; this rough estimate is also less than a third of the $8.33 million in damages necessary to justify restrictions on imports from WPC, however it is of the same order of magnitude.

We close this cost-benefit discussion with two observations. First, if policy makers want to use broad import restrictions to reduce total expected NIS in 2020, it will be significantly cheaper to do so by targeting trade with WPC rather than ATM. intuitively, this is because MIR_{WPC} shows no signs of attenuating. Second, broad intuitively, this is because MIR_{WPC} shows no signs of attenuating. Second, broad import restrictions do not appear to be a cost-effective tool for stemming NIS invasions into San Francisco Bay. Regardless of trade partner, costs appear to outweigh benefits.

The model and parameter estimates from this research provide some support for the theoretical hypothesis that cumulative introductions are a concave function of cumulative imports, though the shipping technology effect tends to dampen, even reverse (in the WPC region) this effect. While the attenuation effect from cumulative shipping in WPC was statistically indistinguishable from zero, both the ION and ATM regions showed a significant rate of decline in the baseline rate of introduction as functions of cumulative shipping. We found that: (1) a trade region's baseline infectiousness ($\mathbf{b_i}$) is a poor predictor of the marginal invasion risk, a measure of the regions current infectiousness; and (2) $\hat{b}_{WPC}$ is 20 times smaller than $\hat{b}_{ION}$ and 30 times smaller than $\hat{b}_{ATM}$, yet the WPC region poses the largest current marginal risk. This result obtains because of the near-zero attenuation rate over shipping volume in WPC. When combined with forecasts of large trade volumes from WPC, this result suggests that many new species are expected to arrive from that region (about 52 new species between 1995 and 2020). Thus, biologists should expect to encounter new species from WPC in far greater numbers than for any other region. Simple volume restrictions on imports to reduce NIS introductions are not advisable based on coarse cost-benefit calculations.

Final Words

Overall, this collection of research on controlling trade-related NIS introductions provides insight into the welfare and biological outcomes of both blunt and differentiated policy instruments, as well as the empirical challenge of progressing from the former to the latter. We have highlighted the promise and potential pitfalls of implementing various pre-invasion policy instruments. Decision makers interested in efficiency and overall welfare should attend to the tradeoff between NIS control and the consumption value of imports, internalizing benefits from cleaner goods to those in a position to manage infectiousness and the observable heterogeneity in risk posed by various trading partners.

Summary points:

- Increasing trade tariffs to control introductions can lead to increased damages in certain cases, for example, when increasing land under cultivation increases exposure to NIS damage.
- Levels of crop and ecological damage can move in opposite directions due to changes in trade policy (tariff).
- Crop damage alone can be a poor proxy for the severity of the NIS problem since, in isolation, it may mispredict the sign of change in damage from a particular policy.
- When both tariffs and monitoring are available to regulators, the optimal monitoring intensity may be, after a point, decreasing in the infection rate until, at some limit, no monitoring is desired.
- If an importer is allowed to discriminate amongst heterogeneous trading partners with its tariff, then it can use this instrument to select its optimal trading partner. However, if the importer is constrained by trading agreements, such that only its monitoring intensity may be partner specific, it must choose either a suboptimal trading partner or suboptimal instrument levels.
- In some (but not all) cases, we find evidence that the marginal invasion rate per unit of imports falls as trade history with a region accumulates. However, this attenuation is counteracted by a worsening invasion rate over time, which may serve as a proxy for technological changes in shipping and ecosystem vulnerability.
- There are significant differences in the current marginal invasion rate over imports across trading regions. Because variation also exists in how the marginal invasion rate changes over cumulative trade volume, historic invasions from a particular trading partner are an unreliable proxy for future risk.
- Simple volume restrictions on imports to reduce NIS introductions are not advisable based on coarse cost-benefit calculations.

Research and Informational Needs:

- Optimal policies for prevention, detection, and post-introduction management are ultimately interdependent. What are the implications of this interdependency on conclusions reached when each is considered in isolation?
- The infectiousness of trade and the expected damage from invasion are important determinants of policy, but only partially understood. Methods for making invasive species prevention and management decisions under

uncertainty, and the appropriate databases for informing such models, should be developed.

- Responses of foreign firms to NIS policies should be empirically examined to assess the validity of theoretical models discussed above and explored in other recent work.

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