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

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Abstract
Unintentional introductions of non-indigenous plants, animals, and microbes cause significant ecological and agricultural crop damage worldwide; trade in both manufactured and agricultural goods has been identified as 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. Contrary to popular belief, we show that it is possible for freer trade to reduce damage arising from exotic species invasions. We also show how current measures of this damage—heavily weighted toward damages to agriculture—serve as misleading indicators of how restrictions to trade affect total losses arising from exotic species introductions.

Keywords: exotic species, trade, protectionism, environment
1 Introduction

Biological invasions by non-indigenous species\(^1\) 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 US alone is between $4.7 and $6.5 billion annually (OTA 1993); subsequent research revises that estimate for the US upward to over a hundred billion dollars a year (Pimental et al. 1999).\(^2\) Non-indigenous 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 1996). However, the relationship between protectionism and damage from exotic

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\(^1\) A non-indigenous 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 Pimental et al. calculation—and tend to overlook damage to non-monetized assets such as functioning ecosystems; consequently, 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 would be incurred in the absence of viable populations of non-native species are not deducted. For example, $27 billion of the Pimental et al. estimate comes from damages and control costs associated with non-native crop weeds. Since it is plausible that native species would either become or expand their presence as crop weeds in the absence of the non-native species, the Pimental et al. figure overestimates the true marginal cost of the non-invasive species they survey.
species is not so simple.

Using a stylized model of commodities trade, we explore how the damage arising from stochastic, unintentional\(^3\) 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. 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 and 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 reductions 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 mitigate agriculture-related damage.

\(^3\) The OTA estimates that only 12% of intentional introductions are harmful, as compared to 44% for unintended introductions; consequently, we focus only on the latter. (OTA 1993, p.62)
ages (US General Accounting Office 2000). 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. (1989), di Castri (1989) and Parker et al. (1999). 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 2000 and Kasulo 2000) and analyses of control and risk reduction methods (e.g. Shogren et al. 1999 and Shogren 2000). With the exception of a preliminary empirical analysis by Dalmazzone (2000), none explicitly incorporate the role of commodity trade in their analysis. Thus the present paper serves as a first pass at establishing theoretic relationships between invasives related damage, patterns of trade, and protectionism.

The remainder of the paper is laid out as follows. The model is described and

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4 Using a linear regression model, Dalmazzone finds a negative and statistically significant relationship between import duties and presence of non-native species; the influence of 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 non-agricultural) and country of origin.
results derived in section 2. Section 3 offers a discussion of caveats and section 4 concludes.

## 2 Model

Biological research on invasive species has generated several rules of thumb governing introduction and establishment of non-indigenous species that we take as 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 1989). Furthermore, evidence from avian populations indicates that successful introductions of non-native species is positively correlated with the number of failed introductions to that same region (Case 1996), suggesting that another factor influencing successful introduction is simple 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 is 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 interarrival time between two successive introductions is an exponentially distributed random variable\(^5\) with mean \(1/\lambda\). We assume \(\lambda\) 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 \(k = 1, \ldots, K\) 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 \(d_{ki}\), a random variable with cumulative density function \(\Phi^k(x; A)\), where \(A\) is the amount of agricultural production in Home.\(^7\)

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\(^5\) Modelling exponentially distributed inter-arrival 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 non-established species. When the pool of exotics is finite, however, we might instead expect \(\lambda\) 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 \(\lambda\) depends only on \(M\).

\(^6\) In our analysis, changes in Home’s tariff rate do not alter the identity of Home’s trading partner. However, when analyzing customs unions and free trade areas—policies which may change the set of partners with which a country trades—\(q\) should instead be modelled as endogenous. This would reflect the biological property that success rates are increasing in the similarity between the physical environments of host and original locations (Brown 1989).

\(^7\) The cumulative density function of \(d_{ki}\) may depend on \(A\) for several reasons. More agricultural activity implies 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.
We assume damage is cumulative through time. Let the random variable \( t_i \) be the arrival time of the \( i^{th} \) successful introduction. Then present value of type-\( k \) damage through time \( T \) caused by the \( i^{th} \) successful introduction is given by

\[
D^k_i(T) = e^{-rt_i} \int_{t_i}^{T} d^k_i e^{-rt} dt = d^k_i e^{-rt_i} \left[ \frac{e^{-rt_i} - e^{-rT}}{r} \right]
\] (1)

where \( r \) is the discount rate. Define the cumulative density function for \( D^k_i(T) \), conditional on \( t_i \), by \( F^k_t (\delta; A) \), 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 \( \delta \), given agricultural production is \( A \).

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 1993).

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

\[
D^k(T) = \sum_{i=1}^{J(T)} D^k_i
\] (2)

which, by Ross (1996) Theorem 2.3.1, is a Compound Poisson random variable with Poisson parameter \( T \mu(M) \) and component distribution \( \frac{1}{T} \int_0^T F^k_t (\delta; A) dt \).

(See appendix for proof.)

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8 In practice some invasive species are controlled or eradicated by the host government. Generalization of our model to permit these responses is discussed in section 3.

9 For example if \( d^k_i \sim U[0, A] \), then \( D^k_i(T) \sim U[0, Ae^{-rt_i} \left( \frac{e^{-rt_i} - e^{-rT}}{r} \right)] \), and \( F^k_t (\delta; A) = \frac{\delta}{Ae^{-rt_i} \left( \frac{e^{-rt_i} - e^{-rT}}{r} \right)} \) for \( \delta \in [0, Ae^{-rt_i} \left( \frac{e^{-rt_i} - e^{-rT}}{r} \right)] \).
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:

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

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 paper.

In order 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, input and output markets are perfectly competitive, and input supplies are perfectly inelastic.

We assume for simplicity that Home is a small open economy such that world prices are exogenous. Define \( \tau \) 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 \( \tau \)

\(^{10}\) We follow the popular convention of assuming no cross-hauling of goods even though transport costs are not explicitly modelled.
\[ \frac{dM}{d\tau} = \epsilon_M \frac{M}{P} \frac{dP}{d\tau} \]  

(4)

gives

\[ \epsilon_M \equiv \frac{dM}{dP} \frac{P}{M} \]  

is the elasticity of imports with respect to the domestic price of agricultural goods, \( P \). Given that \( \frac{M}{P} \) is non-negative then 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 \( \epsilon_M \)) 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 \( dP/d\tau = P^* \). Differentiating the expression for \( M_A \) with respect to \( P \), converting to elasticities and, for simplicity, evaluating at \( \tau = 0 \) gives

\[ \epsilon_M \bigg|_{\tau=0, M=M_A>0} = - \left[ \epsilon_C \frac{C}{M} + \epsilon_A \frac{A}{M} \right] < 0 \]  

(5)

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\(^\text{11}\).

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 \( dP/d\tau = -\frac{P^*}{(1+\tau)^2} < 0 \) and

\[ \epsilon_M \bigg|_{\tau=0, M=M_Y>0} = P^* \left[ \epsilon_C \frac{C}{M} + \epsilon_A \frac{A}{M} \right] > 0 \]  

(6)

Combining (4) with (5) and (6) gives the expected result that increased protectionism reduces the volume of imports into Home. Since imports serve as a platform

\(^{11}\) We assume away the possibility of Giffen goods.
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), (5) and (6), then

\[
\frac{d\mu(M)}{d\tau} = q \left( \frac{d\lambda}{dM} \frac{dM}{d\tau} \right) < 0.
\]

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 non-agricultural 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 Jenkins (1996) and others in 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 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
\[
\frac{dE[D^k]}{d\tau} = [\epsilon^F + \epsilon^A + \epsilon^M] q\lambda E_\delta \left[ \int_0^T F^k_t(\delta; A(t)) dt \right] \frac{dP}{d\tau}
\]  
where \(\epsilon^F\) is the elasticity of expected type \(k\) damage to the level of agricultural activity \((\epsilon^F \equiv \frac{dE_\delta[\int_0^T F^k_t(\delta; A(t)) dt]}{dA} \frac{A}{E_\delta[\int_0^T F^k_t(\delta; A(t)) dt]})\) 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 \(\epsilon^\lambda\) and \(\epsilon^A\) are both positive; \(E_\delta \left[ \int_0^T F^k_t(\delta; A(t)) dt \right]\) is positive so long as expected type \(k\) damage is positive (which we assume to be the case\(^{12}\)); the sign of \(\epsilon^M\) for each type of importer is given by equations (5) and (6).

Only the sign of \(\epsilon^F\) 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 \(\epsilon^F > 0\), and
2. “Neutral” Damages - Types of damage for which \(\epsilon^F \simeq 0\),
3. “Diminished” Damages - Types of damage for which \(\epsilon^F < 0\).

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

\(^{12}\) 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.
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. 2000).

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; 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, we obtain the following proposition.

**Proposition 2** For a small open economy that initially imports agricultural goods, an increase in the tariff rate $\tau$

(i) unambiguously reduces expected Neutral and Diminished type damages and

(ii) raises expected Augmented type damages $k$ if and only if

\[ \epsilon A > \frac{\epsilon C}{M} \left[ \epsilon C + 1 \right] ; \]
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 if and only if

\[-\epsilon F_k > \epsilon^A \frac{AP^*}{\epsilon^A A + 1} \]

**Proof** Using (5) to substitute in for $\epsilon^M$ in (7) and rearranging gives

\[
\frac{dE[D^k]}{d\tau} = \left\{ \epsilon F_k - \frac{\epsilon^A A}{M} \left[ \frac{\epsilon^C C}{\epsilon^A A + 1} \right] \right\} P^* \epsilon^A q \lambda E_\delta \left[ \int_0^T F^k_t (\delta; A(t)) dt \right]
\]

when Home is an importer of agricultural goods and

\[
\frac{dE[D^k]}{d\tau} = - \left\{ \epsilon F_k + \frac{\epsilon^A P^* A}{M} \left[ \frac{\epsilon^C C}{\epsilon^A A + 1} \right] \right\} P^* \epsilon^A q \lambda E_\delta \left[ \int_0^T F^k_t (\delta; A(t)) dt \right]
\]

when Home instead exports agricultural goods. Noting that $P^* \epsilon^A q \lambda E_\delta \left[ \int_0^T F^k_t (\delta; A(t)) dt \right]$ is positive and invoking the definitions of Augmented, Neutral and Diminished type damages based on their signs completes the proof.

These results are summarized in the following table:

<table>
<thead>
<tr>
<th>Sign of $\frac{dE[D^k]}{d\tau}$</th>
<th>Augmented</th>
<th>Neutral</th>
<th>Diminished</th>
</tr>
</thead>
<tbody>
<tr>
<td>Importer of Ag. goods</td>
<td>?</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Exporter of Ag. goods</td>
<td>-</td>
<td>-</td>
<td>?</td>
</tr>
</tbody>
</table>

Proposition 2 supports our claim that, for some countries, reduced trade may indeed **raise** the expected damage arising from exotic species. In our simple model reduced trade volumes do indeed reduce the expected number of successfully introduced exotic species (c.f. proposition 1). But because the policies used to reduce trade—in our case a tariff—also affect the production mix in an economy, they consequently affect 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. For a country that imports agricultural products, then by proposition 2 when Augmented type damages are relatively sensitive to agricultural activity ($\epsilon F_k$ large), the introduction rate is relatively
insensitive to trade volumes ($e^\lambda$ small), and/or the price elasticity of demand for agricultural goods is low relative to the price elasticity of Home’s agricultural supply, then we can expect increased protectionism to lead to increased Augmented type damage. Depending on the relative magnitudes of Augmented, Neutral and Diminished type damages in the host country, overall damage can actually rise with protectionism.

This latter possibility raises an interesting problem. Since Neutral and Augmented type damages may change in different directions following an alteration in trade policy, then 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 invasive species. In 2000, a total of approximately $632 million was obligated by federal departments towards 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 communities\textsuperscript{13} (United States General Accounting Office 2000). Given that invasives are considered the “second largest threat (globally) ... to biodiversity” (Williamson 1999, p.5), and are linked to the decline of 400 of the 958

\textsuperscript{13}Including the US Fish and Wildlife Service.
species on the US’s list of endangered species (Pimental et al. 1999), it is apparent that invasives related damages to non-agricultural 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.

3 Caveats

3.1 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 paper 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 US’s 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 re-orientation 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.\textsuperscript{14} Of course we do not promote
such introductions, as it would be superior to eliminate the inefficient subsidies to
begin with. We offer this example merely to re-iterate the point from the literature
on environmental double-dividends that pre-existing distortions alter the welfare im-
pacts of policy changes, even possibly to the extent of changing the signs of those
welfare impacts.

3.2 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 from
a given arrival or the time between introductions. In the case of control, $d^k_i$ can be
viewed as the sum of (controlled) damage and control costs; where eradication is
viable $d^k_i$ would be modelled as a temporary cost incurred every time a particular
species is re-introduced 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
\textsuperscript{14} We thank Tom Heller for suggesting this possibility.
monitoring for these species should be incorporated into the damage associated with
the arrival of a particular species \( i \). Other restricted species are ones 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 of the UK 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 as monitoring efforts to control damage from exotic species
introductions.

4 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 intro-
ductions 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, fos-
ter 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.

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 ecolog-
ically 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.

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
$D^k \equiv \sum_{i=1}^{J} D^k_i$. By Kingman’s Colouring Theorem $J$ is a Poisson random variable
with mean $T\mu(M)$; the $D^k_i$, however, are not i.i.d., since their distributions depend
on their respective arrival times. Yet, following Ross (1996), we can calculate the
distribution of $D^k$ by first conditioning on $J$,

$$Pr\{D^k \leq \delta\} = \sum_{n=0}^{\infty} Pr\left\{\sum_{i=1}^{J} D^k_i \leq \delta \left| J = n\right\} \frac{e^{-\mu(M)T}[\mu(M)T]^n}{n!} , \tag{8}$$

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 1996, 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

\[
Pr \left\{ \sum_{i=1}^{J} D^k_i \leq \delta \middle| J = n \right\} = Pr \left\{ \sum_{i=1}^{n} X_i \leq \delta \right\}
\]  

(9)

Also note that the \(X_i\)’s have identical distributions:

\[
Pr\{X_i \leq \delta\} = \frac{1}{T} \int_0^T F^k_t(\delta; A) dt.
\]  

(10)

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 as given by equation 10.

**References**


