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Abstract

Unintentional introductions of non-indigenous plants, animals, and microbes cause significant ecological and agricultural crop damage worldwide. There is an emerging empirical link between international trade and the frequency and damage of such introductions. We explore the effects of domestic agricultural protection on exotic species introductions. In contrast to the commonly held belief that agricultural protection harms the environment, we show that increasing agricultural protection may reduce ecological damage from exotic species introductions. Contrary to common policy, we demonstrate that an estimate of pecuniary damage from crop loss is an inappropriate proxy for ecological damage from exotic species introductions.

Keywords: agricultural policies, environmental damage, exotic species, trade

1 Introduction

Introductions of non-indigenous species 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

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1993); subsequent research revises that estimate for the US upward to over a hundred billion dollars a year (Pimental et al. 1999). Moreover, since these estimates derive mostly from costs calculated for agriculture[1], there is consensus that these numbers are lower bounds. There are numerous pathways by which non-indigenous species enter a country: contaminated agricultural products, timber, potted plants, ballast water and packing materials are primary conduits for unintentional introductions[2]. We focus on introductions facilitated by commodities trade and explore how changes in agricultural protection affect patterns of trade and subsequent damage to local agricultural and ecological systems from exotic species introductions.

In our stochastic model, exotic species introductions, success, and damage are functions of the volume of trade and agricultural production. The model is coupled with results from international trade theory that link volumes of production and trade to agricultural policies such as output subsidies. This simple structure generates several compelling insights. First, we show that increases in agricultural subsidies may improve overall ecosystem health despite common opposition to agricultural protectionism by environmental advocates. This arises because protectionist trade policies in agriculture importing countries reduces imports, often from species-rich tropical regions, such that the rate of exotic species introductions will likely fall with reduced subsidies.

Second, we establish that crop damages are a poor proxy for overall damages

[1] Agriculture related costs alone make up between 90% and 93% of the OTA estimate and over half of the Pimental et al. calculation. Other significant contributions come from human health care costs and damage to forestry, fisheries, and recreation.

[2] Some exotic species are introduced intentionally, however they are not our focus as the OTA estimates that only 12% of intentional introductions are harmful, as compared to 44% for unintended introductions (OTA 1993, p.62)

associated with biological invasions. Crop damage arising from biological invasions may rise as a result of increased protectionism, either because there are more crops available to be damaged or because there is more agricultural land available on which non-native species can gain a foothold. But because increased protectionism will reduce the volume of imports in agriculture importing countries, ecological—and hence total—invasion-related damage may nonetheless fall.

Third, we argue that the ecological impacts of increasing agricultural subsidies may be markedly different for agriculture exporting versus agriculture importing countries. For countries that initially export agricultural products, increases in production subsidies will lead to an increase in both the volume of agricultural output and in the volume of trade, with unambiguously negative consequences for overall ecological health. In sum, the ecological consequences of raising agricultural subsidies are reversed in agriculture importing countries.

In section 2 we discuss the relevant economic and ecological literatures. We then describe our model in section 3, derive results in section 4, and briefly conclude in section 5.

2 Literature Review

An exotic species, also referred to as an alien, transplanted, nonindigenous 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), reproduced in Williams and

Meffe (1995), p.2). Ecologists have studied the consequences of invasive species extensively; see Drake et al. (1989), di Castri (1989), Parker et al. (1999), and Shogren (1999) for overviews. This research has established several patterns governing successful exotic species introductions. For example, successfully introduced exotic species tend to be native to nonisolated habitats within continents and their success is enhanced with the similarity in physical environments between the original and exotic locations (Brown 1989). Furthermore, species that inhabit disturbed environments tend to be successful at invading human-modified environments (Brown 1989). These and other empirical observations suggest that predictions of the frequency and severity of exotic species introductions can be made on the basis of factors such as similarity in physical environments between trading partners, trade volume, and the extent to which the home country modifies its natural environment.

Despite the extensive study of the ecological impacts of non-indigenous species, rigorous economic treatment of the problem is lacking. The little attention paid by economists to the problem of invasive species has focused largely on case studies (e.g. Knowler and Barbier 2000 and Kasulo 2000) and analysis of control and risk reduction methods (e.g. Shogren et al. 1999 and Shogren 2000). With the exception of Dalmazzone (2000), none explicitly incorporate the role of commodity trade in their analysis. Using a linear regression model, Dalmazzone finds a strong, positive and statistically significant relationship between the ratio of exotic to native species in a region and both its GDP/capita (lagged) and its population density. Indicators of disturbance such as percentage of land devoted to agriculture and pasture are also positively correlated (and statistically significant). Dalmazzone finds weaker evidence of a link between susceptibility to biological invasions and engagement in trade: although she 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. Given the biological rules of thumb governing invasions, a superior econometric specification would decompose imports by type (agricultural versus non-agricultural) and country of origin, as recognized by Dalmazzone. Moreover, we believe empirical testing would benefit from a more thorough understanding of the mechanisms in which trade policies and flows affect introduction and damage rates. The present paper serves as a first pass at establishing these relationships theoretically.

3 Model

As a consequence of trade, a small open economy ("Home") is susceptible to damages from exotic species invasions. We make the following biophysical assumptions which are widely accepted in the literature:

- Arrivals of exotic species to a particular location is a stochastic process.
- An introduced individual's success at coping with the new environment is random, suggesting that a particular species may require several invasion "attempts" before it is successful.

- Each successfully invading species causes a random amount of damage that is cumulative from the time of arrival onwards.

3.1 Stochastic Introductions, Success, and Damage

We operationalize the assumptions above into a stochastic model of biological invasions using the following three steps:

1. *Introduction* - An introduction occurs when human activity facilitates the transport of an exotic species to Home, though the introduction need not take hold in its new location. We assume that the interarrival time between two successive exotic species introductions is an exponentially distributed random variable[3] with mean $1/\lambda$. We assume λ is an increasing function 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 p; p will also be referred to as the probability of success. We assume p is constant.[4]

3. *Damage* - Successfully introduced species can cause various types of damage including ecological catastrophe and pecuniary losses to agriculture. The instantaneous damage of type k—measured in dollars—caused by the i^{th} successful

[3] The exponential distribution has the unique property of being "memoryless" and is often used to describe the time between successive arrivals. The memoryless property means that the probability that it takes at least $s + t$ days for an exotic species to arrive given that it has not arrive in t days is the same as the initial probability that it takes at least s days to arrive.

[4] In our analysis, changes in Home's agricultural policy 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—p should instead be modeled 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).

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.[5] The sign of $\frac{d\Phi^k(x;A)}{dA}$ depends on whether the i^{th} successfully introduced species causes predominately ecological or pecuniary damage. We return to this point in section 4.

We assume damage is cumulative through time. Let t_i be the arrival time of the i^{th} successful introduction. Then present value of type-k damage through time τ caused by the i^{th} successful introduction is given by

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

where r is the discount rate. Define the cumulative density function for $D_i^k(\tau)$, conditional on t_i, by $F_{t_i}^k(\delta; A)$, which gives the probability that a successful arrival at time t_i has a present value of type-k damage by time τ of less than δ, given agricultural production is A.[6]

If there are $J(\tau)$ successful introductions by time τ, then the present value of type-k damage by time τ is as follows:

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

where $J(\tau)$ and D_i^k are random variables. In order to economize on notation, in the analysis to follow we drop the τ terms in the expressions for damage, number of introduced species and number of successfully introduced species.

[5] The cumulative density function of d_i^k may depend on A for several reasons. First, more agricultural activity implies larger volumes of crops are present and susceptible to destruction by pests, either before or after harvest. And second, larger crop sizes correspond to larger areas under cultivation and hence to higher levels of "disturbance" of native ecosystems, increasing the size of the foothold from which non-native species can base an invasion.

[6] For example if $d_i^k \sim U[0, A]$, then $D_i^k(\tau) \sim U[0, Ae^{-rt_i}\left(\frac{e^{-rt_i} - e^{-r\tau}}{r}\right)]$, and $F_{t_i}^k(\delta; A) = \frac{\delta}{Ae^{-rt_i}\left(\frac{e^{-rt_i} - e^{-r\tau}}{r}\right)}$ for $\delta \in [0, Ae^{-rt_i}\left(\frac{e^{-rt_i} - e^{-r\tau}}{r}\right)]$.

3.2 Introductions, Damages, and Trade

This section formally characterizes the stochastic processes governing introductions and damages through time. Lemmas developed here will be used in section 4 to prove our main results. Let N and J be the number of introductions and successful introductions (respectively) to Home by time τ. Then, we immediately have the following lemma:

Lemma 1 [Introductions]: *N is a Poisson Process (PP) with rate $\lambda(M)$, and J is a PP with rate $\mu(M) \equiv p\lambda(M)$; $\mu' > 0$.*

Proof *By definition, any stochastic counting process with exponentially distributed interarrival times (with a constant parameter) is a Poisson process with rate equal to the inverse of the mean of the exponential arrival time process.*
By the Colouring Theorem (Kingman 1993), if we independently "color" each arriving introduction as "successful" with probability p and "unsuccessful" with probability $1-p$, the number of successful introductions and the number of unsuccessful introductions by time τ are independent Poisson processes with rates $p\lambda(M)$ and $(1-p)\lambda(M)$, respectively. Furthermore, $\mu' = p\lambda' > 0$.

But how much can we say about the *damages* caused by these introductions? Under the assumptions of this model, the present value of type-k damages by time τ has a known distribution. This is summarized in the following lemma:

Lemma 2 *Present value of cumulative type-k damage by time τ, D^k, is a compound Poisson random variable with Poisson parameter $\tau\mu(M)$ and component distribution $\frac{1}{\tau}\int_0^\tau F_t^k(\delta; A)dt$.*

Proof *See appendix.*

Using Lemma 2 and known results for the compound Poisson random variable, we can immediately write the expected value of type-k damage through time τ as follows:

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

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

$$D \equiv \sum_k D^k \,.$$

In order to derive results concerning stochastic arrivals of and damage from exotic species, we 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. Define S as a production subsidy in agriculture and denote the second sector, manufacturing, by Y. Denote the world price of agricultural goods by P; let manufactures be numeraire. Define by M_j the Home country's net imports of good j. In our two country framework, balanced trade requires $PM_A + M_Y = 0$. This implies that at most one good is imported and so $M = max\{M_A, M_Y\}$.[7]

Using this simple framework we have the following lemma:

Lemma 3 *When $S = 0$ initially and Home is a small[8] open economy engaged in balanced trade, then*

$$\frac{dM}{dS} = -\frac{dA}{dS} = -\epsilon^A \frac{A}{P} < 0 \tag{4}$$

if Home initially imports agricultural goods (i.e. $M_A > 0$), and

$$\frac{dM}{dS} = P\frac{dA}{dS} = A\epsilon^A > 0 \tag{5}$$

if Home initially exports agricultural goods (i.e. $M_Y > 0$), where ϵ^A is the elasticity of Home agricultural output ($\epsilon^A \equiv \frac{dA}{dP}\frac{P}{A}$) with respect to the price faced by Home agricultural producers.

[7] In the absence of transportation costs, it is possible that gross imports exceed net imports of any particular good, since trade partners may engage in costless cross-hauling of goods. However, when production exhibits constant returns to scale and markets are perfectly competitive, any arbitrarily small transportation cost will eliminate cross-hauling, such that gross imports equal net imports. We adopt the popular convention of assuming no cross-hauling of goods even though transport costs are not explicitly modeled.

[8] In trade theory, a country is considered small if its own behavior has no affect on world relative prices.

Proof *See appendix.*

The reader should note that, although our focus is on agricultural production subsidies, the analysis of more directly protectionist policies such as import tariffs or export taxes requires only small variation in lemma . The interested reader is directed to Woodland (1982). Cases in which Home is not a small country, in which the production subsidy S is not initially zero, or in which cross-hauling occurs are discussed in section 4.1. In the next section we employ Lemmas 1-3.2 to derive results about the likely effects of changes in domestic agricultural policy on damages from exotic species introductions.

4 Results

We explore the effects of agricultural protectionism, via an increase in subsidies to domestic agricultural producers, on expected damage arising from biological invasions. It is shown that the magnitude of change in expected damage (and indeed, its sign) depend critically on two things: (1) the responsiveness of damages to changes in agricultural output and (2) the response of imports to agricultural subsidies. We show that offering (small) subsidies in an agriculture importing country will reduce both its rate of introductions and the ecological damage caused by the introductions. We further demonstrate that changes in crop damage are a misleading proxy for the effects of protectionist policy on ecological and total damages arising from biological invasions. This latter claim 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. We begin with the following proposition:

Proposition 1 *For a small open economy that is an* $\begin{bmatrix} importer \\ exporter \end{bmatrix}$ *of agricultural goods, increasing domestic agricultural subsidies* $\begin{bmatrix} decreases \\ increases \end{bmatrix}$ *the rate of exotic species introductions.*

Proof *The arrival rate of exotic species to Home is* $\lambda(M)$ *per unit time, the rate of the Poisson Process* N. *Since* $\lambda'(M) > 0$ *and, by Lemma 3.2* $\frac{dM}{dS}$ $\begin{bmatrix} < 0 \\ > 0 \end{bmatrix}$ *when Home is an* $\begin{bmatrix} importer \\ exporter \end{bmatrix}$ *of agricultural goods, then* $\frac{d\lambda}{dS} = \underbrace{\frac{d\lambda}{dM}}_{+} \underbrace{\frac{dM}{dS}}_{-,+}$.

Proposition 1 makes the simple point that increased support for Home's agriculture industry may reduce the rate at which exotic species are introduced because of the effects agricultural subsidies have on the volume of trade. For countries that import agricultural goods, production subsidies lead increased output of locally produced agricultural goods to displace imports, thereby reducing the overall volume of trade as the country moves toward self-sufficiency. As reduced volume of trade reduces the size of the platform for non-native species introductions into a country, the expected rate of introductions N, and consequently the number of non-native species that take hold J, is thereby reduced.

Alternately, if a country instead initially exports agricultural goods, an increase in S raises the volume of trade since it induces greater agricultural output, exports of which finance greater imports of manufactured goods. Although there is a tendency to equate species introductions with imports of agricultural goods, trade in non-agricultural goods also frequently serves as a conduit for biological introductions, either through contaminated ballast water from ships, or infestations of packing materials and manufactured goods themselves. It is possible that λ may depend differently on imports of different types—we abstract from this issue in the interest of simplicity—nonetheless the larger volume of trade arising from subsidies in agriculture exporting countries increases the platform for introductions and so raises the expected values of N and J.

Based on proposition 1 it is tempting to join the chorus that calls for reduced trade as a means to stem the influx of non-native species. However not all successful introductions cause damage, and moreover the extent of damage caused is endogenous. In order to establish the impact that changes in agricultural subsidies have on expected damage, we ask the following question: If domestic agricultural subsidies were marginally increased at time 0, what would be the effect on the present value of type-k damage through time τ? That is, we seek the sign of the derivative, $\frac{dE[D^k]}{dS}$. Differentiating (3) and factoring out time invariant terms gives

$$\frac{dE[D^k]}{dS} = p\left[\underbrace{\lambda\, E_\delta\left[\int_0^\tau \frac{dF_t^k(\delta; A(S))}{dA}dt\right]}_{\Psi_1^k}\underbrace{\frac{dA(S)}{dS}}_{+} + \underbrace{\frac{d\lambda}{dM}}_{+}\underbrace{\frac{dM}{dS}}_{\Psi_2}\underbrace{E_\delta\left[\int_0^\tau F_t^k(\delta; A(S))dt\right]}_{+}\right] \tag{6}$$

the sign of which is ambiguous. The first ambiguous term (Ψ_1^k) describes the responsiveness of expected type-k damage from a given number of successfully introduced species to changes in the level of agricultural activity. The second ambiguous term (Ψ_2) depends on the effect of subsidies on net imports (its sign is covered by Lemma 3.2).

At this point it is convenient to disaggregate the many types of damage that can be caused to Home into the following three categories:

1. "Neutral" Damages - Types of damage for which $E_\delta\left[\int_0^\tau \frac{dF_t^k(\delta;A(S))}{dA}dt\right] \simeq 0$,
2. "Augmented" Damages - Types of damage for which $E_\delta\left[\int_0^\tau \frac{dF_t^k(\delta;A(S))}{dA}dt\right] > 0$, and
3. "Diminished" Damages - Types of damage for which $E_\delta\left[\int_0^\tau \frac{dF_t^k(\delta;A(S))}{dA}dt\right] < 0$.

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 invasion related damage are unlikely to depend directly on the level of agricultural activity. Introductions affecting marine and aquatic systems are good examples of this: invading mollusks foul water intake systems at power generation facilities; introduced fish 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 concerning the effects of agricultural output subsidies on expected damages in importing and exporting countries:

Proposition 2 *For a small open economy that initially imports agricultural goods, an increase in the output subsidy S unambiguously reduces expected Neutral and Diminished type damages; the effect of $dS > 0$ on expected Augmented type damages is ambiguous.*

Proof *For an agriculture importing economy, $\frac{dM}{dS} < 0$ (lemma 3.2) and hence Ψ_2 is negative. If Ψ_1^k is either negative or positive but sufficiently close to zero, as in the case of Diminished and Neutral type damages, then (6) is unambiguously negative; otherwise the sign of (6) is ambiguous.*

Proposition 3 *For a small open economy that initially exports agricultural goods, an increase in the output subsidy S unambiguously raises expected Neutral and Augmented type damages; the effect of $dS > 0$ on expected Diminished type damages is ambiguous.*

Proof *For an exporter of agricultural goods, $\frac{dM}{dS} > 0$ by Lemma 3.2 and hence Ψ_2 is positive. If Ψ_1^k is either positive or negative but sufficiently close to zero, as in the case of Augmented and Neutral type damages, then (6) is unambiguously positive; otherwise the sign of (6) is ambiguous.*

These results are summarized in the following table:

sign($\frac{dE[D]}{dS}$)	Neutral	Augmented	Diminished
Importer	-	?	-
Exporter	+	+	?

In order to interpret these propositions we focus on damage in an agriculture importing country; the interpretation for an exporter relies on identical concepts.

¿From proposition 1 an increase in the subsidy reduces the rate of introductions into an agriculture importing country. However from proposition 2 the effect on total damage is ambiguous: although expected Neutral and Diminished damage is reduced because there are fewer (expected) introductions, it is possible that expected Augmented damage is larger since domestic agriculture has expanded. If Augmented type damages are highly sensitive to agricultural activity, or the introduction rate is insensitive to trade volumes, then we can expect increased agricultural subsidies to lead to increased invasion related damage. If instead introduction rates are sufficiently sensitive to the volume of trade, then an increase in agricultural subsidies may instead reduce expected invasion related damage.

This latter possibility raises an interesting problem. Since Neutral and Augmented type damages may change in different directions following an alteration in agricultural policy, then estimates of invasion related damage that are based on one type of damage serve as poor—even misleading—indicators of total damage. As noted in the introduction, most real-world estimates of invasion related damage derive predominately from estimates of damage to crops and livestock. However, as proposition 2 indicates, crop (Augmented) damage may be increasing while Neutral and Diminished damages, and hence total damages, are decreasing. This insight confirms our earlier conjecture: economic measures of crop damage are a misleading indicator of total damages arising from biological invasions. For the policy change considered here, an increase in the agricultural output subsidy S changes in crop damage overestimate changes in total damage, and may indicate an increase in total damage even when total damage is in fact declining.

As outlined in proposition 3, the effects on an increase in S on damages in an agricultural exporter differ from the effects felt by an importer. Again higher S spurs local agricultural production, however for an agricultural exporter this finances greater imports. Consequently both the rate of successful introductions and the volume of susceptible crops rise. Combined these two effects lead to an unambiguous increase in both crop and ecological damage in the agricultural importer. For the case of a simple production subsidy this suggests that, for agriculture exporting countries, invasion related crop damage serves as an adequate proxy for the sign of ecological and total invasion related damage. However, since more complex policies—for example a combination of subsidies to producers *and* consumers of agriculture—may instead generate changes in crop and ecological damage of opposite signs, we reiterate our general concern over the use of crop damages as a proxy for total invasion related damages.

4.1 Caveats

4.1.1 Model Variations

In this section we discuss the likely consequences of relaxing some of the important assumptions of our model. The distribution of interarrival times for successive introductions is stationary in this model. More appropriately, perhaps, we can think of the arrival rate as dependent on the number of successful introductions in the past. This would be appropriate, for example, if there was a finite pool of exotic species which was being "whittled away" as introductions became successful. In real life, the pool of exotic species is orders of magnitude larger than, say, the expected number of successful introductions in a given year—suggesting that our approximation of the process as homogeneous with respect to time is appropriate.

We have also made several simplifying assumptions concerning the nature of the commodities trade: Home is a small, undistorted economy that does not engage in intra-industry trade. If Home is instead a large country in the market for agricultural goods, then changes in the Home subsidy rate that spur local production also affect world prices. Under general conditions[9] it can be shown that an increase in S lowers the world price of agricultural goods if Home initially imports agricultural goods. This price change induces a change in local consumption such that (4) overestimates the magnitude of the change in Home imports: as the world price of agricultural goods falls, Home consumers want to buy more, so Home imports fall by less than the increase in Home production of agricultural goods. Indeed, if the elasticity of import demand in Home's trade partner is less than unity, Home imports of agricultural goods actually rise with an increase in S (not shown). Interpreting Propositions 2 and 3 in this context reveals that the usefulness of agricultural subsidies as an indirect means of reducing successful introductions of non-native species is limited, or even reversed, when prices on world markets are responsive to local policy changes.

Another caveat concerns the extent to which the Home economy is initially distorted. In the case where $S \neq 0$ initially then Home production does not maximize Home GDP given world relative prices. Similar to the case of a large open economy, when GDP is not initially maximized then (4) does not accurately represent the change in imports arising from a change in S since consumer demands also change. In particular, if $S > 0$ initially then $dS > 0$ further reduces aggregate income; if agricultural goods are inferior then consumer demand decreases (such that (4) overestimates the magnitude of $\frac{dM}{dS}$), if agricultural goods are normal then consumer demand increases such that (4) underestimates the magnitude of $\frac{dM}{dS}$). This sort of

[9] In particular, if the import demand elasticities in Home and in Home's trade partner sum to a number greater than one then the Marshall Lerner condition for stability of a trading equilibrium holds (see Woodland 1982) such that $\frac{dP}{dS} < 0$ if $M_A > 0$ initially.

distortion—industrial mix that does not maximize GDP—alters the magnitude of $\frac{dM}{dS}$ but does not meaningfully alter propositions 2 and 3.

Finally, suppose that countries engage in intra-industry trade in goods. In such a case, changes in net imports misrepresent the true impacts of trade policy changes since rates of exotic species introductions depend not on net imports but *gross* imports. For example, while the United States is a net exporter of agricultural goods (US net exports of agricultural goods in 2000 was valued at $12,632 million), its imports of agricultural goods are substantial: $37,755 million in 2000 (US Census Bureau, 2001). Cross-hauling of goods can arise for a variety of reasons, and the implications for the validity of propositions 2 and 3 depends on the underlying source of the cross-hauling.

First, agricultural commodities include a large variety of goods, from coffee to corn to vegetables and fruit. Some of these goods the US predominately imports (coffee) and some of these it predominately exports (corn). Reinterpreting S in our model as a subsidy to a single agricultural industry—corn—and subsuming the non-subsidized sector—coffee—in the Y industry would be sufficient to generalize our model to include such cases.

However some goods are both imported and exported, such as vegetables and fruit. Some of this cross-hauling can be explained easily by the fact many countries are geographically large and diverse. For example, although apples are grown in Washington State, it may be cheaper for Alaskans to import them from British Columbia. Cross-hauling derived from this source could also be accommodated easily into our model by making the state, rather than the country, the unit of analysis.

Remaining explanations for cross-hauling of goods across regions are product differentiation—e.g. consumers view Gala apples as imperfect substitutes for Fuji applies—and imperfect competition—large fixed costs restrict competition and firms engage in potentially costly intra-industry trade in the search of abnormal profits. We do not address cases of cross-hauling arising from these sources. However, we believe that the essence of the problem will remain: in our model above domestically subsidized agricultural output either displaces imported products in domestic consumption (reducing M) or finances more imports (raising M). In the presence of intra-industry trade these effects may occur simultaneously and whichever dominates determines the sign of $\frac{dM}{dS}$ and hence the sign of Ψ_2 in a modified model. We believe that treating Ψ_2 as negative or positive (and Home, respectively, as an importer or exporter of agricultural goods) as the case may be would generalize propositions 2 and 3 to the case in which agricultural products are cross-hauled.

4.1.2 Averting Behavior

As discussed earlier, one of the means by which exotic species impose damage on the host country is through destruction of crops. 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.[10] 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 impacts of policy changes, even possibly to the extent of changing the signs of those welfare impacts.

5 Conclusion

Environmental advocates often criticize agricultural protectionism on the grounds that it promotes inefficiently excessive input use. On the other hand, such policies tend to increase domestic production of agricultural products, thereby reducing the demand for imports. One potentially severe consequence of greater agricultural imports is the inadvertent bundling with harmful exotic species. In this paper we explore the effects of relaxing domestic agricultural protection on exotic species introductions.

[10] We thank Tom Heller for suggesting this possibility.

We develop a simple model that synthesizes a stochastic model of species invasions and results from international trade theory. We show that agricultural protectionism reduces ecological damage from exotic species introductions in agriculture importing countries and raises it in agriculture exporting countries. This result is driven by both economic and ecological forces. First, as subsidies and tariffs increase, imports of agricultural products fall; since agriculture tends to be produced by species-rich continental nations, the rate of introductions falls.

However, since domestic protection tends to increase Home agricultural production, the monetary (as opposed to ecological) harm from any one exotic species is higher. So although the rate of introductions is lower, its effect on agricultural crop damage must ultimately be weighed against the larger size of susceptible crops, so the net impact could go either way.

Because agricultural sectors are monetized, we conjecture that detecting biological invasions causing pecuniary damage is more likely than detecting an invasion with only ecological damage. We find that the rate of introductions causing pecuniary 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. Moreover, as the US reduces its agricultural protectionism in keeping with its Uruguay round commitments, we may see these estimates of invasion related damage fall, even though ecological and total damages may in fact rise.

Appendix

Proof of Lemma 2

A function $\sum_{i=1}^{J} X_i$ is defined as a compound Poisson random variable if the X_i are i.i.d. random variables that are independent of J, a Poisson random variable. By definition $D^k \equiv \sum_{i=1}^{J} D_i^k$. To prove D^k is a compound Poisson random variable, it is sufficient to show that $\sum_{i=1}^{J} D_i^k$ has the same distribution as a compound Poisson random variable.

By Lemma 1, J is a Poisson random variable with mean $\tau\mu(M)$. The D_i^k, however, are not i.i.d., since their distributions depend on their respective arrival times. However, we can calculate the distribution of D^k by first conditioning on J:

$$Pr\{D^k \leq \delta\} = \sum_{n=0}^{\infty} Pr\left\{ \sum_{i=1}^{J} D_i^k \leq \delta \,\middle|\, J = n \right\} \frac{e^{-\mu(M)\tau}[\mu(M)\tau]^n}{n!} \,. \tag{7}$$

The problem is, we do not know the arrival times of arrivals 1, 2, ..., J. However, following Ross (1996), 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 $(0, \tau)$ (Ross 1996, Theorem 2.3.1). So, we draw n times at random from the uniform distribution over $[0, \tau]$ 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

$$Pr\left\{ \sum_{i=1}^{J} D_i^k \leq \delta \,\middle|\, J = n \right\} = Pr\left\{ \sum_{i=1}^{n} X_i \leq \delta \right\} \tag{8}$$

Also note that the X_i's have identical distributions:

$$Pr\{X_i \leq \delta\} = \frac{1}{\tau} \int_0^{\tau} F_t^k(\delta; A)dt \,. \tag{9}$$

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 $\tau\mu(M)$ and the X_i's are i.i.d. random variables with cumulative density given by equation 9.

Proof of Lemma 3

In a small open economy in which consumer and producer prices are initially undistorted (i.e. $S = 0$ initially), aggregate income and hence consumer demands are unaffected by a marginal increase in S such that $\frac{dM_A}{dS} = -\frac{dA}{dS} = -\frac{dA}{dP}\frac{d[P+S]}{dS} = -\epsilon^A \frac{A}{P}$. In the case where Home initially imports agricultural goods $\frac{dM}{dS} = \frac{dM_A}{dS}$; this verifies (4). If instead Home is an exporter of agricultural goods, then $\frac{dM}{dS} = \frac{dM_Y}{dS}$. By balanced trade $\frac{dM_Y}{dS} = -P\frac{dM_A}{dS} = P\frac{dA}{dS} = A\epsilon^A$, which verifies (5). That ϵ^A is positive under reasonable conditions when production in Home is initially diversified is a well established result; see, for example, Woodland (1982).

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