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Importing exotic plants and the risk of invasion: are market-based instruments adequate?

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Abstract

Exotic plant species are often intentionally imported into regions outside of their normal range as ornamental plants or as breeding stock, thereby generating benefits for consumers and producers. However, one of the unintended side effects of such introductions is that the exotic plant species may become invasive. Prohibiting sale of this type of exotic plant species, on the basis that it may become invasive, will have social costs in the form of foregone consumer benefits and nursery profits. We develop a model of a private commercial plant breeding industry that imports an exotic plant species into a region. The risk associated with invasion is modeled using a probabilistic 'hazard function', the key determinants of which are the characteristics of the exotic plant and the number of commercial nurseries contributing to its dispersal. We consider the possibility of employing market-based instruments (e.g., Pigovian tax) consistent with the concept of 'introducers pay', to regulate the nursery industry. We then provide an empirical illustration using the historical introduction of saltcedar (*Tamarisk* spp.) into the United States. Our results indicate that the mere presence of a risk of invasion does not mean that it is socially optimal to prevent commercial sales of an exotic plant species. Indeed, there appear to be plausible forms of the functional relationships involved that require only a modest reduction in the private industry optimum. In contrast, no sales of the exotic plant should occur at all under several sets of assumptions about the level of invasion risk and the linkage between dispersal sites and invasion hazard.

Keywords: Biological invasion; Introducers pay tax; Saltcedar; Tamarisk; Economics

1. Introduction

Nonindigenous, or "exotic" plant species are often intentionally imported into regions outside of their normal range as plant or breeding stock for agricultural, horticultural or domestic gardening activities.

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However, one of the unintended side effects of such introductions is that the exotic plant species may be accidentally introduced into the wider environment of the new host region, with dramatic impacts. For example, the cumulative losses to the U.S. economy from invasive plants has been estimated at $600 million over the period 1906 to 1991 (OTA, 1993). Recent estimates suggest that the annual losses from invasive plants in the United States may be far larger (Pimentel et al., this issue). For example, the exotic saltcedar (*Tamarisk* spp.) has invaded up to 23 states, disrupting irrigation systems, hydropower generation, municipal water supplies and flood control investments. One estimate puts the annual damages from this species alone at $121 to 291 million (Zavaleta, 2000).

Economic analysis of the problem of invasive species is emerging as a new area of interest among economists (Barbier and Knowler, in press; Perrings et al., 2002; Barbier, 2001; Naylor, 2000; Knowler and Barbier, 2000). In most treatments of the economics of invasion, the invasive species is seen as imposing costs without contributing any benefits in return. This approach accords with the standard treatment of pollution abatement, and results in policy prescriptions that tradeoff residual pollution damages against the costs of abatement, settling at equilibrium on a mix that maximizes social welfare, usually by minimizing damages plus control costs (for example, see Keeler et al., 1972). However, those invasives that have been deliberately introduced typically have some perceived benefit as a rationale for their introduction in the first place. This potential benefit adds an additional element not taken into account in traditional pollution economics. As an example, horticultural operations, such as nurseries, may find it profitable to introduce exotic species since they can earn profits from doing so, although the plant may become invasive and incur damages and control costs as a result. Thus, prohibiting sale of the exotic has social costs in the form of foregone consumer benefits and nursery profits, and these must be considered in a proper analysis of the economics of invasion.

One important aspect of an unintended invasion by an exotic plant species is that the decision by the commercial nursery to import, breed and sell it is taken ex ante of any ultimate invasion. That is, the likelihood, timing and magnitude of economic losses associated with a possible invasion are not known with certainty and can only be known ex post of an invasion, although importers may be aware that many exotic plant species carry some potential for invasion. Given this uncertainty, the economic assessment of the threat of plant invasion is concerned with assessing the probability distribution of potential damages associated with the sale of exotic plant species.

The outline and main findings of this paper are as follows. The next section develops a model of a private commercial plant breeding industry that imports an exotic plant species into a region by establishing nurseries at n locations until the marginal profit to the industry of the last nursery is zero. Subsequent sections develop the economic analysis of the accidental risk of invasion associated with the commercial plant industry importing exotic plant species. This problem has similarities to a standard duration problem, where the ‘spell’ represents the number of periods after introduction of the species without invasion taking place. The risk that invasion will occur in a particular period, given that it has not become invasive yet, can be described by a hazard function. We postulate that the key determinants of the hazard are the exogenous characteristics of the exotic plant itself and the number of commercial nurseries selling the exotic plant and thus contributing to dispersal. The problem for the decision-maker is to choose the optimal number of nurseries that balances the tradeoff between the profits of the commercial plant breeding industry and the expected losses associated with the risk of accidental introduction. Our model implies that the government's optimal choice of nurseries in the long run will be less than that of a competitive plant breeding industry. As a result, we consider the possibility of employing regulatory or market-based instruments (e.g., standards versus taxes) to ensure that the plant breeding industry internalizes the expected social cost of an accidental invasion associated with establishing new nurseries. In a later section, we provide an empirical illustration of our model using biological and economic data relating to the introduction of saltcedar (*Tamarisk* spp.) in North America. The final section provides further discussion of the possible policy implications of our model and simulation.

2. A model of a commercial nursery industry

Assume that there is a single commercial plant importation and breeding industry in a specific regional economy. The industry imports breeding material of an exotic species, i.e., a species that is nonindigenous to the environment of the region, and breeds and raises the species for sale through independent and competing nurseries located throughout the region. To focus the analysis, we assume that there are n such locations, and one plant breeding firm or "nursery" at each location.

Let q be the total supply of the exotic plant produced from imported breeding material by the i=1,. . .,n nurseries comprising the plant breeding industry, while $\mathbf{x}=(x_1,...x_m)$ are the aggregate factor inputs employed by the industry. The price that the industry receives for the plant in the region is p, and the corresponding factor prices are $\mathbf{w}=(w_1,...w_m)$.[2] Denoting the industry profit function as $\pi=\pi(p, \mathbf{w}, n)$ and its cost function as $C(q, \mathbf{w})$, we assume that the structure of the industry allows it to have the following profit function:

$$\pi(p,\mathbf{w},n) = \max_q\,[pq - C(q,\mathbf{w})], \quad q = \sum_{i=1}^{n} q_i,$$
$$C(q,\mathbf{w}) = \min_{\mathbf{x}}\{\mathbf{wx;Prodfnct} = q; x>0\} \tag{1}$$

Eq. (1) defines the profit function of the industry in terms of the maximum profit as a function of the plant price, p, and the factor prices, $\mathbf{w}$. We note that industry supply, q, is the total amount of the exotic plant supplied to the regional market by the n nurseries, and that the cost function is the minimum cost to the industry of producing q units of the plant, taking into account the given factor prices, $\mathbf{w}$. While it is arguable that such a plant species might face a downward sloping demand curve, requiring us to include consumers' surplus as part of the social benefits from its distribution and sale, we assume this is not the case. This approach allows us to remain consistent with our later empirical modeling.[3]

The properties of the profit function are the following:

$$\frac{\partial\pi(p,\mathbf{w},n)}{\partial p} = q = \sum_{i=1}^{n} q_i, \quad -\frac{\partial\pi(p,\mathbf{w},n)}{\partial w_j} = x_j,$$
$$j = 1,...m, \quad \frac{\partial\pi(p,\mathbf{w},n)}{\partial n} \begin{array}{l} = 0 \text{ for } n = n^p \\ >0 \text{ for } n<n^p \end{array} \tag{2}$$

The first two expressions of Eq. (2) are essentially Hotelling's lemma applied at the level of an industry. These expressions determine the supply function and the jth input's demand function for the entire industry, respectively. The third expression is unique to our problem, as it determines the total number of locations in the region where nurseries will be established by the plant breeding industry. That is, the total profits of the industry are positive, but the marginal profit of the last nursery established at the nth location is zero. We assume that this latter condition holds in the short and long run.[4]

In sum, given the profit function of the commercial plant breeding industry specified in Eq. (1), the three conditions in Eq. (2) determine the industry's total

[2] We assume that these output and input prices are equilibrium prices determined by respective supply and demand conditions. It should be noted that these equilibrium prices will be affected by the number of nurseries in the industry. For example, output price is determined by $p=p(n)$, $p'<0$, $p\geq p^*$ where p^* denotes the equilibrium price at which profits for the entire industry are driven to some minimal level (but not zero in this case, see Footnote 4) at the optimal supply of industry output. Therefore, as the number of nurseries increases, the equilibrium price must get closer and closer to p^*. In what follows, we assume that such price effects of a change in the number of nurseries are subsumed in the total impact on profits, i.e. π_n.

[3] For example, if the plant had close substitutes, then conceivably it would face a perfectly elastic demand curve.

[4] This condition is consistent with our plant breeding industry comprising competitive nurseries that display increasing or U-shaped average costs but there is also restricted entry, analogous to the farming industry discussed by Varian (1984, pp. 85–91). In our case, the reason for the restricted entry is that there are a finite number of "prime" locations in the region for establishing plant breeding nurseries, due to the geographical distribution of consumers and input suppliers (i.e., distance to markets) or to the variable quality of the land and other environmental conditions required by nurseries. The result is that nurseries will be established quickly on all the prime locations, until the last location and nursery established yields zero marginal profit to the industry. Thus, both in the short and long run, each inframarginal nursery and the industry as a whole will be making positive profits, but the marginal nursery will not add to the profits of the industry.

supply of the exotic plant, the total amount of each factor used in breeding the plant, and the total number of locations, n, where nurseries will be established in the region. In equilibrium, with given input and output prices, the industry will choose the total number of locations for its nurseries that maximizes its profits, which we designate as n^p, and the market-clearing level of supply of the exotic plant, $q=q(p, \mathbf{w}, n^p)$.

2.1. Introducing a risk of invasion

Suppose that the commercial plant species carries some risk of becoming invasive and causing economic losses. We can incorporate this risk as a hazard for which the likelihood and timing of occurrence and magnitude of economic losses are unknown. Such an approach falls under the heading of models of duration and catastrophic collapse. If in some future time period after introduction the commercial plant species turns out to be invasive, we assume commercial sales are terminated instantly. Thereafter, damages from the invasion are incurred as a penalty in addition to the loss in nursery profits.

Assuming the exotic plant species can become invasive at some point in the future, then we can denote τ as a random variable describing the timing of the invasion. In our model, we assume that the profit stream generated by commercial sales of the exotic plant species terminates at that point. Allowing for discounting of profits at rate δ, we can show the present value of industry profit under a risk of invasion as:

$$\mathrm{PV}(\pi) = \int_0^{\tau} e^{-\delta t}\pi(n(t))\mathrm{d}t \tag{3}$$

where an invasion occurring at the unknown time τ truncates the present value calculation of profits.[5] In keeping with the previous section, we expect that $\pi_n>0$ and $\pi_{nn}<0$, provided that the industry has not reached an equilibrium number of nurseries at which the marginal profits of the last outlet added are zero.[6]

Should an invasion occur, then losses will be incurred that consist of ecosystem damages as well as the costs of control efforts and adaptive responses, and these will presumably grow over time as the invasive spreads. For any $t>\tau$, the damages can be expressed as the product of the total area invaded, $A(t)$, and the average losses per hectare (ha) invaded, c. When discounted to the time of invasion τ, the present value of these losses, G, is:

$$G(\tau) = \int_{\tau}^{\infty} e^{-\delta(t-\tau)}cA(t)\mathrm{d}t \tag{4}$$

We can now formulate a statement for the expected net social benefits, $V(n(t))$, from selling the commercial species when there exists a risk that it may turn out to be invasive. Taking E as the expectations operator, this statement is:

$$V(n(t)) = E\left\{ \int_0^{\tau} \pi(n(t))e^{-\delta t}\mathrm{d}t - G(\tau)e^{-\delta\tau} \right\} \tag{5}$$

From the social planner's perspective, we wish to maximize the expectation represented by Eq. (5). One way of representing the risk of invasion in Eq. (5) is to use a hazard rate function, $h(t)$. The hazard rate describes the probability that the commercial plant will become invasive at time t given that it has not become invasive up to that time (t). It is defined formally as:

$$h(t) = \lim_{\Delta t \to 0} \{\Pr(\text{invasion occurs in}(t, t+\Delta t) \,|\, \text{for sale at } t)/\Delta t\} \tag{6}$$

Since invasion requires the chance combination of invasive characteristics present in the exotic plant species, plus dispersal into a suitable environment, these influences should be included as arguments in the hazard rate function. The invasiveness of the

[5] More realistically, we might expect some lag between the time at which the exotic plant becomes invasive and the recognition of this, leading to the consequent cessation of commercial sales. While more rigorous approaches for incorporating delay effects exist (see Kamien and Schwartz, 1991, p. 248), we could also address this concern more simply by defining the damages from invasion at time τ appropriately.

[6] As will be clear presently, we make this assumption in order to distinguish the equilibrium condition 2(c) for the optimal number of nurseries when the plant industry does not consider any risk of invasion with the equilibrium condition for n derived for the following model that does consider the risk of invasion.

commercial plant species is incorporated into the hazard function as a set of covariates that we define as vector **a**. Dispersal depends on the variety of commercial sales locations, represented by the number of commercial nurseries selling the plant species in any period t, denoted as $n(t)$. Thus, we define the hazard function so that it does not directly depend on time, i.e., not duration dependent, but allow it to depend on a time-varying covariate $n(t)$ and a fixed vector of covariates **a**. The resulting hazard function can be expressed as:

$$h(t) = h(n(t), \mathbf{a}) h_n>0, h_{nn}<0, h_{\mathbf{a}}>0, h_{aa}<0, \tag{7}$$

with integrated hazard $\int_0^t h(z)\mathrm{d}z$, where z is the variable of integration.

Following Reed and Heras (1992), we define a new state variable, $y(t)$, that is equal to the integrated hazard:

$$y(t) = \int_0^t h(z)\mathrm{d}z \tag{8}$$

It is immediately apparent from Eq. (8) that the equation of motion governing the state variable $y(t)$ is simply the hazard function:

$$\dot{y}(t) = h(n(t), \mathbf{a}) \tag{9}$$

By taking the expectation of Eq. (5) with respect to the random variable τ, Eq. (5) can be restated as:

$$V(n(t)) = \int_0^\infty [\pi(n(t)) + \delta G(\tau)]\mathrm{e}^{-\delta t - y(t)}\mathrm{d}t + G(0) \tag{10}$$

In Eq. (10), the state variable $y(t)$ augments the discount rate and does not directly enter into the objective functional. In the next section, we use Eq. (10) to determine the optimal number of nurseries at each point in time when invasion risk is present and compare this to the situation when either no risk exists or it is simply ignored.

2.2. Social welfare maximization with a risk of invasion

Since our focus here is on control at the level of commercial sales of the exotic plant species, we assume that the biological characteristics of the exotic plant, **a**, are fixed so that we can suppress this argument. Social welfare maximization is achieved by maximizing Eq. (10) over n, subject to Eq. (9).[7] Suppressing the variable t, Reed and Heras define a conditional current value Hamiltonian, which can be expressed here as:

$$H = \{\pi(n) + \delta G\} + \lambda h(n) \tag{11}$$

where λ is the standard current value multiplier divided by the term $\exp\{-y(t)\}$. The first-order conditions for this problem are:

$$\frac{\partial H}{\partial n} = \pi_n + \lambda h_n = 0$$

$$-\frac{\partial H}{\partial y} = \dot{\lambda} - [\delta + h(n)]\lambda = \pi(n) + \delta G$$

$$\frac{\partial H}{\partial \lambda} = h(n) \tag{12}$$

We can use these first-order conditions to derive the time path for the optimal number of nurseries selling the exotic plant, n^*, at each point in time:

$$\dot{n} = \frac{\pi_n[\delta + h(n^*)] - h_n[\pi(n^*) + \delta G]}{\pi_{nn} - \frac{\pi_n}{h_n} h_{nn}} \tag{13}$$

To facilitate comparison with the last equilibrium condition shown in Eq. (2), which is the short- and long-run profit condition for the number of nurseries chosen by the plant breeding industry in the absence of any consideration of the risk of invasion, we can rearrange Eq. (13) to yield the following dynamic profit condition:

$$\pi_n - \frac{h_n[\pi(n) + \delta G] + \dot{n}\pi_{nn}}{\delta + h(n) + \dot{n}\frac{h_{nn}}{h_n}} = 0 \tag{14}$$

When there is a risk of invasion, Eq. (14) demonstrates that the social optimum is no longer determined by a static equilibrium condition requiring that the addition of one more nursery selling the exotic plant species yield zero profits. Instead, the decision-maker must take into account the contribution to the

[7] We have also dropped a constant term that is not required for the optimization procedure.

risk of invasion (and the resulting expected social costs) from permitting one more nursery to sell the exotic plant species. These social costs consist of the contribution of an extra outlet to the hazard function (h_n) multiplied by the penalty should invasion occur. This penalty consists of the loss in profits due to the suspension of sales of the exotic plant species, $\pi(n)$, plus the annualized value of damages from invasion, δG. The denominator in Eq. (14) shows the augmented discount rate, which converts the second term in Eq. (14) to a present value. In effect, the hazard function acts as a risk premium added to the risk-free discount rate. Finally, the condition evolves over time as the industry grows, as indicated by the $\mathrm{d}n/\mathrm{d}t$ terms in Eq. (14).

Assuming that the industry eventually reaches long run equilibrium in terms of the number of nurseries, n^e, equilibrium profits can be determined from Eq. (14):

$$\pi_n - \frac{h_n(n^e)[\pi(n^e) + \delta G]}{\delta + h(n^e)} = 0 \tag{15}$$

Eq. (15) shows that in the long run, the contribution of a marginal outlet to industry profits must be equated to the expected social costs of this additional nursery. At long-run equilibrium, the optimal number of commercial nurseries, n^e, will be less than under no risk of invasion, n^p, since all the terms in Eq. (15) are positive (we assume the industry is earning positive profits or would shut down). Since marginal profits at equilibrium must be greater under a risk of invasion, the shape of the curve defining industry profits ensures that $n^e < n^p$.

Of particular interest in Eq. (15) is the relative influence of the hazard function and its associated marginal term. Since the hazard function acts as a premium on the social discount rate, this serves to increase the size of the nursery industry as the hazard increases (Clarke and Reed, 1994). This counter-intuitive result stems from the well-known observation that increasing risk leads to a desire to discount more heavily, thereby speeding up consumption. Since invasion is inevitable in our model, it follows that the commercial nursery industry should grow larger to take advantage of its commercial opportunities before the invasion takes place. In contrast, the marginal hazard term in Eq. (15) has the opposite effect—since more nurseries lead to a greater risk of invasion, there is a penalty associated with a larger industry. Which effect dominates, as the hazard changes, depends on the specification of the hazard function and its magnitude.[8]

A final point of discussion concerns the case when no amount of the exotic plant species should be sold at all. This situation would occur when the risk of an invasion, in combination with its potential economic losses, create expected social costs that exceed marginal profits from marketing the exotic, at all possible sizes of the industry. Since we assume that π, $h_n > 0$, the condition leading to this outcome is:

$$\frac{h_n[\pi(n) + \delta G] + \dot{n}\pi_{nn}}{\delta + h(n) + \frac{h_{nn}}{h_n}\dot{n}} > \pi_n, \ \forall n \tag{16}$$

If condition (16) is met, then no sales of the exotic plant species are warranted from a social perspective and the exotic plant is effectively 'screened out' from commercial distribution. Such a result would be more likely for exotic plant species with a high marginal hazard and if the potential damage costs from invasion are very large.

2.3. Policy implications with a risk of invasion

Economic theory suggests that an unregulated nursery industry would not take into account the risk of invasion posed by the exotic species that it markets. Instead, it would behave as if there was no risk of invasion as it adjusted towards an equilibrium number of commercial outlets, where $\pi_n = 0$. Therefore, the industry would consist of too many commercial outlets selling the exotic plant species relative to the socially optimal number. The policy dilemma consists of the need to identify and implement policy measures that alter incentives so that the industry grows to its optimal size and no further, recognizing that this optimal size includes the possibility that sales of the exotic plant species should be prohibited altogether.

[8] A similar argument can be constructed for the discount rate δ, as it appears in both the numerator and denominator of the second term in Eq. (15). In contrast, higher social costs of invasion (G) unequivocally lead to a smaller industry.

One market-based regulatory option is to internalize the risk of invasion via the institution of a Pigovian tax or charge. Assuming all the necessary information to design such a tax was available (a big assumption—see below), it would have the effect of restricting the number of commercial outlets selling the exotic plant species to the optimal number. Such a tax has been referred to as an introducers pay tax in the natural science literature (Brooks, 1997), but so far this concept has not been adopted by economists.

In the model presented in the previous section, the appropriate introducers pay tax, ψ, is identified as the second term in Eq. (14), for the case where industry equilibrium has not been achieved yet. At the long-run equilibrium, the tax reduces to the second term in expression (15). As discussed above, the magnitude of the tax in the long run depends on the potential economic losses should invasion occur, the sensitivity of the hazard of invasion to additional commercial outlets selling the exotic, and the social discount rate augmented to include the hazard rate as well.

Another obvious policy approach is the introduction of a conventional pollution standard to screen exotic plant species before they are marketed commercially. An appropriate level of risk would have to be established for the entire nursery industry, based on the willingness of society to tolerate the possibility of an invasion. The standard could take the form of an optimal threshold for plant characteristics relating to invasiveness, $\mathbf{a^*}$, and would require screening and licensing of all exotic plant species. As described here, the standard would be applied at the appropriate border, whether external or internal (e.g., state or provincial), with the intent of screening out all potential invasives whose expected net social benefits were negative for $n>0$. However, it would provide no regulatory control over potential invasives where a positive number of nurseries were socially optimal, but this number was lower than under no regulation. In this sense, the Pigovian tax may have superior characteristics in addition to the usual argument for greater economic efficiency.

Other market-based instruments that might warrant consideration include tradable permits to sell exotic species, or environmental performance bonds. Each of these instruments has advantages and disadvantages that may make them more or less desirable in the context of potentially invasive commercial plant species.[9] We do not investigate these approaches in detail here and instead leave them for future exploration.

In the next section, we use the example of saltcedar, an invasive shrub marketed by the horticultural industry as an ornamental plant, to illustrate the applications of our model. We concentrate on the prospects for applying a conventional pollution control policy (e.g., pollution tax) to this exotic plant species. Our analysis recognizes that saltcedar has already invaded, providing us with the historical data on its introduction, spread and the ecosystem damages it has caused, that are needed to apply our model empirically. The consequences of taking this approach for managing as yet unknown invaders are discussed later on.

3. An application of the model using data for saltcedar (*Tamarisk* spp.)

In this section, we test our model using data for a well-known invasive plant species that was brought from Eurasia to North America over 100 years ago. Popularly known as saltcedar, this shrub-like plant was imported to serve as a windbreak, to anchor soil and prevent erosion and, more importantly from the perspective of this paper, as an ornamental plant (Zavaleta, 2000). Over the period since its introduction, and particularly during the last 50 years, it has invaded a large number of riparian floodplains throughout the U.S. Southwest. Zavaleta indicates that it now occupies from 470,000 to 650,000 ha in 23 states, having increased its coverage by as much as 200,000 ha during the 1990s alone.

Since saltcedar has also been valued as an ornamental plant, it can serve as a useful illustration for as yet unknown exotic plant species that have commercial value but also may have invasive qualities. In the following discussion, we assume that an exotic plant species has similarities to saltcedar and that decision-makers can assess potential invasiveness

[9] For example, Costanza and Perrings (1990) explore the possibility of environmental bonds and these may have some appeal in the case of commercial exotic plants. However, Shogren et al. (1993) caution on the use of such an instrument and several of their concerns appear relevant to the importation of exotic plants.

and know the probable costs of an invasion should it occur at some future date. The following sections describe the various empirical relationships needed to apply the model of earlier sections to this hypothetical exotic plant species.

3.1. Estimating the hazard function for potentially invasive plant species

In modeling the hazard function, we assume that the hazard is independent of duration but relies on several covariates, one of which is time-varying, $n(t)$. To model the influence of the covariates, we use a proportional hazard model (Kiefer, 1988), expressed as:

$$h(\tau_i) = \alpha_0(\tau_i)\phi(n(t), \mathbf{a}) \quad (17)$$

where τ_i is the timing of invasion for plant species i, α_0 is the baseline hazard, usually defined at the mean value of the regressors. The function $\Phi(n(t),\mathbf{a})$ shifts the baseline hazard up or down, depending on the direction of the influence of the covariates. Typically, $\Phi(n(t),\mathbf{a})$ is specified in exponential form and is estimated using Cox's (1972) partial likelihood estimator. Estimating the proportional hazard model requires observations on the timing of introduction and invasion (τ) for individual plant species, along with data describing their characteristics and the number of nurseries selling the plant during each time period. Such a database does not exist at present, so we were forced to take a more ad hoc approach.

We assume the function $\Phi(n(t),\mathbf{a})$ is the product of two distinct functions, $f(n(t))$ and $k(\mathbf{a})$. Thus, the inherent invasiveness of the exotic plant is modeled distinctly from the influence of nurseries as potential dispersal sites, with the latter serving to scale the hazard function accordingly. Ignoring the function $f(n(t))$ for the moment, a semiparametric approach was used to derive a non duration dependent hazard that is a function of plant characteristics $\mathbf{a}$ alone.

Relating these plant characteristics to the timing of invasion, or "time to failure", was a challenge. Given the lack of suitable data, we used a simplifying procedure that assumed plant species could be ranked according to their historical invasiveness (as perceived by experts). Such assessments are not uncommon and certainly more plentiful than historical data on the timing of invasions themselves. If the categories of invasion risk (high, medium, low or whatever) that were available from such assessments could be 'mapped' in a temporal sense, then they could be interpreted as an indication of the approximate time to invasion. If the problem is approached in this way, then time is rescaled into arbitrary (and perhaps even unknown) intervals that now correspond to the categories of invasion risk as follows:

Time intervals:	T_1	T_2	T_3	T_4	T_5
Invasion risk category:	1 very high	2 high	3 medium	4 low	5 very low

The time periods T_1, T_2, T_3, $\ldots T_j$, represent arbitrary intervals during which potentially invasive plants with the associated invasion risk shown immediately below would be expected to invade, i.e., a failure time in the usual duration sense.

Using this approach, the data requirements are far less restrictive, and the hazard function can be estimated using an ordered logit procedure suggested by Han and Hausman (1990). In most applications, the estimator used in this procedure is identical to the ordered logit model and depends on an extreme value distribution for the error term (see Greene, 1990).[10] In effect, the model predicts thresholds that determine into which category (invasiveness) an observation falls, as a function of plant characteristics. Knowing the frequency with which observations fall into each category, a hazard rate can be estimated. The output from the model is a set of discrete hazard rates associated with distinct categories of invasive risk.

The data used were from Dalsimer (2000), who surveyed land managers who deal with invasive plants on a routine basis. She asked questions about the biological characteristics of individual plants as well as local ecosystems vulnerable to invasion; the resulting database contained 114 data points, which was sufficient for estimation purposes. The dependent variable consisted of four categories of invasiveness: highly invasive (T_1), moderately invasive (T_2),

[10] If a normal distribution for this term were more appropriate, then an ordered probit model would be used, although there are some additional difficulties.

slightly invasive (T_3), and not yet known to be invasive (T_4). The independent variables used in the model were: proximity to uninfested areas (PROX); plant reproduction, measured as seed production or vine growth per year (SEEDS); resistance to control methods (RESIS); ability to recover from fires/floods (DISAS); and ability to survive wide temperature fluctuations (TEMP). Appendix A provides the estimation results using LIMDEP Version 7.0.

All variables in the estimation were significant (P<0.1), and all demonstrated coefficients with the expected sign, except for TEMP, which had a positive but not highly significant coefficient (P<0.079).[11] The resulting hazard rates for the various categories of invasiveness were: (a) not yet known to be invasive, 0.1206; (b) slightly invasive, 0.3890; and (c) moderately to highly invasive, 0.8155.[12] These hazard rates are interpreted as the probability that species i with characteristics $\mathbf{a}_i$ will invade during the current time interval (e.g., T_2), given that it has not invaded yet.

To complete the hazard function, we needed to incorporate the influence of the covariate $n(t)$ via the function $f(n(t))$. We allow this influence to scale the hazard rates estimated above according to the number of nurseries in the industry that sell the potentially invasive species. We consider two specifications for the function $f(n(t))$ to allow for different formulations of the marginal hazard (h_n):

$$f_1(n(t)) = \frac{n(t)}{4000 + n}$$

$$f_2(n(t)) = \frac{n(t)}{40,000} \tag{18}$$

The first variant, $f_1(n(t))$, is nonlinear and has a positive but decreasing marginal value, i.e., $f_1' > 0$, $f_1'' < 0$, with $\lim_{n \to \infty} \{f(n)\} = 1$. It attains very low values once the number of nurseries is sufficiently large.[13] In the second specification, $f_2(n(t))$, the marginal hazard is constant and, therefore, significantly larger than the marginal hazard for the first variant if the industry is large, i.e., $f_2' = 0.000025$, $f_2'' = 0$, with $\lim_{n \to \infty} \{f(n)\} = \infty$. Multiplying these variants by the hazard rates estimated earlier leads to different values for the final hazard function used in the calculations. These hazard function values describe the relationship between the likelihood of invasion in the current time period, as measured by the nonduration-dependent component of the hazard function, and the number of nurseries selling the exotic plant species during that time period.

3.2. Other relationships required in the empirical analysis

We also require an estimate of nursery industry profits as a function of the size of the industry n. Since we desired to keep our approach relatively simple, industry profits were specified as a quadratic function of operations, n, and data for the U.S. horticulture industry by state from USDA were used to fit the model (USDA, 2001). Variable and fixed costs for all horticultural operations were deducted from total industry sales to obtain a notional value for industry profits, and this was then expressed per 100,000 population for each state (to normalize across states of varying sizes). Fixed costs consisted of the value of land and buildings, depreciated at 2% per year, and machinery and equipment, depreciated at 15% per year. Similarly, the number of horticultural operations was expressed for each state on a per 100,000 population basis. When a simple second-order polynomial was fitted to industry profits as a function of the number of operations, the following relationship was obtained:

$$\pi(n) = 373.63 + 92.9n - 3.463n^2 \tag{19}$$

Expression (19) is concave and, therefore, consistent with the profit expression described in the previous

[11] This anomalous result likely is explained by the small proportion of observations exhibiting a low tolerance to temperature variation (only 7 out of 114 total observations). A check of the data reveals these observations tend to be associated with less invasive species, but the small number of observations involved suggests this may be more coincidental than scientific. Nonetheless, we decided to retain this variable in our estimation.

[12] The LIMDEP routine estimates an identical hazard rate for the last two categories.

[13] For example, there were 23,758 horticultural operations contributing to the data on industry profits.

section. Not surprisingly, the explanatory power of Eq. (19) is quite low, as there are numerous factors differentiating the demand and supply of horticultural products across states that are not taken into account in our simplified model. Yet, it displays the expected property that most data points are to the left of its peak (Fig. 1).

For use in the calculations, two adjustments were needed. First, Eq. (19) was scaled up from operations and profits per 100,000 population to a national estimate using the U.S. population of 270.2 million in July, 1998. Second, since a single exotic plant species would not likely account for all industry profits, we used a scaling factor to test different shares of profits associated with a representative exotic plant species (0.1% to 100%).

In addition, we require an estimate of the invasion damages, assuming the importation of the exotic plant results in an invasion occurring at time τ. The resulting economic losses are $G(\tau)$ and were estimated using Eq. (4). Shigesada and Kawasaki (1997) consider a number of models to describe the progress of an invasion over time, $\mathrm{d}A/\mathrm{d}t$. Given the evidence for saltcedar, which we use as our representative exotic plant species, a logistic model seemed an appropriate choice. Defining the intrinsic rate of growth of the invaded area as r, and the maximum area that could be invaded as K, gives:

$$\frac{\mathrm{d}A}{\mathrm{d}t} = \dot{A} = rA(t)\left(1 - \frac{A(t)}{K}\right) \tag{20}$$

Solving Eq. (20) for $A(t)$, we can formulate a statement for the present value of invasion damages at time τ, the point at which invasion begins:

$$G(\tau) = c\int_{\tau}^{\infty} \frac{K\mathrm{e}^{-\delta(t-\tau)}}{1 + \left[\frac{K-A(\tau)}{A(\tau)}\right]\mathrm{e}^{-r(t-\tau)}}\mathrm{d}t \tag{21}$$

where c is the per ha damage cost of the invasion and $A(\tau)$ is the initial area invaded, which we set at 1 ha. The maximum area that could be invaded, K, was set at 2 million ha with an alternative, higher value of 3 million ha used as well (Zavaleta, personal communication, 2003). Since the current area invaded was cited earlier as 470,000 to 650,000 ha, the value of r was calculated for the endpoints in this range, yielding upper and lower values for r of 0.08945 and 0.09247, respectively. Zavaleta also estimates the costs of the invasion by saltcedar in the United States, including losses associated with reduced irrigation water supplies, lowered hydropower generation, foregone

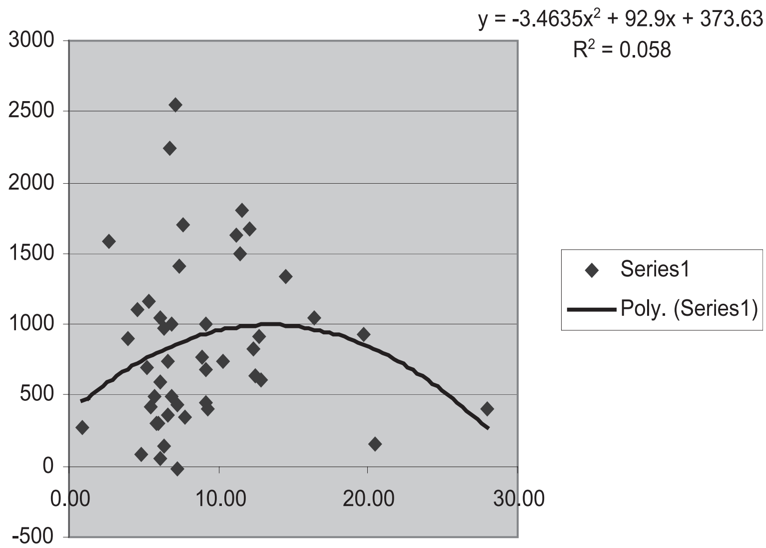

Fig. 1. U.S. horticulture industry profits per 100,000 population, by state (vertical axis), and the number of operations per 100,000 population, by state (horizontal axis).

Table 1
Indicative optimal solution values for the long-run equilibrium number of nurseries selling a potentially invasive exotic plant species and the associated introducers pay tax, under various model assumptions

Share of profits	Model (a)		Model (b)		Model (c)		Model (d)	
(%)	High hazard	Low hazard	High hazard	Low hazard	High hazard	Low hazard	High hazard	Low hazard
0.1								
Nurseries, n^*	32,584.61	33,727.75	0	4754.18	31,901.23	33,304.86	0	0
Tax, ψ^* (\$/year)	9.34	6.41	–	80.71	11.09	7.49	–	–
1.0								
Nurseries, n^*	32,986.52	33,984.41	0	9220.96	32,924.35	33,944.34	0	8567.41
Tax, ψ^* (\$/year)	83.10	57.51	–	692.54	84.69	58.53	–	709.30
10.0								
Nurseries, n^*	33,025.59	34,009.65	0	9625.80	33,019.43	34,005.66	0	9562.20
Tax, ψ^* (\$/year)	820.93	568.58	–	6821.56	822.51	569.60	–	6837.87
100.0								
Nurseries, n^*	33,029.49	34,012.17	0	9665.94	33,028.87	34,011.77	0	9659.60
Tax, ψ^* (\$/year)	8199.29	5679.30	–	68,112.69	8200.87	5680.32	–	68,128.95

See text for descriptions of the models used in this table.

municipal water supplies and increased flood damages. Based on the lower area invaded (470,000 ha), the resulting estimate for c is \$280 per ha, while for the larger area (650,000 ha) it is \$450 per ha. Both figures were used in the calculations, to give an approximate range of damage costs for a representative invasive plant species similar to saltcedar. Finally, a social discount rate of 5% was used in the analysis.

Inserting the various parameters described above into Eq. (21) provides estimates of the present value of damage costs discounted to time τ. To simplify evaluation of the integral in Eq. (21), we solved for the present value numerically by projecting damages into the future until the point at which the annual discounted value for damages fell to one dollar. Note that the very long gestation period for saltcedar (about 100 years) prior to its rapid spread results in damage costs that are quite low when these are discounted back to the time of initial introduction.[14] Using the lower estimate of damage costs (c=\$280/ha), the present value of economic losses is \$6.0 million, while taking the upper estimate (c=\$450/ha) the present value of economic losses is \$14.5 million. These present values were used in the calculations as estimates of $G(\tau)$.

3.3. Models analyzed

Finally, we devised four different models based on varying assumptions about the empirical relationships described in this section:

Model (a): the nonlinear specification for the influence of industry size on the hazard, $f_1(n)$, together with the low estimate of the damages from invasion;
Model (b): the linear specification for the influence of industry size on the hazard, $f_2(n)$, together with the low estimate of the damages from invasion;
Model (c): the nonlinear specification for the influence of industry size on the hazard, $f_1(n)$, together with the high estimate of the damages from invasion; and,
Model (d): the linear specification for the influence of industry size on the hazard, $f_2(n)$, together with the high estimate of the damages from invasion.

We then made assumptions about the nonduration-dependent component of the hazard rate, k(a), selecting a high hazard case [k(a)=0.8155] and a

[14] Arguably we could have used 50 years ago as a measure of the time at which invasion occurred, since this represents the date at which rapid expansion by saltcedar began. This approach would produce higher damage estimates since the gestation period would be much shorter.

low hazard case [k(a)=0.1206]. In addition, four levels of profitability associated with the exotic plant species were modeled, ranging from 0.1% of industry profits to 100% (see above). Thus, we considered a total of 32 different sets of model assumptions (Table 1).

4. Results and discussion

In the empirical analysis presented in this section, we emphasize the policy implications of our model, using the representative data for saltcedar. While decision-makers will be concerned that exotic plant species could pose a risk of invasion if they are imported into a country for commercial sale, they must also recognize that there are welfare benefits provided by such imports. The policy dilemma, as noted earlier, is to balance these two concerns. Given the apparent advantage of the introducers pay tax, we consider only this approach. Our results are discussed below (see Table 1).

Our results represent long-run equilibrium values and do not consider the adjustment period when the industry is expanding towards its equilibrium size, i.e., Eq. (15) rather than Eq. (14). In all cases, the optimal number of nurseries was lower than the long-run private equilibrium, n^p, where no consideration is given to the risk of invasion (n^p=36,226 nurseries). However, it was clear that the marginal hazard has an important role, since there were marked differences in the results using a nonlinear hazard function in comparison to the linear specification, i.e., Models (a) and (c) versus Models (b) and (d). In the former case, the very small marginal hazard at larger sizes of the industry resulted in a relatively small effect from the presence of a risk of invasion, evident in the minor deviations in the optimal size of the industry from the private outcome (n^p=36,226 nurseries). This observation held even when other modeling assumptions were varied (e.g., size of invasion damages, share of industry profits, etc.), including assumptions about the characteristics of the plant species, as captured by the hazard rate $k(\mathbf{a})$.

Examination of the results using a linear specification for the function $f(n)$, represented by Models (b) and (d), confirm the above observation. The optimal number of nurseries selling the exotic plant was more sensitive to model assumptions with the constant marginal hazard. For example, when the hazard rate is high, no sales of the exotic plant species are desirable, while a positive number of nurseries are permitted to sell the exotic if the hazard rate is low (except in one case). Also note that the offsetting and, therefore, ambiguous influence of the marginal versus total hazard terms in the second term of Eq. (15) is resolved here. For each model, the higher hazard case results in a lower equilibrium number of nurseries and a higher tax. Thus, the marginal hazard effect in the numerator of Eq. (15) dominates the total hazard effect in the denominator of Eq. (15).

Values for the introducers pay tax required to bring about the socially optimal size of the industry were primarily sensitive to the profitability of the exotic plant species. Across all models and parameter assumptions, the introducers pay tax represented less than 1.0% of average profits per nursery. However, there were dramatic differences in the tax between models, and again these appear to result from differences in the marginal hazard function. The introducers pay tax under a constant marginal hazard was approximately 10 times greater than its value when the marginal hazard was diminishing. While the nonduration-dependent component of the hazard rate, $k(\mathbf{a})$, has some impact on the size of the tax; i.e., comparing high versus low hazard for Model (a); there is virtually no effect associated with differing levels of economic losses from invasion, i.e., Model (a) versus Model (c).

5. Conclusion

Our results indicate that the mere presence of a risk of invasion associated with an exotic plant species does not mean that it is socially optimal to prevent commercial sales of the species if it is valued by consumers as an ornamental plant. Indeed, there appear to be plausible forms of the functional relationships involved that require only a modest reduction in the private industry optimum that would ensue in the absence of intervention by decision-makers. However, there are several troubling issues that cannot be so easily ignored in favor of the application of conventional market-based policy prescriptions (e.g., introducers pay tax). For example, the stochastic and ex ante nature of the invasion problem creates worries about the availability of reliable data to model appropriate policy responses. We were able to accomplish our indicative analysis only because we were willing to make several heroic assumptions about critical functional forms, and these are unlikely to be known with any certainty without a substantial data collection effort.

Noneconomists may be especially perplexed to learn that it might be socially optimal to allow commercial sales of a plant similar to saltcedar, in light of the intense concerns about the damages this invasive has caused already. Would we truly wish to allow sales of an exotic species that quite reasonably might become invasive? A precautionary response might be called for in such a case. Nonetheless, we are encouraged that even our economic analysis calls for no such industry under several sets of assumptions about the level of invasion risk and the linkage between dispersal sites and invasion hazard.

In conclusion, a hazard rate formulation has been used in applications involving fisheries (Reed, 1988) or technical innovations in the energy sector (Dasgupta and Heal, 1974). Our analysis suggests that this approach shows promise for modeling a commercially valued plant species that could become invasive.

Appendix A. Ordered logit estimation of plant invasiveness as a function of plant and ecosystem characteristics

Variable	Coefficient (*b*)	*b*/Standard error	Variable mean
(A) Index function for probability			
Constant	5.9456	3.405	–
PROX	0.3079	1.714	3.674
SEEDS	−1.5001	−3.793	2.316
RESIS	−2.2130	−3.200	0.147
DISAS	−0.7518	−2.244	3.432
TEMP	1.3923	1.757	0.926
(B) Threshold parameters for index			
Mu(1)	1.8370	4.188	–
Mu(2)	4.1936	7.227	–

N=95; Log likelihood function: −101.6705; Restricted log likelihood: −126.0813; Chi-squared: 48.8217; Prediction rate=51 correct/95 observations=53.7%.

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