

PROTECTIONISM, TRADE, AND MEASURES OF DAMAGE FROM EXOTIC SPECIES INTRODUCTIONS

CHRISTOPHER COSTELLO AND CAROL MCAUSLAND

Unintentional introductions of nonindigenous plants, animals, and microbes cause significant ecological and agricultural crop damage worldwide. Trade in both manufactured and agricultural goods is a primary vector for such introductions. Fusing simple models of trade and biological introductions, we explore the links between trade, protectionism, and damage arising from exotic species introductions. We show that it is possible for freer trade to reduce damage arising from exotic species invasions. We also show how current measures of damage—heavily weighted toward agricultural damage—serve as misleading indicators of how restrictions to trade affect total losses arising from exotic species introductions.

Key words: exotic species, Poisson process, protectionism, trade.

Biological invasions by nonindigenous species¹ of plants, animals, and microbes cause significant ecological and economic damage worldwide. A 1993 report from the Office of Technology Assessment (OTA) estimates the monetary costs associated with biological invasions in the United States alone is between \$4.7 and \$6.5 billion annually (OTA); subsequent research revises that estimate for the United States upward to over \$100 billion a year (Pimentel et al.).² Nonindigenous species

enter a country either through intentional or unintentional introduction. Of unintentional introductions, primary conduits include contaminated traded goods such as agricultural products and timber, contaminated packing materials, ballast water, and tourism. The prominent role of international trade and transport of commodities in biological invasions has led to the common perception that freer trade will lead to an increase in the scale of biological invasions, and has even prompted the claim that “broad tools such as bans or restrictions of imports may be necessary to protect biodiversity” (Jenkins). However, the relationship between protectionism and *damage* from exotic species is not so simple.

Using a stylized model of commodities trade, we explore how the damage arising from stochastic, unintentional³ introductions of exotic species varies with the volume and pattern of goods trade as well as with instruments of protection. Contrary to common perception, we show that freer trade, by way of reduced protectionism may, instead, lead to *less* damage from exotic species for some countries.

Christopher Costello is assistant professor of environmental and natural resource economics at the Donald Bren School of Environmental Science & Management, University of California, Santa Barbara, and Carol McAusland is assistant professor of economics at the Donald Bren School of Environmental Science & Management and the department of Economics, UCSB.

The authors thank Chris Pyke and Britta Bierwagen for helpful research assistance, Greg Graff for advice on empirical case studies, Bob Deacon and Charlie Kolstad for helpful comments on earlier versions, and two referees for unusually helpful suggestions. This research was funded, in part, by the Institute for Social, Behavioral, and Economic Research at U.C. Santa Barbara.

¹ A nonindigenous species, also referred to as an exotic, alien, transplanted or invasive species, is defined as “a species being moved beyond its natural range or natural zone of potential dispersal . . .” (Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 (Public Law 101-646, 16 USC 4701-4741)). We use the term “biological invasions” to refer to cases where an exotic species becomes established in a free living state and imposes either ecological or pecuniary costs on the host region.

² It is unclear to what extent these estimates reflect the true costs associated with invasive species. The estimates derive mainly from crop damage—agriculture-related costs alone make up between 90% and 93% of the OTA estimate and over half of the Pimentel et al. calculation—and tend to overlook damage to nonmonetized assets such as functioning ecosystems; these estimates may be viewed as lower bounds on the total costs associated with invasives. Conversely, these estimates may be upper bounds on the *marginal* costs associated with invasives, at least with respect to agricultural activity, since costs that are incurred in the absence

of viable populations of nonnative species are not deducted. For example, \$27 billion of the Pimentel et al. estimate come from damages and control costs associated with nonnative crop weeds. Since it is plausible that native species would either become or expand their presence as crop weeds in the absence of the nonnative species, the Pimentel et al. figure overestimates the true marginal cost of the noninvasive species they survey.

³ The OTA (p. 62) estimates that only 12% of intentional introductions are harmful, as compared to 44% for unintended introductions; we focus only on the latter.

This can occur because, although reduced protectionism raises the volume of trade and hence the platform for biological invasions, it also changes the production mix of participating countries and so alters their susceptibility to damage from exotics to begin with. For example, for countries that initially import agricultural products, reduced tariffs will lead to a decrease in the volume of agricultural output. This reduces both the quantity of crops available for damage by exotic pests and the amount of land that is disturbed, thereby aiding the propagation of exotic species. Consequently, while increases in the volume of trade may lead to greater ecological (non-crop-related) damage, possible reduction in crop-related damage may dominate such that total damage falls.

Disaggregating ecological and agricultural crop damage from exotic species is critical in the eventual determination of whether protectionism increases or decreases losses from exotic species introductions. Because they are most easily quantified, estimates of crop damage alone are often used to motivate the severity of the exotic species problem, and federal funding is largely allocated to mitigating agriculture-related damages (U.S. General Accounting Office). We explore the appropriateness of using crop damage as an indicator of overall damage from exotic species; we find that it serves as a poor proxy. As noted above, while crop damage arising from biological invasions may fall as a result of reduced protectionism, ecological damage may simultaneously rise. In the case where changes in ecological damage dominate, not only do changes in crop damage poorly indicate the magnitude of changes in damage from biological invasions, they may mispredict the very direction of the change.

Our model and results can be viewed in the context of two literatures. There is an extensive body of biological research on invasive species. Rules of thumb derived from this literature form the basis for our biological model. Overviews of this literature can be found in Drake et al., di Castri, Parker et al. Substantially less research has been conducted concerning the economics of invasive species. This research largely takes the form of case studies (e.g., Knowler and Barbier, Kasulo) and analyses of control and risk reduction methods (e.g., Shogren, Shogren et al.). With the exception of a preliminary empirical analysis by Dalmazzone, none explicitly incorporate the role of commodity trade in their analy-

sis.⁴ Thus, the present article serves as a first pass at establishing theoretical relationships between invasives-related damage, patterns of trade, and protectionism.

The remainder of the article is structured as follows. The model is described and results derived in the next section. This is followed by a discussion of caveats and, finally, a conclusion.

Model

Biological research on invasive species has generated several rules of thumb governing introduction and establishment of nonindigenous species that we take as the starting points for our analysis. For example, successful establishment of exotic species is facilitated by similarity between the physical environments in the original and exotic locations; it is also aided when the environment has been disturbed by human activity (Brown). Furthermore, evidence from avian populations indicates that successful introduction of nonnative species is positively correlated with the number of failed introductions to that same region (Case), suggesting that another factor influencing successful introduction is simply the frequency of that species' exposure to a particular host region. These empirical observations suggest that the frequency and severity of damage arising from biological invasions are related to the extent to which the host country modifies its natural environment, and the frequency of its exposure to exotic species, i.e., to the volume of its imports.

We translate these rules of thumb into the following stochastic model of introduction, success, and damages associated with invasive species. Denoting the host region as Home, we make use of the following definitions:

1. *Introduction.* An introduction occurs when human activity facilitates the transport of an exotic species to Home, though the species need not take hold in its new location. We assume that the arrival times of exotic species are stochastic and that the

⁴ Using a linear regression model, Dalmazzone finds a negative and statistically significant relationship between import duties and the presence of nonnative species; the influence of the other measure of openness such as trade as a percentage of GDP, volume of merchandise imports, and tourism are all statistically insignificant. We believe these results underplay the importance of trade volumes for rates of exotic species introduction since the biological rules of thumb governing invasions suggest that imports should be disaggregated by type (agricultural versus nonagricultural) and country of origin.

interarrival time between two successive introductions is an exponentially distributed random variable⁵ with mean $1/\lambda$. We assume λ is an increasing function of the volume of imports (M) to reflect the potential of imports to harbor exotic species, $\lambda'(M) > 0$.

2. *Success.* The probability that an introduced species establishes a viable population in Home is denoted by q ; q will also be referred to as the probability of success. We assume q is constant.⁶
3. *Damage.* Successfully introduced species cause $k = 1, \dots, K$ types of damage, for example, loss of habitat for native species, predation on crop plants, and the transmission of disease. The instantaneous damage of type k —measured in dollars and possibly zero—caused by the i th successful introduction is d_i^k , a random variable with cumulative density function $\Phi^k(x; A)$, where A is the amount of agricultural production in Home.⁷

We assume damage is cumulative through time.⁸ Let the random variable t_i be the arrival time of the i th successful introduction. Then, the present value of type- k damage through time T caused by the i th successful introduction is given by

$$(1) \quad D_i^k(T) = e^{-rt_i} \int_{t_i}^T d_i^k e^{-rt} dt \\ = d_i^k e^{-rt_i} \times \left[\frac{e^{-rt_i} - e^{-rT}}{r} \right]$$

where r is the discount rate. Define the cumulative density function for $D_i^k(T)$, conditional on t_i , by $F_t^k(\delta; A)$, which gives the probability that a successful arrival at time t_i has a present value of type- k damage by time T of less than δ , given that agricultural production is A .⁹

Let $J(T)$ be a random variable that denotes the number of successful introductions by time T . Since the interarrival times are distributed exponentially with constant mean $1/\lambda$ and only a fraction q of introduced species are successful, then by Kingman's Colouring Theorem, J is a Poisson process with rate $\mu(M) = q\lambda(M)$ where $\mu'(M) > 0$ (Kingman).

Summing (1) over the J successful introductions by time T gives

$$(2) \quad D^k(T) = \sum_{i=1}^{J(T)} D_i^k$$

which, by the Ross Theorem 2.3.1, is a compound Poisson random variable with Poisson parameter $T\mu(M)$ and component distribution $\frac{1}{T} \int_0^T F_t^k(\delta; A) dt$ (see Appendix for proof).

Using known results for the compound Poisson random variable, we can immediately write the expected value of type- k damage through time T as follows:

$$(3) \quad E[D^k(T)] = T\mu(M)E_\delta \\ \times \left[\frac{1}{T} \int_0^T F_t^k(\delta; A) dt \right] \\ = \mu(M)E_\delta \int_0^T F_t^k(\delta; A) dt.$$

For completeness note that the present value of total damage up to time T will be

$$D(T) \equiv \sum_k D^k(T).$$

In order to economize on notation, we drop T as an argument of D and J for the remainder of the article.

⁵ Modeling exponentially distributed interarrival times with constant mean implicitly assumes that the establishment of a new species in the host country (Home) does not affect the interarrival time of subsequent nonestablished species. When the pool of exotics is finite, however, we might instead expect λ to decrease each time a new exotic is established in Home. However, assuming the mean interarrival time is independent of the number of exotics established in Home generates the same qualitative results concerning the impacts of different trade instruments on damage arising from biological invasions. Since it also simplifies the model considerably, we assume λ depends only on M .

⁶ A constant q is consistent with the "tens rule"—the hypothesis maintained in the literature on biological invasions that approximately 10% of introduced species will become casual, and approximately 10% of casual species will become established—suggests that success is proportional merely to exposure. In application q is likely to vary depending on the similarity between the environments in the origin and host regions (Brown). In our analysis, however, changes in Home's tariff rate do not alter the identity of Home's trading partner. If we analyzed variations in a country's preferential tariff rates, or the effects of customs unions and free trade areas—policies that may change the set of partners with which a country trades— q should instead be modeled as endogenous.

⁷ The cumulative density function of d_i^k may depend on A for several reasons. More agricultural activity implies that larger volumes of crops are present and susceptible to destruction by pests, either before or after harvest. In addition, greater agricultural activity corresponds to larger areas under cultivation and hence to higher levels of disturbance of native ecosystems.

⁸ Some invasive species are controlled or eradicated by the host government. Generalization of our model to permit these responses is discussed in the caveats section.

⁹ For example, if $d_i^k \sim U[0, A]$, then $D_i^k(T) \sim U[0, Ae^{-rt_i} (\frac{e^{-rt_i} - e^{-rT}}{r})]$, and $F_t^k(\delta; A) = \frac{\delta}{Ae^{-rt_i} (\frac{e^{-rt_i} - e^{-rT}}{r})}$ for $\delta \in [0, Ae^{-rt_i} (\frac{e^{-rt_i} - e^{-rT}}{r})]$.

To establish a link between trade policies and damage from exotic species, we next employ a model of commodities trade. We use a simple two-sector model of balanced trade in which production exhibits constant returns to scale and input and output markets are perfectly competitive. We assume for simplicity that Home is a small open economy such that world prices are exogenous. Define τ as an ad valorem tariff on imported goods. Denote the second industry, Manufacturing, by Y . Let the world price of agricultural goods be denoted by P^* and let manufactures be numeraire. Define by M_j the Home country's net imports of good j ; for example, $M_A = C - A$ where C is Home's Marshallian demand for agricultural goods. In our two-country framework, balanced trade requires $P^*M_A + M_Y = 0$ and so $M_Y = -P^*M_A$. Balanced trade also implies that the volume of imported goods is $M = \max\{M_A, M_Y\}$.¹⁰ Differentiating M with respect to τ gives

$$(4) \quad \frac{dM}{d\tau} = \epsilon^M \frac{M}{P} \frac{dP}{d\tau}$$

where $\epsilon^M \equiv \frac{dM}{dP} \frac{P}{M}$ is the elasticity of imports with respect to the domestic price of agricultural goods, P . Given that $\frac{M}{P}$ is nonnegative, the effect of protection on the volume of imports depends on both how responsive imports are to the domestic price of agricultural goods (indicated by ϵ^M) and whether the import tariff raises or lowers that relative price.

Suppose first that Home is an importer of agricultural goods, i.e., $M = M_A > 0$; then the domestic relative price of agricultural goods is $P = P^*(1 + \tau)$ and

$$(5) \quad \frac{dP}{d\tau} = P^*$$

Differentiating the expression for M_A with respect to P , converting to elasticities and, for simplicity, evaluating at $\tau = 0$ gives

$$(6) \quad \epsilon^M \Big|_{\tau=0, M=M_A > 0} = - \left[\epsilon^C \frac{C}{M} + \epsilon^A \frac{A}{M} \right] < 0$$

where $\epsilon^C = -\frac{dC}{dP} \frac{P}{C}$ and $\epsilon^A = \frac{dA}{dP} \frac{P}{A}$ are the elasticities of demand and supply for agricultural goods with respect to its domestic relative price; each of these terms is positive.¹¹

If, instead, Home is an importer of manufactured goods, i.e., $M = M_Y > 0$, then the domestic relative price of agricultural goods is $\frac{P^*}{1+\tau}$; this gives

$$(7) \quad \frac{dP}{d\tau} = -\frac{P^*}{[1 + \tau]^2} < 0$$

and

$$(8) \quad \epsilon^M \Big|_{\tau=0, M=M_Y > 0} = P^* \left[\epsilon^C \frac{C}{M} + \epsilon^A \frac{A}{M} \right] > 0.$$

Combining (4) with (6) and (8) gives the expected result that increased protectionism reduces the volume of imports into Home. Since imports serve as a platform for introductions of exotic species, policies that affect the volume of these imports also have consequences for the rate at which exotic species are successfully introduced to Home.

PROPOSITION 1. *Starting from an initial tariff of zero, increasing the tariff rate decreases the rate of successful exotic species introductions to Home; that is, $\frac{d\mu(M)}{d\tau} < 0$.*

Proof: The number of successful introductions, J , is a Poisson random variable with rate $\mu(M) = q\lambda(M)$. As $\lambda'(M) > 0$ by construction and $\frac{dM}{d\tau} < 0$ by (4), (6) and (8), then $\frac{d\mu(M)}{d\tau} = q \underbrace{\frac{d\lambda}{dM}}_+ \underbrace{\frac{dM}{d\tau}}_- < 0$. ■

Proposition 1 makes the straightforward point that increased protection reduces the number of exotic species successfully introduced to Home simply because tariffs reduce the platform for these introductions that is created by imports to begin with. We reiterate that all types of trade can serve as such platforms. Despite the tendency to equate species introductions with imports of agricultural goods, trade in nonagricultural goods also frequently serves as a conduit for biological introductions—although likely at different rates—either through contaminated ballast water from ships or infestations of packing materials and manufactured goods themselves.

Given Proposition 1, one might be tempted to join the call for reduced trade as a means to stem damage from biological invasions. However, not all successful introductions cause damage, and moreover, the extent of damage caused is endogenous. In order to calculate the impact that protectionism has on expected damage, we ask the following question: If the

¹⁰ We follow the popular convention of assuming no cross-hauling of goods even though transport costs are not explicitly modeled.

¹¹ We assume away the possibility of Giffen goods.

tariff rate on imports was marginally increased at time 0, what would be the effect on the present value of type-*k* damage through time *T*? That is, we seek the sign of the derivative, $\frac{dE[D^k]}{d\tau}$. Differentiating (3), factoring out time-invariant terms and converting to elasticities gives

$$(9) \quad \frac{dE[D^k]}{d\tau} = [\epsilon^{F_k} \epsilon^A + \epsilon^\lambda \epsilon^M] q \lambda E_\delta \times \left[\int_0^T F_t^k(\delta; A(t)) dt \right] \frac{dP}{d\tau}$$

where ϵ^{F_k} is the elasticity of expected type-*k* damage to the level of agricultural activity ($\epsilon^{F_k} \equiv \frac{dE_\delta[\int_0^T F_t^k(\delta; A(t)) dt]}{dA} \frac{A}{E_\delta[\int_0^T F_t^k(\delta; A(t)) dt]}$) and $\epsilon^\lambda \equiv \frac{d\lambda}{dM} \frac{M}{\lambda}$ is the elasticity of the arrival rate with respect to the volume of imports. Terms ϵ^λ and ϵ^A are both positive; $E_\delta[\int_0^T F_t^k(\delta; A(t)) dt]$ is positive so long as the expected type-*k* damage is positive (which we assume to be the case¹²); the sign of ϵ^M for each type of importer is given by equations (6) and (8).

Only the sign of ϵ^{F_k} remains to be determined. To aid in this determination we disaggregate the many types of damage that can be imposed on Home into the following three categories:

1. "Augmented" Damages—Types of damage for which $\epsilon^{F_k} > 0$,
2. "Neutral" Damages—Types of damage for which $\epsilon^{F_k} \simeq 0$,
3. "Diminished" Damages—Types of damage for which $\epsilon^{F_k} < 0$.

Some simple interpretations of these classifications are useful at this point. Damages arising from loss of crops (both prior to and after harvest)—either through infiltration of crop and pasture land by weeds or predation on crops and livestock by pests—increase as the level of agricultural activity increases. Commonly referred to as crop damage, these types fall under the definition of Augmented damage. Other types of damage, not directly related to the loss of sellable agricultural output, may also fall in this category. As noted before, agricultural activity correlates with

ecosystem (e.g., soil) disturbance, which in turn aids the propagation of some invading species. For example, plant invasions throughout the grasslands of Australia and North and South America, some of the most extensive biotic invasions in history, are thought to be facilitated by human-initiated ecosystem disturbance (Mack et al.).

The damages associated with introductions into marine and aquatic systems, on the other hand, are unlikely to be significantly affected by the level of agricultural activity. Examples include invading mollusks that foul water intake systems at power generation facilities, or introduced fish that out-compete native species, creating losses to recreational activities such as sport fishing. In addition, there are numerous examples of exotic species displacing native species, with consequences for non-monetized assets such as ecosystem health and biodiversity. These examples meet the definition of Neutral damage. In subsequent discussion we will also refer to these types as ecological damage.

We do not know of extant examples of invasion-related damage meeting our definition of Diminished damage; we retain this category, however, so as to maintain comprehensive propositions.

Using the decomposition of damage types into these three categories, and using expressions for $dP/d\tau$ from (5) and (7), we obtain the following proposition.

PROPOSITION 2. *For a small open economy that initially imports agricultural goods, an increase in the tariff rate τ*

- (i) *unambiguously reduces expected Neutral and Diminished-type damages and*
- (ii) *raises expected Augmented-type damages *k* if and only if*

$$(10) \quad \epsilon^{F_k} > -\epsilon^\lambda \frac{\epsilon^M}{\epsilon^A}$$

if, instead, the country exports agricultural goods, then an increase in its tariff rate

- (iii) *unambiguously reduces expected Augmented and Neutral-type damages and*
- (iv) *raises expected Diminished-type damages *k* if and only if*

$$\epsilon^{F_k} < -\epsilon^\lambda \frac{\epsilon^M}{\epsilon^A}.$$

¹² Some exotic species may indeed be beneficial to their host environment, such as wheat to the New World. However, since many such beneficial exotics are or have already been introduced *intentionally* they are outside the scope of this analysis.

Proof: Substituting for $dP/d\tau$ using (5) in (9) and rearranging gives

$$\frac{dE[D^k]}{d\tau} = \left\{ \epsilon^{F_k} + \epsilon^\lambda \frac{\epsilon^M}{\epsilon^A} \right\} P^* \epsilon^A q \lambda E_\delta \times \left[\int_0^T F_t^k(\delta; A(t)) dt \right]$$

when Home is an importer of agricultural goods and, using (7),

$$\frac{dE[D^k]}{d\tau} = - \left\{ \epsilon^{F_k} + \epsilon^\lambda \frac{\epsilon^M}{\epsilon^A} \right\} P^* \epsilon^A q \lambda E_\delta \times \left[\int_0^T F_t^k(\delta; A(t)) dt \right]$$

when Home, instead, exports agricultural goods; as discussed earlier $P^* \epsilon^A q \lambda E_\delta [\int_0^T F_t^k(\delta; A(t)) dt]$ is positive. ■

These results are summarized in the following table:

$\text{sign}(\frac{dE[D^k]}{d\tau})$	Augmented	Neutral	Diminished
Importer of Ag. goods	?	-	-
Exporter of Ag. goods	-	-	?

When Tariffs Raise Damage from Exotics

The most interesting element of Proposition 2 is part ii: An import tariff may raise the expected damage arising from exotic species. We interpret below some of the key elasticities in Proposition 2 and discuss general conditions under which this outcome is more (or less) likely to occur.

In our simple model, the effect of trade barriers on the arrival rate of new exotic species is as exactly as one would expect: an increase in the tariff on imports reduces the volume of trade, and so long as trade is a conduit for introductions, the expected arrival rate of new exotic species falls as a consequence (c.f. Proposition 1). But because the policies used to reduce trade invariably distort domestic prices, they also affect the production mix in an economy. And this distortion has consequences for the extent to which a country is susceptible to damage from invasives, both by influencing the magnitude of crops available for damage and

by altering the level of cultivation and hence disturbance in the host country.

Specifically, for an agricultural importer, expression (10) reveals that whether a tariff on imports will reduce or increase Augmented-type damages depends in part on the sensitivity of those types of damages to agricultural output as indicated by ϵ^{F_k} ; it also depends on the elasticity of the introduction rate with respect to the volume of imports (ϵ^λ), the price elasticity of domestic agricultural supply (ϵ^A), and the price elasticity of import demand (ϵ^M). We will discuss values of these elasticities in turn below, starting with the last.

Precise measures of the price responsiveness of import demand are difficult to construct, as they are confounded by factors such as exchange rate fluctuations. However, as indicated by equations (6) and (8), the elasticity of import demand ϵ^M can be constructed from the own price elasticities of agricultural consumption ϵ^C and supply ϵ^A . For example, (6)—reproduced below—shows that when a country is an importer of agricultural goods then

$$\epsilon^M \Big|_{\substack{\tau=0 \\ M=M_A > 0}} = - \left[\epsilon^C \frac{C}{M} + \epsilon^A \frac{A}{M} \right] < 0$$

and so the elasticity of import demand is smaller in absolute value the lesser consumption is price elastic, ceteris paribus. Since ϵ^C tends to decline with a country's per capita income¹³ then, other things being equal, we would expect ϵ^M to be smaller in absolute value—and so the more likely is a trade barrier to raise Augmented-type damages—in higher-income countries.

The other elasticity determining ϵ^M is the elasticity of agricultural output ϵ^A ; from (6) a larger value of ϵ^A implies a larger value of $|\epsilon^M|$, ceteris paribus. However, for the larger question of whether import tariffs raise or lower expected Augmented-type damages for an importer of agricultural goods, the ratio ϵ^M/ϵ^A is more relevant. Taking this ratio using (6) reveals that the more price elastic is agricultural output—i.e., the larger is ϵ^A —then the more likely it is that Augmented-type damages rise with trade restrictions. Estimates of ϵ^A reveal considerable variation in supply elasticities

¹³ Using 1980 data from over fifty countries, Thiel, Chung, and Seale calculate Slutsky, Frisch, and Cournot own-price elasticities of demand for food. They find that these elasticities are lower for countries with higher per capita income. For example, they calculate that the Cournot own-price elasticity of food in Tanzania, the poorest country in their sample, is 0.77 while that for the United States is 0.12.

across countries, regions, and commodities.¹⁴ While it is commonly believed that the value of ϵ^A for a given country or commodity is influenced by “quasi-fixed” factors such as available land for cultivation, suitability of a crop to a country’s climate and geography, irrigation and other infrastructure, and the availability of more productive varieties (see, e.g., McGuirk and Mundlak), not widely applicable “rules of thumb” arise from empirical estimates.¹⁵

The final elasticity of interest, ϵ^λ , measures the responsiveness of the introduction rate to the volume of trade. In the present model we have assumed trade is the single conduit for introductions of new exotic species,¹⁶ either via import of contaminated goods, packing materials, or ballast water. Although it is not a requirement of the model, for purposes of comparison, it is reasonable to assume that $\epsilon^\lambda = 1$. This assertion derives from the simple fact that while contamination rates of traded goods appear to vary with the country of origin of imported goods and by the mode of transport, these characteristics would be unaffected by a uniform barrier to trade such as a tariff. Moreover, for a given trade partner, we have found no evidence that the rate of hitchhiking is anything but proportional to the volume of a given traded commodity,¹⁷ suggesting that

unintentional introductions exhibit no apparent economies or diseconomies with regard to the volume of trade. One likely explanation is the pervasive use of containers—ubiquitous, sea-worthy trailers prevalent in marine, rail, and road transport—which appear to prevent economies of scale in inspection and even fumigation of imported goods and their packing materials.¹⁸

The above discussion illuminates the factors influencing the values of each of the key elasticities in expression (10). Because estimates of even conceptually straightforward elasticities such as ϵ^C and ϵ^A can vary widely depending on the estimation techniques and methods, we are reluctant to make country- or commodity-specific predictions as to when the counterintuitive result proposed in Proposition 2 will occur. Instead, we prefer to summarize our analysis with the general prediction that barriers to trade are more likely to backfire as a means of preventing damage from exotic species when the country in question is an importer of agricultural goods, when the country’s citizens are in a high-income group and so demand for agricultural goods is price insensitive, and when there is substantial potential for domestic agriculture to expand in response to high local prices. Perhaps, even more important, the less significant trade is as a vector of introductions relative to other pathways such as tourism or range expansion, the more likely it is that trade barriers will backfire as a means of reducing damages associated with exotic species.

The above evidence suggests the question: do empirical examples exist in which increased protection increases domestic agricultural production and subsequent damage from newly introduced exotic species? We conclude this section with such an illustrative example of exotics-related damage in a sector protected from competition from imports, albeit taken from a country that few would argue is a “small” open economy.

Tariffs and quotas on sugar imports into the United States are a popular example of protectionism in textbooks on international

¹⁴ For example, estimates of the long-run own price elasticities of supply of rice, wheat, and coarse grains are markedly lower (0.20, 0.60, and 0.60) in Japan than they are in the European Community (0.40, 0.90, and 0.92) and the United States (0.75, 0.80, and 0.75) (Tyers and Anderson). Estimates from developing nations further illustrate that within-country supply elasticities can span large ranges across agricultural commodities. Examples include Argentina, where elasticity estimates range from 0.13 for sorghum to 1.48 for corn (Fulginiti and Perrin), India, where long-run supply elasticities range from 0.16 for rice to 0.78 for wheat (McGuirk and Mundlak), and Sri Lanka where rice production is somewhat inelastic (0.11) (Gunawardana and Oczkowski), but green leaf tea is closer to unit elasticity (0.86) (Roberts).

¹⁵ Diebold and Lamb attribute this “nagging and recurring problem” of the variability in supply response estimates across crops, regions, and time periods, to the use of an econometric estimator with undesirable statistical properties.

¹⁶ A more comprehensive approach would explicitly model introductions via tourism and range expansion as well; inclusion of these alternate pathways would tend to reduce the sensitivity of the overall introduction rate to the volume of trade since the elasticity with respect to trade volumes of introduction rates via these other vectors is likely zero.

¹⁷ For example, preliminary random inspections by the U.S. Animal and Plant Health Inspection Service (APHIS) indicate that approximately 51.8% of maritime shipments and 8.5% of air shipments contain solid wood packing materials (SWPM) (USDA, Animal and Plant Health Inspection Service and Forest Service, p. 25), and infection rates of SWPMs vary by type: surveys of wooden spools from China revealed infection rates with live insects between 22% and 24%, braces for granite blocks imported into Canada were found to contain live insects 32% of the time. (USDA, Animal and Plant Health Inspection Service and Forest Service, pp. 27–28).

¹⁸ A joint report from the USDA, APHIS, and the U.S. Forest Service reports that “containerized cargo is usually packed tightly in the trailer and often stacked to the roof, preventing inspection of all but a small percentage of the shipment visible at the tailgate (i.e., open doors). . . Importers must pay high fees ranging from \$800 to \$1500 per container for removing or devanning cargo to facilitate inspection. Inspectors are often reluctant to impose these additional costs on importers unless there is reasonable certainty pests will be found.” (USDA, Animal and Plant Health Inspection Service and Forest Service, p. 25).

trade. Overt protection for the U.S. sugar industry has been growing since 1934; current U.S. sugar prices are over double the prices in the rest of the world (USDA 2002). Over the same period, land under sugarcane production grew at an average annual rate of 1.6%,¹⁹ arguably against the United States comparative advantage. Harvested acreage for all agricultural crops declined slightly over this period (at an average annual rate of 0.1%²⁰). Protection has not, however, rendered the industry immune to damages from new exotic pests. Mexican Rice Borer, first discovered in the United States in 1980 in the Rio Grande Valley sugarcane fields, today infests at least 20% of Texas sugarcane (Legaspi, Poprawski, and Legaspi). Texas' annual gross cane harvest is valued at approximately \$64 million; estimates of the annual damages imposed by the pest on the Texas sugarcane industry range from \$10 to \$20 million (Legaspi et al.). The Mexican rice borer is believed to have been introduced unintentionally via traded goods from Mexico, and has been intercepted at Texas ports as a hitchhiker on sugarcane, lemon grass, sorghum, and broomcorn. This example suggests that our theoretical proposition may already be playing out in practice.

Crop Damage as a Proxy for Total Damage

Each part of Proposition 2 discusses conditions under which an import tariff will increase or decrease a different type of damage associated with exotics. How a tariff affects *total* expected damages depends on the sum of these changes. The fact that a tariff may simultaneously reduce Neutral-type damages and increase Augmented-type damages raises an interesting problem. Simply, estimates of invasion-related damage that are based on one type of damage serve as poor—even misleading—indicators of total damage. This point is particularly important if we believe pecuniary losses to agricultural production are more easily observed than ecological damage from exotic pests and hence form the basis for policy decisions. As noted in the introduction, most real-world estimates of invasion-related damage derive predominately from estimates of damage to crops and livestock. In the United States, other indicators also suggest that crop-related damage is given top priority in efforts to reduce damage from inva-

sive species. In 2000, a total of approximately \$632 million was obligated by federal departments toward invasive species activities, 88% of which came from sources interested in protecting U.S. agricultural crops from invasives-related damage. Approximately 4% of this allocation was spent by agencies responsible for the conservation of biological diversity and ecological communities²¹ (U.S. General Accounting Office). Given that invasives are considered the “second largest threat (globally) . . . to biodiversity” (Williamson, p.5), and are linked to the decline of 400 of the 958 species on the United States list of endangered species (Pimentel et al.), it is apparent that invasives-related damages to nonagricultural assets are also substantial. Yet, as Proposition 2 indicates, policy changes that lead to reduced crop (Augmented) damage—reduced protectionism—may simultaneously increase ecological (Neutral) damages. If we treat damages arising in agriculture as a proxy for overall costs related to invasives, we may misjudge not only the magnitude of these costs but also the qualitative effect that trade policy has on the problem.

Caveats

In this article we explore the links between trade, protectionism, and damage arising from exotic species introductions. Several confounding, yet in some cases realistic, factors have been left out of our model to maintain clarity; we address some of them here.

Redundant and Complementary Introductions

In our model, the rate of successful introductions depends only on the volume of imports. In practice, there exist cases in which the introduction rate may also depend on the number of previously successful introductions. First, some introductions may be redundant given the composition of existing successfully introduced exotics.²² This can happen when the incumbent and newcomer pests occupy a similar ecological niche, such as the spotted and diffuse knapweeds in the northwestern United States,²³ or when two pests damage

²¹ Including the U.S. Fish and Wildlife Service.

²² We thank an anonymous referee for pointing out and discussing this possibility.

²³ Diffuse and spotted knapweeds, along with other noxious weeds such as squarrose knapweed, yellow star thistle, and Russian knapweed, cause severe ecological and pecuniary damage to rangelands of western North America. Diffuse knapweed, a

¹⁹ Based on authors' calculations from USDA (2001) data.

²⁰ Based on authors' calculations from USDA (2001) data.

the same agricultural crop. Alternately, the damages created by a newly introduced species may be augmented by the presence of a complementary, incumbent exotic species. Examples of complementary introductions include fig trees and wasps in Florida²⁴ and cheatgrass and yellow star thistle in the northern great plains of North America.²⁵ And finally, some exotic species may serve to reduce the damage associated with resident exotics, as when a newly introduced species preys upon an existing invasive, serving as intentional or unintentional biological control agents.²⁶

For redundant arrivals the rate of successful introductions falls in the number of previous successes; it rises for species that express complementarity with previously introduced species. Capturing this possibility analytically requires a modeling approach more general than the one adopted here, and is intractable. Intuitively, however, we believe that incorporating such a possibility would not alter the main result of this research: with redundant or complementary introductions, protectionism reduces the volume of imports (and therefore the rate of introductions) but leads

to increased domestic agricultural production, leaving ambiguous the net effect of protectionism on damage from exotic species. If the rate of successful introductions is declining (increasing) in the number of exotic species already thriving in a country, then the magnitude of this ambiguity is reduced (increased), but the inherent ambiguity persists.

Nonetheless, quantifying the size and sign of the effects of trade restrictions on expected future damages from exotic species, whether damaging species are redundant (arriving at a decreasing rate, controlling for trade volume) or complementary, is an important empirical issue. We expect to address this question empirically in the future.

Averting Behavior

As discussed earlier, one of the means by which exotic species impose damage on the host country is through crop destruction. In the interest of simplicity, throughout this article we have assumed that industrial mix responds to producer prices but not to net harvest rates, such that producers do not engage in “averting behavior.” Farmers planting more corn and less wheat in response to the establishment of the Russian Wheat Aphid in the United States, or using costly pesticides to combat wheat aphids, are examples of averting behavior. In an economy in which producers face undistorted—i.e., world—prices such averting behavior would reduce the magnitude of, but not change the sign of, crop damages imposed by biological invasions. If, however, producers initially faced distorted prices then biological invasions may actually generate net benefits to an economy. For example, the provision of subsidized water to agriculture in the United States’ southwestern states induces the cultivation of water-intensive crops, despite that region’s dry climate. Introduction into that region of a pest that preys on water-intensive crops would induce a reorientation of agriculture away from water-intensive crops, offsetting at least to a partial extent the effect of the water subsidies and possibly even raising welfare.²⁷ Of course, we do not promote such introductions, as it would be superior to eliminating inefficient subsidies to begin with. We offer this example merely to reiterate the point from the literature on environmental double dividends that preexisting distortions alter the welfare impacts of policy changes, even possibly

European and Asian native, hitchhiked into North America in the late 1800s as a contaminant of alfalfa seed. It currently infests 326 counties in the western United States and is considered a major threat to both grazed and undisturbed rangeland (Montana State University Extension Service, Montana Weed Control Association). Occupying a similar niche, and often infesting the same sites, is the central European native, spotted knapweed, which was also unintentionally introduced as seed contaminant. First discovered in Montana in the 1920s, spotted knapweed currently infests over 7 million acres in the western United States (Cox, Beck).

²⁴ Introduced as ornamentals, nonnative *Ficus* species (fig trees) in Florida have historically failed to establish free populations in the wild because each species is pollinated by a specific type of wasp. Within the last thirty years, however, import of contaminated seed and fruit has led to the importation of the wasps complementary to lofty fig, banyan, and laurel fig; each of these fig species has since become invasive to Florida, causing a variety of problems including sprouting on and causing structural damage to highway bridges (Simberloff, Schmitz, and Brown, pp. 90–91).

²⁵ Cheatgrass, first established in British Columbia in 1899, has spread throughout the grasslands of the northern great basin, and is widely recognized as a major threat to native grassland ecosystems. Cheatgrass invades native shrublands by occupying bare ground between shrubs. Due to its high susceptibility to fire, cheatgrass-invaded ecosystems tend to burn more readily, and because native shrubs (most significantly basin sagebrush) rarely resprout, cheatgrass density ultimately increases. These newly fire-disturbed ecosystems facilitate invasion of the yellow star thistle, which is unable to invade healthy perennial grasslands, and since the 1950s has become a major rangeland pest, invading almost 10 million acres of the intermontane west (Cox).

²⁶ For example, the larvae of *Parapoynx diminutalis*, an Asian pyralid moth, feed on the highly invasive aquatic plant hydrilla, and the larvae of *Megastigmus transvaalensis*, an African Torymid wasp, feed on Brazilian pepper fruits (Simberloff, Schmitz, and Brown, p. 97). However, exotics that prey on other exotics are more commonly introduced intentionally: Hill and Greathead report that “more than 5000 natural enemies of insects and mites have been introduced for classical biological control” (p. 208).

²⁷ We thank Tom Heller for suggesting this possibility.

to the extent of changing the signs of those welfare impacts.

Eradication, Control and Monitoring

We have not explicitly considered policies such as eradication, control, or monitoring at the border, each of which may affect either the expected damage associated with a given arrival or the time between introductions. In the case of control, d_i^k can be viewed as the sum of (controlled) damage and control costs; where eradication is viable d_i^k would be modeled as a temporary cost incurred every time a particular species is reintroduced to Home. The remaining policy, monitoring of goods at ports of entry, could be incorporated into our simple framework in two ways. The majority of monitoring in the United States is for restricted species. Many of these "black-listed" species are restricted because they have already caused problems in the host nation (and are now either controlled or have been eradicated). Costs associated with monitoring for these species should be incorporated into the damage associated with the arrival of a particular species i . Other restricted species are those that have caused problems in a similar region abroad—the 2000 outbreak of foot-and-mouth disease in the United Kingdom and subsequent import bans by trade partners is a prominent example—and general monitoring for these "new" species by the Home country can be viewed as a non-revenue-generating trade tax by the Home country with results similar to those of a tariff. We are currently engaged in researching the optimal mix of trade taxes and monitoring efforts to control damage from exotic species introductions.

Conclusion

We develop a simple model synthesizing biological properties of species invasions with results from international trade theory. We show that protectionism, by way of an import tariff, reduces non-crop-related (ecological) damage from exotic species introductions but can raise crop-related, and hence, total damage in agriculture-importing countries. This outcome is shown to be possible because, although protectionism reduces the rate at which exotic species are introduced to the host country, it also induces price distortions that, in the case of an importer of agricultural goods, foster the expansion of agricultural activity.

This increases both the amount of crops available for damage by exotic pests as well as the area of disturbed land available for propagation of such pests. Using stylized empirical facts for various agricultural crops in multiple countries, we interpret and discuss the conditions under which this counterintuitive result is likely to occur.

Because agricultural sectors are monetized, we conjecture that detecting biological invasions causing crop-related damage is more likely than detecting an invasion with only ecological damage. We find that the rate of introductions causing crop damages provides minimal (if not outright misleading) information about the rate of ecologically damaging invasions. This has important implications for the use of existing estimates of invasion related damage: while existing estimates are staggering, they omit invasion related costs to biodiversity and other non-monetized assets.

[Received August 2001;
accepted December 2002.]

References

- Beck, K.G. "Diffuse and Spotted Knapweed." Natural Resources Fact Sheet 3.110, Colorado State University Cooperative Extension, 2001.
- Brown, J. "Patterns, Modes and Extents of Invasions by Vertebrates." In J. Drake, H. Mooney, F. di Castri, R. Groves, F. Druger, M. Rejmanek, and M. Williamson eds., *Biological Invasions: A Global Perspective*. New York: John Wiley, 1989, pp. 85–110.
- Case, T. "Global Patterns in the Establishment and Distribution of Exotic Birds." *Biological Conservation* 78(1996):69–96.
- Cox, G. *Alien Species in North America and Hawaii: Impacts on Natural Ecosystems*. Washington DC: Island Press, 1999.
- Dalmazzone, S. "Economic Factors Affecting Vulnerability to Biological Invasions." In C. Perrings, M. Williamson, and S. Dalmazzone, eds., *The Economics of Biological Invasions*. Cheltenham UK Northampton MA: Edward Elgar, 2000, pp. 17–30.
- di Castri, F. "History of Biological Invasions with Special Emphasis on the Old World." In J. Drake, H. Mooney, F. di Castri, R. Groves, F. Druger, M. Rejmanek, and M. Williamson eds., *Biological Invasions: A Global Perspective*. New York: John Wiley, 1989, pp. 1–26.
- Diebold, F., and R. Lamb. "Why are Estimates of Agricultural Supply Response so Variable?" *Journal of Econometrics* 76(1997):357–73.

- Drake, J., H. Mooney, F. di Castri, R. Groves, F. Druger, M. Rejmanek, and M. Williamson. *Biological Invasions: A Global Perspective*. New York: John Wiley, 1989.
- Fulginiti, L., and R. Perrin. "Argentine Agricultural Policy in a Multiple-input, Multiple-output Framework." *American Journal of Agricultural Economics* 72(1990):279–88.
- Gunawardana, P.J., and E.A. Oczkowski. "Government Policies and Agricultural Supply Response: Paddy in Sri Lanka." *Journal of Agricultural Economics* 43(1992):231–42.
- Hill, G., and D. Greathead. "Economic Evaluation in Classical Biological Control." In C. Perrings, M. Williamson, and S. Dalmazzone, eds., *The Economics of Biological Invasions*. Cheltenham UK Northampton MA: Edward Elgar, 2000, pp. 208–226.
- Jenkins, P. "Free Trade and Exotic Species Introductions." *Conservation Biology* 10(1996):300–2.
- Kasulo, V. "The Impact of Invasive Species in African Lakes." In C. Perrings, M. Williamson, and S. Dalmazzone, eds., *The Economics of Biological Invasions*. Cheltenham UK Northampton MA: Edward Elgar, 2000, pp. 183–207.
- Kingman, J.F. *Poisson Processes*. New York: Oxford Science Publications, 1993.
- Knowler, D., and E. Barbier. "The Economics of an Invading Species: A Theoretical Model and Case Study Application." In C. Perrings, M. Williamson, and S. Dalmazzone, eds., *The Economics of Biological Invasions*. Cheltenham UK Northampton MA: Edward Elgar, 2000, pp. 70–93.
- Legaspi, J., B. Legaspi, E. King, and R. Saldana. "Mexican Rice Borer, *Eoreuma loftini* in the Lower Rio Grande Valley of Texas: Its History and Control." *Subtropical Plant Science* 48(1997):53–64.
- Legaspi, J., T. Poprawski, and B. Legaspi. "Laboratory and Field Evaluation of *Beauveria bassiana* Against Sugarcane Stalkborers in the Lower Rio Grande Valley of Texas." *Journal of Economic Entomology* 93(2000):54–9.
- Mack, R., D. Simberloff, M. Lonsdale, H. Evans, M. Clout, and F. Bazzaz. "Biotic Invasions: Causes, Epidemiology, Global Consequences and Control." *Issues in Ecology* 5(2000):1–20.
- McGuirk, A., and Y. Mundlak. "The Transition of Punjab Agriculture: A Choice of Technique Approach." *American Journal of Agricultural Economics* 74(1992):132–43.
- Montana State University Extension Service. "Montana Knapweeds: Identification, Biology and Management." Bozeman MT, 2001.
- Montana Weed Control Association. "Spotted Knapweed." URL: <http://www.intweed.org/Identification/Knapweed/knapweed.html>, 2001.
- OTA (Office of Technology Assessment). *Harmful Nonindigenous Species in the United States*. Technical Report, United States Congress, Washington DC, 1993.
- Parker, I.M., et al. "Impact: Toward a Framework for Understanding the Ecological Effects of Invaders." *Biological Invasions* 1(1999):3–19.
- Pimentel, D., L. Lack, R. Zuniga, and D. Morrison. "Environmental and Economic Costs of Nonindigenous Species in the United States." *Bioscience* 1(2000):53–67.
- Roberts, J. "A Micro-economic Analysis of Tea Production Using a Separable Restricted Profit Function." *Journal of Agricultural Economics* 40(1989):185–97.
- Ross, S. *Stochastic Processes*, 2nd ed. New York: John Wiley, 1996.
- Shogren, J. "Risk Reduction Strategies Against the Explosive Invader." In C. Perrings, M. Williamson, and S. Dalmazzone, eds., *The Economics of Biological Invasions*. Cheltenham UK Northampton MA: Edward Elgar, 2000, pp. 56–69.
- Shogren, J., et al. "Why Economics Matters for Endangered Species Protection." *Conservation Biology* 13(1999):1257–61.
- Simberloff, D., D. Schmitz, and T. Brown. *Strangers in Paradise*. Washington DC: Island Press, 1997.
- Thiel, H., C. Chung, and J. Seale Jr. *International Evidence on Consumption Patterns*. Greenwich, CT: JAI Press, 1989.
- Tyers, R., and K. Anderson. "Price Elasticities in International Food Trade: Synthetic Estimates from a Global Model." *Journal of Policy Modeling* 11(1989):315–44.
- United States Department of Agriculture. *Track Records: United States Crop Productions*. Technical Report, URL: <http://www.usda.gov/nass/pubs/trackrec/track01d.htm>, 2001.
- . *Sugar: World Markets and Trade*. Circular series fs 02-01, 2002.
- U.S. General Accounting Office. *Invasive Species: Federal and Selected State Funding to Address Harmful, Nonnative Species*. Technical Report GAO/RCED-00-219, Report to Congressional Committees, 2000.
- USDA, APHIS, and USFS. *Pest Risk Assessment for Importation of Solid Wood Packing Materials into the United States*. Technical Report, URL: <http://www.aphis.usda.gov/ppq/praswpm/complete.pdf>, 2000.
- Williamson, M. "Invasions." *Ecography* 22(1999):5–12.

Appendix

D^k(T) as a Compound Poisson Random Variable

A function $\sum_{i=1}^N X_i$ is defined as a compound Poisson random variable if the X_i are i.i.d. random variables that are independent of N , a Poisson random variable. Recall $D^k \equiv \sum_{i=1}^J D_i^k$. By Kingman's Colouring Theorem J is a Poisson random variable with mean $T\mu(M)$; the D_i^k , however, are not i.i.d., since their distributions depend on their respective arrival times. Yet, following Ross, we can calculate the distribution of D^k by first conditioning on J ,

$$(11) \quad \Pr\{D^k \leq \delta\} = \sum_{n=0}^{\infty} \Pr\left\{ \sum_{i=1}^J D_i^k \leq \delta \mid J = n \right\} \times \frac{e^{-\mu(M)T} [\mu(M)T]^n}{n!}$$

and noting that, although the arrival times of species 1, 2, ..., J are unknown, given $J = n$ the arrival times of the n successful introductions have the

same distribution as the order statistics corresponding to n independent random variables uniformly distributed on the interval $(0, T)$ (Ross, Theorem 2.3.1). That is, if we draw n times at random from the uniform distribution over $[0, T]$ and let X_i be the damage from the i th such draw, then X_i is independent of X_j ($i \neq j$) and we can express

$$(12) \quad \Pr\left\{ \sum_{i=1}^J D_i^k \leq \delta \mid J = n \right\} = \Pr\left\{ \sum_{i=1}^n X_i \leq \delta \right\}.$$

Also note that the X_i 's have identical distributions

$$(13) \quad \Pr\{X_i \leq \delta\} = \frac{1}{T} \int_0^T F_i^k(\delta; A) dt.$$

Therefore, the distribution of D^k is the same as that of $\sum_{i=1}^J X_i$ in which J is a Poisson random variable with mean $T\mu(M)$ and the X_i 's are i.i.d. random variables with cumulative density in given by equation (13).