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Trade, the Damage from Alien Species, and the Effects of Protectionism Under  
Alternate Market Structures

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# **Trade, the Damage from Alien Species, and the Effects of Protectionism Under Alternate Market Structures<sup>1</sup>**

by

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## Abstract

We first construct three measures of the expected damage from the unintentional introduction of alien species into a country called Home. We then focus on four market structures. First, perfect competition prevails in both Home and Foreign and Home is a small country. Second, the Home and the Foreign markets are both perfectly competitive but Home is now a large country. Third, the exporter in Foreign is a monopolist and there are no import competing firms in Home. Finally, the Foreign exporter and the import competing firm in Home engage in Cournot competition. In all four scenarios, we analyze the impact of small and optimal Home tariffs on prices, exports, imports, the damage from alien species, and social welfare, in Home. *Inter alia*, our analysis identifies conditions under which it makes sense to use trade policy (tariffs) to regulate invasive species and conditions under which it does not.

Keywords: Alien Species, International Trade, Market Structure, Social Welfare, Tariff

JEL Codes: Q560, F130, F180

## 1. Introduction

The fact that alien species (also known as invasive or non-native species) have been and continue to be introduced into one part of the world from another is not new. What is new is the realization that such introductions, particularly the unintentional ones, have often been very costly for the concerned nations. In this regard, consider the case of the United States. A report by the Office of Technology Assessment (OTA (1993)) declared that the annual monetary damage resulting from biological invasions is between \$4.7 and \$6.5 billion. More recent research by Pimentel *et al.* (2000) has concluded that the total annual monetary damage from invasive species is in fact over \$100 billion.

Researchers now recognize that maritime trade in goods comprises a sizeable proportion of the world's total international trade in goods. Ships are the primary vehicle in maritime trade and consequently they are routinely used to carry goods of all kinds—often in containers—from one country to another. Now, international trade theorists have demonstrated that there are benefits to the nations involved in such voluntary trade. This notwithstanding, in recent times, natural resource and environmental economists have contended that these gains are likely to be smaller than what most researchers have believed thus far. Why? As Perrings *et al.* (2000), Costello and McAusland (2003), Batabyal (2004), Batabyal *et al.* (2005), and Margolis *et al.* (2005) have noted, this is because in addition to carrying goods between nations, ships have also managed to carry an assortment of deleterious non-native plant and animal species from one part of the world to another.

As far as unintentional introductions—the primary focus of this paper—are concerned, there are two main ways in which alien species have been carried from one part of the world to another. First, many invasive species have been introduced into a country, often inadvertently, by ships

discarding their ballast water. Cargo ships usually carry ballast water in order to increase vessel stability when they are not carrying full loads. When these ships come into a seaport, this ballast water must be jettisoned before cargo can be loaded. This manner of species introductions is important and the problem of managing alien species that have been introduced into a particular nation by means of the discharge of ballast water has now received some attention in the economics literature (see Nunes and Van den Bergh (2004), and Yang and Perakis (2004), and Batabyal and Beladi (2006)).

The second way in which alien species have been introduced into a particular country is by means of contaminated goods—agricultural goods readily come to mind—that may or may not be carried in containers. In this regard, the reader should note that invasive species can remain concealed in containers for long periods of time. In addition, material such as wood—that is often used to pack the cargo in the containers—may itself contain alien species. In fact, as pointed out by Costello and McAusland (2003), a joint report from the United States Department of Agriculture (USDA), the Animal and Plant Health Inspection Service (APHIS), and the United States Forest Service (USFS) has noted that nearly 51.8% of maritime shipments contain solid wood packing materials and that infection rates for solid wood packing materials are substantial (USDA, APHIS, and USFS (2000, p. 25)). For example, inspections of wooden spools from China revealed infection rates between 22% and 24% and inspections of braces for granite blocks imported into Canada were found to hold live insects 32% of the time (USDA, APHIS, and USFS (2000, pp. 27-28)).

Economists and ecologists are both very interested in managing invasive species. This is because—see the first paragraph of this section—biological invasions can and often have proven to be very costly from an economic standpoint. In addition to these economic costs, the work of

Vitousek *et al.* (1996), Simberloff *et al.* (1997), Costello and McAusland (2003), and others reminds us that alien species can alter ecosystem processes, act as vectors of diseases, and diminish biological diversity. In this regard, Cox (1993) has observed that out of 256 vertebrate extinctions with a known cause, 109 are the outcome of biological invasions. This discussion tells us that non-native species have been and continue to be a great menace to society.

It is only very recently that economists have begun to analyze questions pertaining to invasive species management. For instance, Eiswerth and Johnson (2002) have studied an intertemporal model of alien species stock management. They note that the optimal level of management effort is responsive to ecological factors that are not only species and site specific but also stochastic in nature. Second, Olson and Roy (2002) have used a stochastic framework to examine the circumstances under which it is optimal to wipe out an invasive species and the circumstances under which it is not optimal to do so. Third, Horan *et al.* (2002) have analyzed the properties of management approaches under full information and under uncertainty. Fourth, Batabyal *et al.* (2005) have observed that there is a tension between economic cost minimization and inspection stringency in invasive species management. Finally, Batabyal and Beladi (2006) have analyzed maximization problems stemming from the steady state analysis of two multi-person inspection regimes.

Despite the known connection between goods trade between countries and the damage from alien species, with the exception of Jenkins (1996), ecologists in general have paid *scant attention* to the role of trade policy in mitigating the damage from alien species introductions. Jenkins (1996) has contended that it may be necessary to use trade policy (bans and restrictions) to protect biological diversity. Very recently, a small number of papers have begun to analyze issues at the

interface of international trade and invasive species management. Barbier and Shogren (2004) have analyzed a growth model in which a biological invasion occurs as a spillover effect from the importation of capital goods. They show that when a biological invasion diminishes the productivity of all firms in the economy, the government ought to impose an output tax to equate the private and the social desires for consumption growth and capital accumulation. Costello and McAusland (2003) and McAusland and Costello (2004) have studied the impact that tariffs have on the damage from invasive species introductions. Costello and McAusland (2003) show that a tariff can either decrease or increase the damage from invasive species. McAusland and Costello (2004) show that although it is always optimal to use tariffs to control the damage from alien species, the same cannot be said about inspections. In particular, in their model, there are several circumstances in which it is optimal to not inspect imported goods at all. Prestemon *et al.* (2006) study international trade in forest products and show that trade liberalization will have a negligible effect on US imports of Siberian logs and on the risk of a biological invasion. Finally, using an integrated model with an international trade component, Zhao *et al.* (2006) demonstrate the consumer and the producer responses to livestock disease outbreaks and the welfare effects of alternate invasive species management policies.

Although the papers cited in the previous paragraph have certainly advanced our understanding of the impacts of trade policy on the damage from invasive species, three outstanding questions concerning the desirability of using trade policy to manage invasive species remain. Therefore, the purpose of this paper is to analyze these three questions in detail. First, unlike the extant literature, we use a two country model to study the efficacy of tariffs—as an invasive species

management tool—under four *different market structures*.<sup>4</sup> Second, we focus not just on small tariffs but on *small and on optimal* tariffs. Finally, our emphasis is less on the impact that tariffs have on the damage from invasive species *per se* and more on the *impacts of tariffs on social welfare* when social welfare depends in part on the damage from alien species.<sup>5</sup>

The rest of this paper is organized as follows. Section 2.1 briefly describes our two country model. Sections 2.2 to 2.4 construct three measures of the expected damage in Home from the introduction of alien species. Section 3.1 continues the description of our two country model. Then, this section derives a general expression for the change in Home social welfare as a function of a change in the Home tariff. Section 3.2 analyzes the impact of small and optimal tariffs imposed by Home on the damage from invasive species, on prices, on exports and imports, and on social welfare in Home for the case in which perfect competition prevails in both Home and Foreign and Home is a small country. Section 3.3 does the same for the case in which the Home and the Foreign markets are both perfectly competitive but Home is now a large country. Section 3.4 conducts a similar analysis for the case in which the exporter in Foreign is a monopolist and there are no import competing firms in Home. Section 3.5 also conducts the same kind of analysis as the previous three sections but now the Foreign exporter and the import competing firm in Home engage in Cournot competition. Section 3.6 first discusses the form of the dependence of all the tariff expressions on the expected total damage from alien species introductions in Home. Next, this section comments

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For analyses of tariffs in other contexts, see Parai (1999), Biswas and Marjit (2007), and Vishwasrao *et al.* (2007).

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We are not suggesting that this paper is the first to study the impacts of tariffs on social welfare when social welfare depends in part on the damage from alien species. This issue has also been looked at by McAusland and Costello (2004) and by Margolis *et al.* (2005). Instead, what we are suggesting is that, to the best of our knowledge, this paper is the first to *collectively* study the three questions stated earlier in this paragraph.



briefly on scenarios in which the above discussed form of dependence would be different. Section 4 concludes and offers suggestions for future research on the subject of this paper.

## **2. Three Measures of Damage in Home from Stochastic Alien Species Introductions**

### ***2.1. Preliminaries***

The world consists of two countries called Home and Foreign. Foreign exports and Home imports a specific good that could be either an agricultural good or a manufactured good. Over time, the import of this good also results in the *probabilistic* introduction of alien species from Foreign into Home. Initially, because of scientific uncertainty, citizens and the relevant authorities in Home do not realize that these unintentionally introduced alien species cause agricultural and/or ecological damage in Home. However, with the passage of time, scientific evidence implicating the alien species emerges and then it becomes clear to the citizens and to the aforementioned authorities that the stochastic introductions of these alien species and the resulting monetary damage are *linked* to the import of the good in question from Foreign. With this realization come calls for the use of trade policies to restrict imports and thereby reduce the introduction of the deleterious alien species.

Given this temporal sequence of events, we now construct three measures of the expected damage in Home from the stochastic introduction of alien species. The measures in sections 2.2 and 2.3 are monetary measures of damage and the measure in section 2.4 is a physical measure of damage. The damage measures in sections 2.2 and 2.4 are based on the work of Batabyal and Nijkamp (2007) and the damage measure in section 2.3 is based on the analysis in Batabyal and Beladi (2001). Why are we focusing on three measures of damage? This is because we would like to ascertain whether alternate specifications of the damage metric have a similar or a dissimilar qualitative impact on the various small and optimal tariff expressions that we derive in sections 3.2

to 3.5 below.

## 2.2. First Measure of Damage

We model the stochastic nexus between the arrival of a possibly injurious alien species and the attendant monetary damage that results if this species is able to establish itself in the new habitat of Home. In this regard, we shall say that the monetary damages associated with the possibly successful introduction of alien species “arrive” at Home in accordance with a Poisson process with rate  $\lambda$  and  $\lambda=\lambda(m)$ . In other words, the arrival rate of the monetary damages stemming from the stochastic introduction of alien species is a function of the volume of imports  $m$ . Further, we suppose that as the volume of imports goes up, the arrival rate of the monetary damages also goes up. Therefore, we have  $\lambda'(m)>0$ . The *amounts* of the successive monetary damages are independent random variables that are assumed to have the common discrete distribution  $a_k = -\pi^k [k \log_e(1-\pi)]^{-1}$ , where  $k=1,2,3,\dots$  and the parameter  $\pi \in (0,1)$ . Our task now is to ascertain the distribution of the total monetary damage in an interval  $[0,t]$  and, without loss of generality, we suppose that this interval is a calendar year.

Let us now compute the generating function of the discrete probability distribution specified in the previous paragraph.<sup>6</sup> Because the common discrete distribution  $a_k = -\pi^k [k \log_e(1-\pi)]^{-1}$ ,  $k=1,2,3,\dots$  has the natural logarithm function in it, to make further progress, we want to work with a series expansion of the natural logarithm function. This series expansion is given by

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See Kulkarni (1995, pp. 579-584) and Tijms (2003, pp. 449-455) for textbook accounts of the generating function.

$$-\log_e(1-x) = \sum_{k=0}^{\infty} \frac{x^k}{k}, \quad |x| < 1. \quad (1)$$

Further, Theorem 1.2.1 in Tijms (2003, p. 19) tells us that the generating function of the total monetary damage in a year can be written in terms of the exponential  $e$ . Now, using this result from Theorem 1.2.1, the series expansion in equation (1), and some thought, we are able to conclude that the generating function of the total monetary damage in a year is given by

$$e^{-\lambda\{1-A(z)\}}, \quad A(z) = \frac{\log_e(1-\pi z)}{\log_e(1-\pi)}, \quad |z| \leq 1. \quad (2)$$

After several algebraic steps, the generating function in equation (2) can be written as

$$\left[ \frac{(1-\pi)}{(1-\pi z)} \right]^{-\lambda \log_e(1-\pi)}, \quad |z| \leq 1. \quad (3)$$

Consulting Kulkarni (1995, p. 584) it is clear that the generating function in equation (3) is the generating function of a random variable that has a negative binomial distribution with parameters  $-\lambda \log_e(1-\pi)$  and  $(1-\pi)$ . Therefore, we reason that the total monetary damage from biological invasions in a calendar year has a negative binomial distribution with the above specified parameters.

Using standard formulae for the negative binomial distribution, we can tell that the expected total monetary damage from biological invasions in a calendar year or  $E[D_1]$  is

$$E[D_1] = \frac{-\pi \lambda}{\{(1-\pi) \log_e(1-\pi)\}}. \quad (4)$$

Equation (4) gives us our first measure of the damage from stochastic alien species introductions in

Home. The right-hand-side (RHS) of equation (4) is positive because the numerator and the denominator on the RHS are both negative. The reader will note that the expected total monetary damage from biological invasions in a calendar year is given by a particular ratio. The numerator of this ratio is the (negative) product of the rate  $\lambda$  of the Poisson arrival process of the monetary damages and the parameter  $\pi$  of the discrete distribution function of the amounts of the consecutive monetary damages. The denominator is the product of a simple function of the parameter  $\pi$ , i.e.,  $(1-\pi)$ , and the natural logarithm of this same function. Inspection of the above expression for the expected value tells us that as the rate  $\lambda$  of the Poisson arrival process increases in magnitude the expected total monetary damage from biological invasions goes up. We now compute our second measure of the monetary damage from alien species introductions.

### 2.3. Second measure of damage

As in section 2.2, we wish to compute the *expected* total monetary damage in the interval  $[0,t]$  which, without loss of generality, is a calendar year. Once again, we assume that alien species are introduced into Home in accordance with a Poisson process with rate  $\lambda$ , where  $\lambda=\lambda(m)$  and  $\lambda'(m)>0$ . In words, the rate of introduction of alien species into Home,  $\lambda$ , is a function of the volume of imports  $m$ , and this introduction rate is an increasing function of the volume of imports.<sup>7</sup> The *ith* introduction causes monetary damage  $M_i$ ,  $i \geq 1$ . The  $M_i$  are assumed to be independent and identically distributed (i.i.d.) and they are also assumed to be independent of the total number of alien species introductions by time  $t$ ,  $N(t)$ . As one might expect, the monetary damage from a specific

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These assumptions have also been made by Costello and McAusland (2003). For more on the Poisson process, the reader should consult Ross (1996, chapter 2) or Tijms (2003, chapter 1).

introduction in the calendar year  $[0, t]$  is typically not constant but variable. Therefore, we suppose that the monetary damage from a specific alien species introduction decreases exponentially over time. Mathematically, this means that if the initial damage from a particular species introduction is  $M$ , then at some later time  $t$ , the damage is  $Me^{-\alpha t}$ , where  $\alpha$  is the parameter or the rate of the exponential distribution.

With the above description in place we can now tell that the total monetary damage from invasive species introductions into Home in a calendar year is

$$D_2 = \sum_{i=1}^{N(t)} M_i e^{-\alpha(t-A_i)}, \quad (5)$$

where  $A_i$  is the arrival time of the  $i$ th introduction. Obviously,  $D_2$  is a random variable. Therefore, let us now compute  $E[D_2]$ , the expected dollar damage from alien species introductions into Home in a calendar year. Conditioning on  $N(t)$ , the total number of introductions by time  $t$ , we get

$$E[D_2] = \sum_{j=0}^{\infty} E[D_2/N(t)=j] e^{-\alpha t} \left\{ \frac{(\alpha t)^j}{j!} \right\}. \quad (6)$$

Theorem 2.3.1 in Ross (1996, p. 67) tells us that conditioned on  $N(t)=j$ , the unordered arrival times  $A_1, \dots, A_j$  are distributed as independent, uniform random variables in the interval  $[0, t]$ . From this, we deduce that given  $N(t)=j$ ,  $D_2$  has the same distribution as  $\sum_{i=1}^j M_i e^{-\alpha(t-G_i)}$ , where the  $G_i$ ,  $i=1, \dots, j$  are independent and uniformly distributed random variables in  $[0, t]$ . Putting these last two pieces of information together, we get

$$E[D_2/N(t)=j] = jE[M]E[e^{-\alpha(t-G)}], \quad (7)$$

where  $E[M]$  is the initial monetary damage caused by a particular introduction and  $G$  is a uniformly distributed random variable in  $[0, t]$ . To compute the last expectation on the RHS of equation (7), observe that

$$E[e^{-\alpha(t-G)}] = \int_0^t \frac{1}{t} e^{-\alpha(t-g)} dg = \left( \frac{1 - e^{-\alpha t}}{\alpha t} \right). \quad (8)$$

Using equation (8), we can now write

$$E[D_2/N(t)] = N(t) E[M] \left( \frac{1 - e^{-\alpha t}}{\alpha t} \right). \quad (9)$$

Finally, taking expectations and using the fact that  $E[N(t)] = \lambda t$ , we obtain

$$E[D_2] = \left( \frac{\lambda E[M]}{\alpha} \right) (1 - e^{-\alpha t}). \quad (10)$$

Equation (10) gives us our second measure for the expected monetary damage in Home from the stochastic introduction of invasive species in the interval  $[0, t]$  that is a calendar year.

This expected monetary damage depends on the mean initial monetary damage from an introduction ( $E[M]$ ), on the rate ( $\alpha$ ) of the exponential distribution, and most importantly for our purpose, on the rate ( $\lambda$ ) at which alien species are being introduced into Home. Recall that because  $\lambda = \lambda(m)$ , the expected monetary damage metric given by equation (10) also depends on the volume of imports ( $m$ ) coming into Home. We now proceed to compute our third and final measure of the damage from alien species introductions. This metric is a physical measure of damage.

#### ***2.4. Third measure of damage***

Upon arrival in Home, ships unload their containers carrying cargo. The arrival of these containers—and the possible discharge of ballast water—coincides with the arrival of a whole host of potentially deleterious alien animal and plant species. Consistent with the approach adopted in sections 2.2 and 2.3, we suppose that the arrival process of these alien species can be described with a Poisson process with rate  $\lambda$ .<sup>8</sup> What’s different in our construction of this third measure of damage is that unlike most of the previous literature on this subject, we suppose that this rate  $\lambda$  of the Poisson arrival process is a *random variable* that follows a gamma distribution with shape parameter  $\alpha$  and scale parameter  $\beta$ .<sup>9</sup> As in sections 2.2 and 2.3, we assume that the time interval of interest  $[0, t]$  is a calendar year. The task before us now is to compute the total number of biological invasions in this calendar year.

Let  $p_k$  denote the probability that there are  $k$  biological invasions in a year. Then, using the law of conditional probabilities and the fact that the rate  $\lambda$  of the alien species arrival process is gamma distributed with parameters  $(\alpha, \beta)$ , we reason that

$$p_k = \int_0^{\infty} e^{-x} \frac{x^k}{k!} \beta^\alpha \left( \frac{x^{\alpha-1}}{\Gamma(\alpha)} \right) e^{-\beta x} dx, \quad (11)$$

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See Costello and McAusland (2003), Batabyal and Nijkamp (2005), and Batabyal and Lee (2006) for additional details on this point.

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See Ross (1996, p. 18) and Tijms (2003, pp. 441-442) for more on the gamma distribution. We are using the gamma distribution to characterize the rate  $\lambda$  because of four reasons. First, this distribution has been used previously in the natural resource economics literature—see Batabyal and Nijkamp (in press)—to study stochastic arrival processes. Second, the gamma distribution is a general two parameter distribution for positive random variables. Third, many other probability distribution functions are variants of the gamma distribution. Finally, in Bayesian inference, the conjugate prior of the unknown rate parameter  $\lambda$  is commonly modeled with the gamma distribution.

where  $\Gamma(\alpha)$  is the gamma function.

Now, we know that the gamma density function  $\gamma^\delta \{x^{\delta-1}/\Gamma(\delta)\}e^{-\gamma x}$  integrates to unity over the interval  $(0, \infty)$  for any  $\gamma, \delta > 0$ . Therefore, after several steps of algebra, we see that

$$p_k = \frac{\Gamma(\alpha+k)}{\Gamma(\alpha)\Gamma(k+1)} \left(\frac{\beta}{1+\beta}\right)^\alpha \left(\frac{1}{1+\beta}\right)^k, \quad k=0,1,2,\dots \quad (12)$$

Consulting Ross (1996, p. 16), it is clear that equation (12) describes the probability mass function of a negative binomial random variable with parameters  $\alpha$  and  $\beta/(\beta+1)$ . Therefore, the total number of biological invasions in a calendar year has a negative binomial distribution with parameters  $\alpha$  and  $\beta/(\beta+1)$ .

Using standard formulae for the negative binomial distribution, it is straightforward to confirm that the expected number of biological invasions in a calendar year or  $E[D_3]$  is

$$E[D_3] = \alpha/\beta. \quad (13)$$

Equation (13) gives us our third and final measure of damage from stochastic alien species introductions in Home. Specifically, this equation tells us that the expected number of biological invasions in a calendar year is given by the ratio of the shape parameter  $\alpha$  of the gamma distribution to the scale parameter  $\beta$  of this same distribution. As  $\alpha$  increases in magnitude the expected number of biological invasions goes up and as  $\beta$  increases in magnitude, the expected number of biological invasions goes down. We now move on to analyze the effects of small and optimal tariffs imposed by Home on the expected damage from invasive species, on prices, on exports and imports, and on social welfare in Home for four alternate market structures.

### 3. Tariffs and Alien Species Management



### 3.1. Tariffs and social welfare in Home

Our two country model is adapted from the standard two country trade model discussed in Feenstra (2004, chapter 7). Home imports a single (agricultural or manufactured) good from Foreign. The price of the import good in Home is  $p$  and its world price is  $p^*$ .<sup>10</sup> To keep the subsequent analysis straightforward and to avoid focusing on too many cases, we shall analyze the effects of a Home instituted *specific* import tariff  $\tau$ .<sup>11</sup> Given  $\tau$ , it is clear that  $p=p^*+\tau$ . In addition to the import good, we suppose that the second (numeraire) good is also traded at the fixed world price of unity. Labor ( $L$ ) is the only factor of production and we suppose that each unit of the numeraire good requires one unit of labor. Therefore, wages in Home are also unity and hence total labor income in Home equals the fixed supply of labor  $L$ . The reader will note that we are in a partial equilibrium setting in which wages are fixed and trade is balanced through flows of the numeraire good.

The output of the good in question in Home is  $q$  and the industry cost of producing this good is  $c(q)$  where  $c'(q)>0$  and  $c''(q)>0$ . Imports are denoted by the scalar  $m=d(p)-q$ , where  $d(p)$  is the demand function for the good whose output is  $q$  and we suppose that  $d'(p)<0$ . The tariff revenue  $\tau m$  is returned to the citizens of Home and these citizens also obtain the profits of the import competing industry  $pq-c(q)$ . Given this specification, we can now write the social welfare function in Home at time  $t$  as

$$W\{p, L+\tau m+pq-c(q), E[D_i]\} \equiv W(\tau), \quad i=1,2,3. \quad (14)$$

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In the rest of this paper we shall adopt the convention of denoting the relevant Foreign functions and variables with the \* superscript.

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Results for an *ad valorem* tariff can be expected to be qualitatively similar to that for a specific tariff.

We see that social welfare in Home depends on prices ( $p$ ), income ( $L+\tau m+pq-c(q)$ ), and the expected total damage (see equations (4), (10), and (13)) from the probabilistic introduction of alien species ( $E[D_i]$ ),  $i=1,2,3$ . The social welfare function described by equation (14) is like an indirect utility function for Home as a whole with one caveat and that caveat is this:<sup>12</sup> Home's welfare at time  $t$  also depends *negatively* on the expected damage from the introduction of alien species.

We are now in a position to analyze the impact of the specific tariff on prices, quantities, mean damage, and social welfare under alternate market structures. To this end, let us first derive a general expression for the change in social welfare when a tariff is put in place by Home. The derivation of this general expression will be helped by first noting that

$$\frac{dE[D_1]}{d\tau} = \frac{-\pi}{(1-\pi)\log_e(1-\pi)} \frac{d\lambda}{dm} \frac{dm}{dp} \frac{dp}{d\tau}, \quad \frac{dE[D_2]}{d\tau} = \frac{E[M](1-e^{-\alpha})}{\alpha} \frac{d\lambda}{dm} \frac{dm}{dp} \frac{dp}{d\tau}, \quad \frac{dE[D_3]}{d\tau} = 0 \quad (15)$$

Continuing with the derivation, we assume that  $p$  and  $q$  both depend on the tariff  $\tau$ . Totally differentiating equation (14) with respect to  $\tau$ , we get

$$\frac{dW}{d\tau} = -d(p) \frac{dp}{d\tau} + m + \left\{ \tau \frac{dm}{dp} + q + Z_i \frac{\partial W}{\partial (E[D_i])} \frac{d\lambda}{dm} \frac{dm}{dp} \right\} \frac{dp}{d\tau} + \{p-c'(q)\} \frac{dq}{d\tau}, \quad i=1,2,3, \quad (16)$$

where

$$Z_1 = [-\pi/\{(1-\pi)\log_e(1-\pi)\}] > 0, \quad Z_2 = [\{E[M](1-e^{-\alpha})\}/\alpha] > 0, \quad Z_3 = 0, \quad (17)$$

and we have used the fact that  $\partial W/\partial p = -d(p)$ . Now note that  $m = d(p) - q$  and because  $p = p^* + \tau$ , we

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<sup>12</sup>

For additional details on this point see Feenstra (2004, pp. 213-214).

have  $\{1 - dp/d\tau\} = -dp^*/d\tau$ . Using these two pieces of information, we can simplify equation (16).

This simplification yields

$$\frac{dW}{d\tau} = \left\{ \tau \frac{dm}{dp} + Z_i \frac{\partial W}{\partial(E[D_i])} \frac{d\lambda}{dm} \frac{dm}{dp} \right\} \frac{dp}{d\tau} - m \frac{dp^*}{d\tau} + \{p - c'(q)\} \frac{dq}{d\tau}, \quad i=1,2,3. \quad (18)$$

Let us examine the three terms on the RHS of equation (18) in greater detail. The first term can be thought of as the efficiency effect of the tariff. The second term is the effect of the tariff on the foreign price  $p^*$  or the terms of trade effect. Finally, the third term is the price-cost margin multiplied by the change in the industry output. In the remainder of this paper, we shall use equation (18) repeatedly to study the effects of the specific tariff ( $\tau$ ) under alternate market structures. We begin with the case in which perfect competition prevails in both Home and Foreign and Home is a small country.

### 3.2. Perfect competition with Home a small country

When the home economy is perfectly competitive and it is a small country, we have  $p = c'(q)$ , and because  $p^*$  is fixed, we also have  $dp^*/d\tau = 0$  and  $dp/d\tau = 1$ . We now simplify equation (18) using these three results. This gives us

$$\frac{dW}{d\tau} = \tau \frac{dm}{dp} + Z_i \frac{\partial W}{\partial(E[D_i])} \frac{d\lambda}{dm} \frac{dm}{dp}, \quad i=1,2,3, \quad (19)$$

and the  $Z_i$  in equation (19) are given in equation (17). Now recall from the discussion in section 3.1 that the expected damage from alien species introductions affects social welfare in Home negatively and hence  $\partial W/\partial(E[D_i]) < 0$ . We have already noted in section 2 that increasing the volume of imports

increases the rate of introductions and therefore  $d\lambda/dm > 0$ . Finally,  $dm/dp = d'(p) - \{1/c''(q)\}$ . Because the demand function slopes downward and the cost function is strictly convex, we have  $d'(p) < 0$  and  $c''(q) > 0$  and hence  $dm/dp < 0$ . We now use these three results and evaluate equation (19) at  $\tau = 0$ . This gives us

$$\frac{dW}{d\tau} \Big|_{\tau=0} = Z_i \frac{\partial W}{\partial (E[D_i])} \frac{d\lambda}{dm} \frac{dm}{dp} > 0, \quad i=1,2, \quad \frac{dW}{d\tau} \Big|_{\tau=0} = 0, \quad i=3. \quad (20)$$

Equation (20) tells us that when the expected damage in Home from stochastic alien species introductions is *monetary*, i.e., when equations (4) and (10) are relevant, starting from a position of free trade ( $\tau = 0$ ), a *small* tariff unambiguously raises social welfare in Home. In contrast, when the expected damage from stochastic alien species introductions is *physical*, i.e., when equation (13) is pertinent, starting from a position of free trade, a small tariff does not raise welfare. This last result arises because the expected total physical damage—see equations (13), (15), and (17)—is independent of the rate  $\lambda$  of the Poisson arrival process. Put differently, the small tariff has no impact on the expected total damage from alien species introductions and hence this tariff also has no impact on social welfare in Home. Given these results, we now determine the impact of an *optimal* tariff on social welfare in Home. To compute the optimal tariff, we set the RHS of equation (19) equal to zero and then simplify. This gives us

$$\tau_o = -Z_i \frac{\partial W}{\partial (E[D_i])} \frac{d\lambda}{dm} > 0, \quad i=1,2, \quad \tau_o = 0, \quad i=3. \quad (21)$$

Equations (20) and (21) together tell us that when social welfare depends on the expected

damage from the introduction of alien species, small and optimal tariffs both *raise* welfare in Home as long as the expected total damage in Home is monetary, i.e., when equations (4) and (10) are relevant. In contrast, when the expected total damage is physical and independent of the rate  $\lambda$ , a tariff is incapable of affecting social welfare in Home and hence, in this last case, it is optimal to not use a tariff to regulate alien species in Home. Even though Home is a small country, we have seen that in two out of the three cases that we're studying, tariffs have a positive impact on social welfare and hence Home ought to have an activist trade policy in place in these two cases.

Stepping away from the criterion of social welfare for a moment, does a small tariff lower the expected total damage from the introduction of alien species? To answer this question, let us inspect equation (15) carefully. This inspection tells us that  $dE[D_1]/d\tau < 0$ ,  $dE[D_2]/d\tau < 0$ ,  $dE[D_3]/d\tau = 0$ . In this paper, imports are the only means by which alien species are introduced into Home. As a result, because a small tariff reduces the volume of imports when the expected total damage is monetary, i.e.,  $dm/d\tau < 0$ , this same tariff also *lowers* the expected monetary damage in Home from the introduction of alien species.<sup>13</sup> In contrast, when the expected total damage is physical and independent of the rate  $\lambda$ , a small tariff has no impact on the expected total damage. This is what the derivative  $dE[D_3]/d\tau = 0$  in equation (15) is telling us.

It is well known in international trade theory—see Feenstra (2004, p. 216)—that the optimal tariff for a small country is zero. However, our analysis thus far tells us that this result does not hold in *some cases* in which imports and invasive species go together. In fact, as we have just seen, when imports are the only means by which alien species are introduced into Home and the expected total

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Using a different model, Costello and McAusland (2003) have obtained a similar result.

damage from alien species is given by either equation (4) or equation (10), the optimal course of action for Home is to set a positive tariff. We now investigate the effects of a tariff when Home is a large country.

### 3.3. Perfect competition with Home a large country

We now write the world price of imports as  $p^*(\tau)$ . Therefore, because  $p = p^*(\tau) + \tau$ ,  $dp^*/d\tau \neq 0$  and  $dp/d\tau \neq 1$ . However, because the Home economy is perfectly competitive, we still have  $p = c'(q)$ .

Using these three results to simplify equation (18), we get

$$\frac{dW}{d\tau} = \left\{ \tau \frac{dm}{dp} + Z_i \frac{\partial W}{\partial(E[D_i])} \frac{d\lambda}{dm} \frac{dm}{dp} \right\} \frac{dp}{d\tau} - m \frac{dp^*}{d\tau}, \quad i=1,2,3. \quad (22)$$

Now, because Home is a *large* country,  $dp/d\tau \neq 1$ , and we expect that the foreign exporter will absorb a part of the Home tariff. As noted in Feenstra (2004, pp. 218-219), this means that in general, we expect  $dp^*/d\tau < 0$  and  $0 < dp/d\tau < 1$ . Let us now use these two findings and the results stated in section 3.2 to evaluate equation (22) at  $\tau=0$ . This gives us

$$\left. \frac{dW}{d\tau} \right|_{\tau=0} = Z_i \frac{\partial W}{\partial(E[D_i])} \frac{d\lambda}{dm} \frac{dm}{dp} \frac{dp}{d\tau} - m \frac{dp^*}{d\tau} > 0, \quad i=1,2, \quad \left. \frac{dW}{d\tau} \right|_{\tau=0} = -m \frac{dp^*}{d\tau} > 0, \quad i=3. \quad (23)$$

Equation (23) tells us two things of note. First, as in section 3.2, we see that when the expected total damage from alien species is monetary (equations (4) and (10) apply), starting from a position of free trade, a small tariff, once again, *raises* social welfare in Home. Second, and unlike what we saw in section 3.2, when the expected total damage from alien species is physical and independent of  $\lambda$ , the small tariff now is not zero but positive. This is because even though the small tariff is unable to

affect the expected total damage from alien species, because Home is a large country, the small tariff is able to generate a beneficial terms of trade effect and hence—as shown by the  $-m(dp^*/d\tau)$  term in equation (23)—this tariff is positive.

To compute the optimal tariff for Home, we set the RHS of equation (22) equal to zero and then simplify the resulting expression. This gives us

$$\tau_o = \frac{m \frac{dp^*}{d\tau}}{\frac{dm}{dp} \frac{dp}{d\tau}} - Z_i \frac{\partial W}{\partial(E[D_i])} \frac{d\lambda}{dm} > 0, \quad i=1,2, \quad \tau_o = \frac{m \frac{dp^*}{d\tau}}{\frac{dm}{dp} \frac{dp}{d\tau}} > 0, \quad i=3. \quad (24)$$

Equation (24) tells us that for the case of monetary expected total damage from alien species, i.e., for  $i=1,2$ , Home's optimal tariff is positive and is the sum of the terms of trade effect and the damage from alien species effect. In contrast, for the physical damage or the  $i=3$  case, there is no damage from alien species effect to contend with because  $Z_3=0$  but, unlike the case studied in section 3.2, there is still a beneficial terms of trade effect. This is why the optimal tariff in this  $i=3$  case is also positive. The reader will note that the optimal tariff in this  $i=3$  case is equivalent to the optimal import tariff for a large country in the *absence* of damage from alien species.<sup>14</sup> Equation (24) also tells us that when the damage from invasive species introductions *is* an issue, i.e., when  $i=1,2$ , the optimal tariff is not only positive but also larger in magnitude than the optimal tariff with no invasive species damage.

The impact of a small tariff on the expected total damage from alien species introductions into

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See Feenstra (2004, p. 220) for more details on this point.

Home is, once again, given by equation (15). Although  $dp/d\tau \neq 1$  now, as discussed earlier, in general, we expect  $dp/d\tau > 0$  to hold. Therefore, inspection of equation (15) and some thought together tell us that  $dE[D_1]/d\tau < 0$ ,  $dE[D_2]/d\tau < 0$ ,  $dE[D_3]/d\tau = 0$ . Since a small tariff reduces the volume of imports when the expected total damage is monetary, i.e.,  $dm/d\tau < 0$ , this same tariff also *reduces* the expected monetary damage in Home from the introduction of alien species. In contrast, when the expected total damage is physical and independent of  $\lambda$ , a small tariff has no impact on the expected total damage and therefore  $dE[D_3]/d\tau = 0$ . Let us now analyze the effects of tariffs when the exporter in Foreign is a monopolist and there are no import competing firms in Home.

### 3.4. Monopolist in Foreign

In this case we have a single exporter in Foreign and we suppose that there are no import competing firms in Home. The purpose of a tariff is generally to protect domestic firms in Home. So, if there are no domestic firms then, in principle, there is no rationale for an import tariff. However, as we shall see, in our case it is the damage from alien species introductions that provides a rationale for protectionism.

Let us denote the Foreign firm's exports to Home by  $x$ ; this equals Home consumption and therefore we can write  $x = d(p)$ . Inverting this expression, we get the inverse demand function  $p = p(x)$  where  $p'(x) < 0$ . Denote the price received by the Foreign exporter by  $p^* = p(x) - \tau$  and let  $c^*(x)$  denote this firm's cost function. We suppose that  $c^{*'}(x) > 0$  and that  $c^{*''}(x) > 0$ . The Foreign exporter's profit function is  $\pi^*(x) = xp^* - c^*(x) = x\{p(x) - \tau\} - c^*(x)$ . Maximizing this function with respect to the volume of exports  $x$  gives us



$$\pi^{*'}(x) = p(x) + xp'(x) - \{c^{*'}(x) + \tau\} = 0, \quad (25)$$

where  $p(x) + xp'(x)$  is the marginal revenue and  $\{c^{*'}(x) + \tau\}$  is the tariff inclusive marginal cost. Now, totally differentiating equation (25), we get

$$\frac{dx}{d\tau} = \frac{1}{2p'(x) + xp''(x) - c^{*''}(x)} = \frac{1}{\pi^{*''}(x)} < 0 \quad (26)$$

and

$$\frac{dp}{d\tau} = \frac{dp}{dx} \frac{dx}{d\tau} = \frac{p'(x)}{\pi^{*''}(x)} > 0. \quad (27)$$

Equation (26) tells us that the Foreign firm's exports decline as a result of the tariff and equation (27) tells us that the domestic price of the good in question inclusive of the tariff rises.

When  $dp/d\tau = 1$  (as in section 3.2), the so called "pass-through" of the tariff is complete. In other words, the tariff inclusive price  $p$  rises by the same amount as the tariff  $\tau$ . However, when Home is not a small country, the "pass-through" of the tariff will typically be incomplete. When this is the case, we will have  $dp/d\tau < 1$ . This also means that the foreign firm will absorb a part of the tariff. Mathematically, this means that  $dp^*/d\tau < 0$ . It should be clear to the reader that when the pass-through of a tariff is *incomplete*, there is a terms of trade *gain* for Home.

We would now like to derive a condition which tells us when there will be a terms of trade gain for Home. Equation (27) helps provide us with the answer. Because the numerator and the denominator on the RHS of equation (27) are both negative, we conclude that  $dp/d\tau < 1$  if and only if

$$p'(x) > 2p'(x) + xp''(x) - c^{*''}(x). \quad (28)$$

Now, following the discussion in Feenstra (2004, pp. 221-222), we can say that the LHS of the inequality in (28) is the slope of the inverse demand function and the RHS of this inequality is the difference between the slopes of the marginal revenue and the marginal cost functions. To proceed further with the derivation, it will be helpful to suppose that the Foreign cost function  $c^*(x)$  is linear.

Then  $c^{*''}(x) = 0$  and the inequality in (28) reduces to

$$p'(x) > 2p'(x) + xp''(x). \quad (29)$$

The inequality in (29) and some thought together tell us that when the slope of the marginal revenue function *exceeds* that of the inverse demand function,  $dp/d\tau < 1$  and  $dp^*/d\tau < 0$ .

We now determine the impact of the tariff on social welfare in Home. Because there are no import competing firms in Home,  $q = 0$  and therefore  $dq/d\tau = 0$ . Using this result to simplify equation (18), we get

$$\frac{dW}{d\tau} = \left\{ \tau \frac{dm}{dp} + Z_i \frac{\partial W}{\partial (E[D_i])} \frac{d\lambda}{dm} \frac{dm}{dp} \right\} \frac{dp}{d\tau} - m \frac{dp^*}{d\tau}, \quad i=1,2,3. \quad (30)$$

From the discussion in the previous paragraph we know that when the marginal revenue function is steeper than the inverse demand function,  $dp/d\tau < 1$  and  $dp^*/d\tau < 0$ . Using these two results and other results from our earlier analysis, let us evaluate equation (30) at  $\tau = 0$ . We get

$$\left. \frac{dW}{d\tau} \right|_{\tau=0} = Z_i \frac{\partial W}{\partial (E[D_i])} \frac{d\lambda}{dm} \frac{dm}{dp} \frac{dp}{d\tau} - m \frac{dp^*}{d\tau} > 0, \quad i=1,2, \quad \left. \frac{dW}{d\tau} \right|_{\tau=0} = -m \frac{dp^*}{d\tau} > 0, \quad i=3. \quad (31)$$

We see that when the expected total damage from alien species is monetary, i.e., when equations (4)

and (10) apply and  $i=1,2$ , starting from a position of free trade, a small tariff *raises* social welfare in Home. In addition, when the expected damage from alien species is physical and independent of the rate  $\lambda$ , i.e., when  $i=3$ , as in section 3.3, a beneficial terms of trade effect results from the small tariff and this explains why this tariff is—as shown by the last derivative in equation (31)—positive.

Does the optimal tariff also raise welfare? To answer this question, we set the RHS of equation (30) equal to zero and then simplify the resulting expression. This gives us

$$\tau_o = \frac{x \frac{dp^*}{d\tau}}{\frac{dx}{d\tau}} - Z_i \frac{\partial W}{\partial(E[D_i])} \frac{d\lambda}{dm} > 0, \quad i=1,2, \quad \tau_o = \frac{x \frac{dp^*}{d\tau}}{\frac{dx}{d\tau}} > 0, \quad i=3. \quad (32)$$

The optimal import tariff when the exporter in Foreign is a monopolist, when there are no import competing firms in Home, and when the expected total damage from alien species is physical and independent of the rate  $\lambda$  is given by the second expression in (32). This expression is the ratio of two negative quantities and hence the optimal tariff described by this expression is positive. Equation (32) tells us that when the damage from invasive species introductions is monetary, we have  $Z_i > 0$ ,  $i=1,2$ , and in these two instances, the optimal tariff—given by the first expression in (32)—is not only positive but also larger in magnitude than the optimal tariff with physical alien species damage.

As in sections 3.2 and 3.3, equation (15) gives us the impact of a small tariff on the expected total damage from alien species introductions into Home. Equation (27) tells us that  $dp/d\tau > 0$ . Using this and our previous results in equations (15) and (17) tell us that

$dE[D_1]/d\tau < 0$ ,  $dE[D_2]/d\tau < 0$ ,  $dE[D_3]/d\tau = 0$ . Since a small tariff reduces the volume of imports when the expected total damage is monetary, i.e.,  $dm/d\tau < 0$ , this same tariff also *reduces* the expected monetary damage in Home from the introduction of alien species. In contrast, when the expected total damage is physical and independent of  $\lambda$ , a small tariff has no impact on the expected total damage and hence  $dE[D_3]/d\tau = 0$ . We now study the impacts of a tariff when the Foreign exporter and an import competing firm in Home engage in Cournot competition.

### 3.5. Cournot competition

We now have a Home (domestic) firm competing with an exporting firm from Foreign in the domestic market. Let us denote the sales of the Foreign exporting firm by  $x$  and that of the Home import competing firm by  $q$  so that aggregate consumption of the good in question at Home is  $y = q + x$ . Following the logic of section 3.4, the pertinent demand function now is  $y = d(p)$  and therefore the relevant inverse demand function is  $p = p(y)$  where  $p'(y) < 0$ .

Using the notation of section 3.4, the profit functions of the Foreign exporter and the Home import competing firm are  $\pi^*(x) = x\{p(y) - \tau\} - c^*(x)$  and  $\pi(q) = qp(y) - c(q)$ . Maximizing these two functions with respect to the choice variables  $x$  and  $q$  respectively, we get

$$\pi^{*'}(x) = p(y) + xp'(y) - \{c^{*'}(x) + \tau\} = 0 \quad (33)$$

and

$$\pi'(q) = p(y) + qp'(y) - c'(q) = 0. \quad (34)$$

The reader can confirm that the two second order conditions for profit maximization are

$\pi^{*''}(x)=2p'(y)+xp''(y)-c^{*''}(x)<0$  and  $\pi''(q)=2p'(y)+qp''(y)-c''(q)<0$ .<sup>15</sup> We now want to determine the impact of the Home tariff on the Foreign firm's exports. In other words, we want to determine the sign of the derivative  $dx/d\tau$ . To determine this sign, we totally differentiate equation (33) and then use the second order condition for  $\pi^{*''}(x)$  given above. This gives us

$$\frac{dx}{d\tau} = \frac{1}{2p'(y)+xp''(y)-c^{*''}(x)} = \frac{1}{\pi^{*''}(x)} < 0. \quad (35)$$

Equation (35) tells us that with the Home tariff in place, the Foreign exporter reduces the amount it wishes to export to Home.

To study the impact of the Home tariff on prices, it will be necessary to first compute the impact of the tariff on total sales  $y=x+q$ . To do this, let us now sum the two first order necessary conditions given in equations (33) and (34). This gives

$$2p(y)+yp'(y)=c'(q)+\{c^{*'}(x)+\tau\}. \quad (36)$$

Totally differentiating equation (36) and then simplifying, we get

$$3p'(y)dy+yp''(y)dy=c''(q)dq+c^{*''}(x)dx+d\tau. \quad (37)$$

Now, as in section 3.4, to progress further it will help to make a simplifying assumption. Therefore, we assume that the cost functions of the two competing firms in Home and in Foreign are both linear.

Then equation (37) can be simplified to give us

$$\frac{dy}{d\tau} = \frac{1}{3p'(y)+yp''(y)}, \quad (38)$$

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We assume that the stability condition  $\pi_{xx}^*\pi_{qq}-\pi_{xq}^*\pi_{qx}>0$  is satisfied.

and, because  $dp/d\tau=(dp/dy)(dy/d\tau)$ , we have

$$\frac{dp}{d\tau} = \frac{p'(y)}{3p'(y)+yp''(y)}. \quad (39)$$

Inspecting the denominators on the RHSs of equations (38) and (39) we see that the impact of the Home tariff on total output ( $y$ ) and the price ( $p$ ) depends significantly on the sign of  $3p'(y)+yp''(y)$ .

When this expression is negative, we have  $dy/d\tau < 0$  and  $dp/d\tau > 0$ . In words, total output with the tariff declines, and the price in Home with the tariff rises. Some thought will convince the reader that the condition  $3p'(y)+yp''(y) < 0$  holds for some inverse demand functions (such as the linear function) but not for all such functions. This tells us that the imposition of a tariff by Home *may* lead to counterintuitive results. Specifically, total output with the tariff may rise ( $dy/d\tau > 0$ ) and the domestic price of the good in question at Home may fall ( $dp/d\tau < 0$ ).

We now focus on the “pass-through” of the tariff  $\tau$ . We know that for there to be a terms of trade gain in Home, we must have  $0 < dp/d\tau < 1$ . Now, when  $3p'(y)+yp''(y) < 0$  holds, from equation (39) we can tell that for  $dp/d\tau < 1$  to hold, we must have

$$p'(y) > 3p'(y)+yp''(y) \Leftrightarrow 0 > 2p'(y)+yp''(y). \quad (40)$$

The expression  $2p'(y)+yp''(y)$  on the RHS of (40) is the slope of the marginal revenue function  $p(y)+yp'(y)$ . Therefore, what (40) is really saying is that when the marginal revenue function is *downward* sloping  $dp/d\tau < 1$  holds or, alternately,  $dp^*/d\tau < 0$  and hence there is a terms of trade gain for Home.

We now ascertain the impact of the tariff on social welfare in Home. Because  $m=x$  in

equilibrium, we use this to rewrite equation (18) as

$$\frac{dW}{d\tau} = \left\{ \tau \frac{dx}{dp} + Z_i \frac{\partial W}{\partial (E[D_i])} \frac{d\lambda}{dx} \frac{dx}{dp} \right\} \frac{dp}{d\tau} - x \frac{dp^*}{d\tau} + \{p - c'(q)\} \frac{dq}{d\tau}, \quad i=1,2,3. \quad (41)$$

From equation (35) we know that  $dx/d\tau < 0$ . Further, as we have just discussed in the previous paragraph, when the inequality in (40) holds, the marginal revenue function is downward sloping and hence  $dp^*/d\tau < 0$ . Finally, because  $dq/d\tau = (dq/dp)(dp/d\tau)$ , in general, we expect  $dq/d\tau > 0$ .<sup>16</sup> Using these three results we can evaluate equation (41) at  $\tau=0$ . This gives us

$$\left. \frac{dW}{d\tau} \right|_{\tau=0} = Z_i \frac{\partial W}{\partial (E[D_i])} \frac{d\lambda}{dx} \frac{dx}{d\tau} - x \frac{dp^*}{d\tau} + \{p - c'(q)\} \frac{dq}{d\tau} > 0, \quad i=1,2,$$

$$\left. \frac{dW}{d\tau} \right|_{\tau=0} = -x \frac{dp^*}{d\tau} + \{p - c'(q)\} \frac{dq}{d\tau} > 0, \quad i=3. \quad (42)$$

Consider the cases in which the expected total damage from alien species introductions is monetary. These are the  $i=1,2$  cases. In these two cases, equation (42) tells us that when the inequality in (40) holds, a small tariff leads to a terms of trade gain ( $dp^*/d\tau < 0$ ). In addition, when  $dq/d\tau > 0$  there is an additional gain from this small tariff. These two positive effects along with the fact that the first term on the RHS of equation (42) with  $Z_i$  in it is positive together tell us that a small tariff raises social welfare in Home. Next, consider the  $i=3$  case in which the expected total damage from alien species

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See Feenstra (2004, pp. 225-226) for a graphical explanation of this line of reasoning.

introductions is physical and independent of  $\lambda$ . In this case  $Z_3=0$  but we still have a beneficial terms of trade effect and a general increase in domestic output as a result of the small tariff. These two positive effects explain why the small tariff in this  $i=3$  case is also positive. The reader should note that in this case of Cournot competition, it is *not* inevitable that a small tariff will lead to an increase in domestic output. It is certainly possible that  $dq/d\tau < 0$  and when this happens, this negative effect will tend to offset the positive terms of trade effect and hence the impact of a small tariff on social welfare in Home may not be positive.

Does the optimal import tariff raise social welfare in Home? To answer this question, we set the RHS of equation (41) equal to zero and then simplify the resulting expression. This gives us

$$\tau_o = \frac{x \frac{dp^*}{dx} - \frac{\{p(y) - c'(q)\} \frac{dq}{dx}}{\frac{dx}{d\tau}} - Z_i \frac{\partial W}{\partial(E[D_i])} \frac{d\lambda}{dx} > 0, \quad i=1,2, \quad \tau_o = \frac{x \frac{dp^*}{dx} - \frac{\{p(y) - c'(q)\} \frac{dq}{dx}}{\frac{dx}{d\tau}}, \quad i=3. \quad (43)$$

Assuming that the inequality in (40) holds, let us first focus on the  $i=1,2$  cases. There are three terms on the RHS of equation (43) to discuss. The first term is positive because both  $dp^*/dx$  and  $dx/d\tau$  are negative. The second term is positive because the numerator is generally positive and the denominator is negative. Finally, the third term is positive because  $Z_i > 0$ ,  $i=1,2$ ,  $\partial W/\partial(E[D(t)]) < 0$ , and  $d\lambda/dx > 0$ . Therefore, the optimal tariff which is the sum of three positive terms is itself positive. Next, focus on the  $i=3$  case. In this case, the expected total damage from alien species introductions is independent of the rate  $\lambda$  and hence this case is like the case in which there is Cournot competition



between the exporting and the import competing firms and there is no damage from invasive species introductions. In this case, Home's optimal tariff is positive and it is the sum of the first two terms as shown in the last derivative in equation (43). Finally, equation (43) tells us that the optimal tariff in the  $i=1,2$  cases is the sum of three positive terms and hence larger in magnitude than the optimal tariff in the  $i=3$  case.

As in sections 3.2, 3.3, and 3.4, equation (15) gives us the impact of a small tariff on the expected total damage from alien species introductions into Home. Using equation (35), the fact that  $m=x$  in equilibrium, and our previous analysis, we reason that  $dE[D_1]/d\tau < 0$ ,  $dE[D_2]/d\tau < 0$ ,  $dE[D_3]/d\tau = 0$ . Since a small tariff diminishes the volume of exports when the expected total damage from alien species is monetary, i.e.,  $dx/d\tau < 0$ , this same tariff also *reduces* the expected monetary damage in Home from the introduction of alien species. In contrast, when the expected total damage is physical and independent of  $\lambda$ , a small tariff has no impact on the expected total damage and hence  $dE[D_3]/d\tau = 0$ . These results about the impact of the tariff on the expected total monetary damage from invasive species in sections 3.2 to 3.5 are similar to and consistent with Proposition 1 in Costello and McAusland (2003, p. 967).

In the strategic trade theory literature of the 1980s, a considerable amount of emphasis was placed on the third term  $\{p - c'(q)\}(dq/d\tau)$  in equation (41) and this third term was often thought of as a profit shifting rationale for the strategic use of tariffs.<sup>17</sup> While this interpretation makes sense when the derivative  $dq/d\tau$  is positive, we have already pointed out that this need not always be the

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See Brander and Spencer (1984), Horstmann and Markusen (1986), and Helpman and Krugman (1989) for more on this literature.

case. Suppose for the moment that  $dq/d\tau$  is positive. Then, what we have seen thus far in this paper is that in addition to any profit shifting rationale, in the presence of monetary damage from alien species introductions, there is a second and arguably more important rationale for the use of import tariffs. Indeed, when tariffs are used as described in this paper, it may be possible to “kill three birds with one stone.” What we mean by this expression is that the Home government may be able to (i) obtain a terms of trade benefit, (ii) shift profits away from the Foreign exporter and toward the domestic import competing firm, and (iii) reduce the monetary damage from deleterious alien species. We now discuss the form of the dependence of all the tariff expressions in this paper on the expected total damage from alien species introductions in Home. Then, we briefly talk about scenarios in which this form of dependence would be different.

### ***3.6. Form of dependence of tariffs on damage from alien species introductions***

We derived three measures of damage from alien species introductions in sections 2.2 through 2.4 of this paper. Of these three measures, the first two measures—equations (4) and (10)—are monetary and the third measure—equation (13)—is physical. In our detailed analysis thus far, we have seen that tariffs are useful policies with which to control the deleterious effects of alien species introductions when equations (4) and (10) are pertinent, i.e., when the damage measure is monetary. This is because in these two cases, the rate  $\lambda$  of the Poisson arrival process directly influences the two derived damage metrics. In contrast, tariffs have no role to play as an alien species control device when equation (13) is germane because in this case, the derived damage metric is independent of  $\lambda$ .

We now note *two features* of our analysis thus far. First, even though equations (4) and (10) are *dissimilar* damage measures, in both these equations, the rate  $\lambda$  enters the damage measure multiplicatively. Second, the three expected damage measures of this paper enter the social welfare

function in Home—see equation (14)—in a *standard* manner. In other words, we have  $W\{p, L+\tau m+pq-c(q), E[D_i]\}$ ,  $i=1,2,3$ . Therefore, when we differentiate this social welfare function with respect to the tariff  $\tau$ , we get the multiplicative term  $(\partial W/\partial\{E[D_i]\})(d\{E[D_i]\}/d\tau)$ . It is these two modeling features that together account for the fact that the  $Z_i$  term affects all our tariff expressions—see equations (20), (21), (23), (24), (31), (32), (42) and (43)—multiplicatively.

We stress that the positivity of most of the tariffs that we have analyzed in this paper is *not* the result of modeling the damage from alien species introductions in a particular way. In fact, as we have shown in this paper, even for dissimilar damage measures, this positivity result largely holds. We conclude this section by pointing out that if the two modeling features delineated in the previous paragraph do not hold then it is possible that the signs of some of the small and the optimal tariffs in the four different market structures that we have analyzed will become ambiguous.

#### 4. Conclusions

In this paper, we provided a theoretical perspective on the impacts of small and optimal specific tariffs when international trade in goods results in the stochastic introductions of alien species from one country to another as a byproduct. Conducting the analysis from the standpoint of the tariff imposing country, i.e., Home, we first derived three—two monetary and one physical—measures of the expected total damage from alien species introductions into Home. Next, we analyzed the effects of small and optimal tariffs under four alternate market structures. Our basic result is that there are several circumstances in which it makes sense to use trade policy (tariffs) to control the damage from alien plant and/or animal species.

The analysis in this paper can be extended in a number of directions. In what follows, we

suggest two possible extensions of this paper's research. First, in our model the rate of alien species introductions depends only on the volume of imports. Therefore, it would be useful to determine the extent to which one can obtain results from a model in which in addition to the volume of imports, the rate of species introductions depends also on the *number of previously successful* introductions. Second, it would be useful to analyze the impacts of import *quotas* to see if our basic result from the previous paragraph also holds in the case of quotas. Studies of alien species management that incorporate these aspects of the problem into the analysis will provide additional insights into a management problem that has considerable economic and ecological implications.

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