A Monopolistic Competition Economic Model of the Horticultural Industry with a Risk of Harmful Plant Invasion

Edward B Barbier[1]
Johnson Gwatipedza[1]
Duncan Knowler[2]
Sarah H. Reichard[3]

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[1]Department of Economics and Finance, University of Wyoming

[2]School of Resource and Environmental Management, Simon Fraser University

[3] Center for Urban Horticulture, College of Forest Resources, University of Washington

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Abstract

The risk of plant invasion associated with commercial nursery operations means that the "privately" optimal number of nurseries established will diverge from the "socially" optimal number that accounts for this risk. We develop a monopolistic competition model of the horticultural industry and estimate the resulting profit function with US and Canadian industry data. Combining the results with a hazard analysis of the ecological characteristics of exotic plants previously introduced in North America, we explore optimal tax simulations for internalizing the risk and costs of a potential plant invasion. The tax is highly sensitive to the share of the exotic plant sales in final profits. If the share is large, then the resulting annual fee to internalize the cost and risk from a potential plant invasion will be high, discouraging the expansion of the nursery industry. However, the annual revenues could fund efforts to mitigate the damages resulting from any accidental plant invasion.

Keywords: monopolistic competition, exotic plant species, biological invasion, horticultural industry, nurseries

JEL classification: D43, Q29

Introduction

The growth in demand for nursery products by consumers has led to the expansion of the horticultural industry in North America. However, this expansion has also increased the risk of accidental introduction of harmful non-native species in host ecosystems. Commercial horticultural activities, especially increased exotic plant material imports and expansion of nursery operations, have become a significant pathway of invasive species to invade the natural environment in North America (Maki and Galatowitsch 2004).

Introduced non-native invasive plant species cause significant damages to the host environment and are regarded as a major threat to native biological diversity in North America. (Mack et al. 2000; Reichard and White 2001). The negative consequences of introducing exotic plants include competition for resources with native species, increased nitrogen fixation in natural areas, changes in hydrological cycles, increased sedimentation, and increased frequency and intensity of cycles. Bell et al (2003) indicate that 40% of the endangered native species are at risk from invasive species. Pimentel et al (2005) estimate total damages to the United States (US) economy from non-native invasive plants in natural areas and agriculture at about $35 billion per year, and that more than 5,000 alien plant species have escaped and invaded the natural areas of the US and displaced several native species. Alien weeds invade approximately 700,000 hectares of US wildlife habitat each year. Over 1,000 introduced exotic plant species have been identified as a threat to the native flora as a result of their aggressive, invasive characteristics (US National Park Service 2007).

Thus, while the North American horticultural industry and its consumers may benefit from selling imported plants, they do not take into account the economic costs from accidental introduction of exotic invasive plant species. These costs are instead borne by the society, and constitute an externality arising from the accidental introduction of exotic invasives into the natural environment. Correcting this externality therefore requires the adoption of appropriate policy measures by the government, which should be based on assessing the risk of accidental introduction of a potential plant invasive species and the costs incurred. The presence of this risk means that the “privately” optimal number of nurseries established by the industry will diverge from the “socially” optimal number that account for the additional costs imposed by this risk.

The purpose of this paper is to derive explicitly the conditions determining the social and private optimal number of nurseries. We also use these conditions to explore a policy intervention in form of a tax (annual license fee) that could induce horticultural nursery firms to internalize the risk of potential invasion and its associated costs, and thus bring private incentives in line with socially optimal levels.[1]

To accomplish this goal, this paper undertakes four major tasks. First, we develop an economic model of the US and Canadian horticultural industry using a general monopolistic competition framework, and we contrast the privately optimal decision of the industry to establish nurseries with the socially optimal decision by a government that also considers the risk of an accidental invasion. We then undertake two empirical estimations. By utilizing survey data on the North American horticultural industry, we estimate the representative firm's profit function, and by using ecological data on the plant characteristics of previously imported plant species, we employ an exponential hazard rate duration model to estimate the probability of a newly introduced exotic species becoming an invasive. We combine these two estimations to carry out simulations of the potential trade-offs between the commercial profits from the nursery industry and expected social damages from the risk of invasion to determine the appropriate tax rate to be imposed on the US and Canadian horticultural industry. We assume in our simulations that the North American industry is importing a new exotic species, which might exhibit potential invasiveness. We base the simulation on the example of a well known invasive species in North America, purple loosestrife.

Implementing economic instruments to control invasive species has received attention in the recent literature (Horan and Lupi 2005; Costello and McAusland 2003; Knowler and Barbier 2005). Horan and Lupi (2005) consider the use of tradable risk permits to control invasive species. Costello and McAusland (2003) analyze the relationship among volumes of goods traded, import tariffs and the impact on accidental invasion. Knowler and Barbier (2005) examine the possible use of "introducer pay" taxes in the horticultural nursery industry. The

[1] Throughout this paper, we refer to the "horticultural industry" or "horticulture industry". This terminology is often used in reference to commercial wholesale or retail plant sales business, or nurseries, when in fact the industry also includes landscape design and maintenance. In the context of our work, we include only business which sells plants or nurseries.

authors focus on the nursery sector of the horticulture industry as a source and a significant pathway for the deliberate introduction of potential invasive plants. Their calculation of the socially optimal number of nurseries takes into account both the contribution to the probability that an ornamental plant becomes invasive and the losses to the industry if the invasion occurs. The authors find that the socially optimal number of nurseries is lower than that of the existing nursery market, and they evaluate the use of taxes to restrict the number of nurseries to the social optimum. The optimal level of taxes is shown to be highly dependent on how the probability of invasion changes with even a marginal increase in the number of nurseries.

In this paper, the work of Knowler and Barbier (2005) is extended and improved in the following ways. First, the commercial decision by the horticultural industry to sell plants at different locations is modeled through incorporating the general monopolistic competition framework as developed by Spence (1976) and Dixit and Stiglitz (1977). The paper relies on the variant of the monopolistic competition model that is employed in the new economic geography literature for policy analysis (Baldwin et al 2003; Fujita, Krugman and Venebles 1999; Neary 2001). The model allows derivation of a specific functional form of the representative nursery firm's short-run profit function, which is then empirically estimated based on a panel analysis across US states and the years 1978, 1987 and 1998. In addition, a separate panel analysis is also conducted across all provinces of Canada over the period 1997 to 2006. The economic dataset for the US panel analysis is from the USDA Horticultural Specialists census data, and for the Canadian horticulture industry from the Annual Greenhouse, Sod and Nursery Survey of Canada (USDA 2001, Statistics Canada 2006). The data are disaggregated into different states and regions, thus allowing for potentially unobserved factors through the inclusion of regional and state-specific fixed effects in the regression analysis.

The monopolistic competition model of the North American horticultural industry allows us to characterize the consumer and producer surplus gained from nursery sales in new locations. However, because each new nursery selling a new exotic plant in a different location increases the risk of a potential plant invasion causing environmental damages, social welfare must include not only consumer and producer surplus from sales but also the expected risk of an accidental invasion and any ensuing environmental damages. We assume that the risk of invasion depends on the characteristics of introduced plants and the total number of nurseries selling products based on these plants, which is supported by the ecological literature on past plant invasions (e.g., Rejmánek and Richardson 1996, Reichard and Hamilton 1997, Pheloung et al. 1999). We formulate this risk as a hazard rate function, and following the approach of Reed and Heras (1992), we transform this stochastic optimization problem into a standard deterministic control model governed by a hazard rate constraint. The hazard rate function forming this constraint depends both on the plant characteristics of the invasive species and also the number of nurseries established by the horticultural industry. We estimated the component of the hazard rate that depends on plant characteristics by employing a new ecological dataset on historical introductions of past exotic herbaceous species introductions in North America. Of the 106 observations in the herbaceous plant dataset, 77 were for species that eventually became invasive and 29 were for species that have not yet or may never become successful invaders. We selected taxonomic, eco-geographic, and biological traits describing the species in our samples based on numerous studies of the traits associated with invasive and non-invasive plants.

We conduct our simulation of a newly introduced invasive plant using estimated damages from the known invasive plant species purple loosestrife (*Lythrum salicaia*) as our example. Purple loosestrife is a Eurasian wetland perennial introduced to North America in the early 1800s as an ornamental plant. It has now become a prolific weed invader of wetlands throughout US temperate zones and the southern portions of Canada from Newfoundland to British Columbia (Brown 2005). The plant rapidly forms nonspecific stands, displacing native plant species that provide food, cover, and breeding areas for a number of wild species. Purple loosestrife is estimated to occur in nine provinces in Canada (Blossey 2002). In Manitoba, purple loosestrife is estimated to cover 5,575 ha of habitat (Henne et al 2005, Lindgren 2003). In the United States Malecki et al (1993) indicate that it is found in 48 states except Alaska, Hawaii and Florida and has been spreading at a rate of 115,000ha/yr. Brown (2005) estimates that about 1.2 million acres (499,000 ha) of wetlands in the Atlantic and Mississippi flyway are considered at risk of invasion, and that as of 2003, the area infested in the United States was about 324,000 acres (131,152 ha). While it is illegal to sell purple loosestrife in some states and provinces, in others the plant is still being sold as an ornamental plant and is widely available throughout North America via internet sales (Kay and Hoyle 2001).

Direct economic costs from purple loosestrife include reduced palatability of hay containing purple loosestrife and the reduction in water flow in irrigation systems. Indirect losses include reduction in waterfowl viewing and hunting opportunities (Blossey 2002). Regarding ecological damages, the invasion of purple loosestrife alters the biochemical and hydrological processes in wetlands. It decreases water storage capacity, reduces the ability for wetlands to attenuate floods, clogs drainage channels and irrigation ponds, and reduces the excess capacity of a wetland to hold and absorb excess water. Purple loosestrife inflicts damage to wetlands by its displacement of native flora, which are essential for food, nest sites, and cover to native wildlife such as birds (Scudder et al 2005). Purple loosestrife is competitively superior over native species; thus, expanding purple loosestrife populations cause local reductions in native species richness (Blossey 2002). In the US purple loosestrife is estimated to incur $45 million per year in control costs and forage losses (Malecki et al 1993). The government of Canada in 2001 estimated that, in the Great Lakes and St Lawrence River Basins, $500 million is spent each year on efforts to eradicate invasive species such as purple loosestrife (Lindgren 2003).

The outline of the paper is as follows: In the next section we develop a theoretical model for the horticultural industry operating under a monopolistic competitive framework in the presence of a trade related environmental externality. We subsequently estimate the short-run profit function for a representative nursery firm employing data from the United States and Canada. Using these results along with our estimates of the hazard rate of invasion by a herbaceous species, and employing damage estimates from purple loosestrife, we conclude by conducting policy simulations on the optimal tax (annual license fee) and the number of nursery firms for the horticultural industry introducing a new exotic plant species with a risk of invasion.

Theoretical Framework of Horticultural Industry Model with Risk of Invasion

The monopolistic competition framework that we adopt fits the “stylized facts” of the North American horticultural industry. According to Singh (1999), the horticultural industry in the United States is large, complex, and comprised of many segments. Nursery growers are diverse, producing hundreds and even thousands of plant taxa on farms of different sizes. The firms sell the nursery taxa directly or through retail outlets to consumers who demand a broader selection.

In many cases, the nursery firms producing different taxa are vertically integrated; that is, they are linked with specific retail outlets to sell differentiated products to local markets. Since the production and retail process is vertically integrated and targeted to specific retail markets, we will consider each supplier to a differentiated product market as a single unit, which we will refer to as a "nursery firm". This allows us to apply the Dixit-Stiglitz monopolistic competition framework to characterize production and supply by a representative nursery firm.

The assumption of a vertically integrated nursery firm that imports plant material and sells it in retail markets is supported by evidence that the North American horticultural industry via its nurseries imports non-native plant species for propagation and delivers plant products directly to the final consumers (Brooker et al 2005; Singh 1999). A survey conducted by Brooker, et al (2005) estimates the nurseries' total annual sales made between wholesalers and retailers. The results show that, for the 44 US States on average, 75% of the nurseries made some wholesale sales and 58% of all firms made some retail sales. Almost half of nursery firm survey respondents purchased source propagation material from Canada and thirty one other countries including Netherlands, Mexico, and Argentina.

The key economic assumptions underlying our horticultural industry model are as follows. We consider an economy producing two goods, a nursery product and a composite good representative of all other production in the economy. The consumers derive utility from a homogeneous composite good, and from consumption of a differentiated nursery good available on the market as many different plant selections or "bundles" that are close substitutes. Consumer preferences are assumed to be quasi-linear in the composite good, which is a simplifying assumption often adopted to improve analytical tractability without detracting from the key results (Baldwin et al. 2003, pp. 43-44; Barbier and Rauscher 2007). Production of the composite good is by constant returns to scale. In contrast, each nursery firm produces its own unique selection of plants under increasing returns to scale, targeted to a specific consumer market in a given location. We assume that the firm has imported a new exotic plant species as a one-time investment. This assumption also implies that the unique bundle of plants sold by each nursery will contain some quantity of plants either based on propagating the imported exotic plant material or the exotic plant itself (Avent 2003). The whole nursery industry is characterized by the Dixit-Stiglitz monopolistic competition framework in production and supply. Throughout the model we assume that the composite good is the numeraire, and its price is normalized to one.

However, by selling the non-native plant species (or plants based on its material) through establishing a new nursery in a different commercial location, the horticultural industry incurs the risk of a potential plant invasion in the natural environment causing extensive damages. The economic costs of such damages caused by harmful non-native plant species are not borne by the industry but by society. Thus, we extend our model to include a social objective function that includes the risk and costs of a potential plant invasion to determine the socially optimal number of nursery firms. This allows us, in turn, to derive the optimal tax for internalizing the externality associated with the risk of an accidental invasion.

Consumers

The consumers derive utility from consumption of a homogenous composite good M , and a continuum of differentiated nursery good X . Consumer utility preferences are assumed to be quasi linear and a representative individual's utility function is expressed as

$$U = M + X = M + \frac{1}{\gamma}\left(\int_{i=1}^{n} q(i)^{\gamma} \, di \right) \tag{1}$$

where $0 < \gamma < 1$ measures the substitutability between the different bundles of plants offered by various nursery firms. That is, it measures the degree to which the representative consumer considers different plant bundles offered in the market to be substitutable such that γ close to 1 denotes perfect substitutability and γ close to 0 denotes no substitution at all. Also $\sigma = 1/(1-\gamma) > 1$ is the elasticity of substitution between any two mixes of nursery products. $q(i)$ is the quantity consumed of each differentiated assortment, or bundle, of the nursery good. The bundle consists of a combination of at least one imported exotic species and native species, assumed to be a single commodity, where $i = 1...n$ is the total number of differentiated bundles of nursery goods available on the market. The consumer maximizes utility (1) subject to the following budget constraint:

$$E = M + \int_{i=1}^{n} p(i)q(i)d\, i \tag{2}$$

where $p(i)$ is the price of the individual differentiated bundle $q(i)$, and E is income. Assuming that the second order sufficient conditions are satisfied, maximization yields a demand function for each nursery good assortment given by

$$q(i) = p(i)^{\frac{1}{\gamma-1}} \tag{3}$$

The demand function for the composite good A is given by

$$M = E - \int_{i=1}^{n} p(i)^{\frac{\gamma}{\gamma-1}} di \tag{4}$$

From equation (3) the inverse demand function for the representative differentiated bundle is

$$p(i) = q(i)^{\gamma-1} \tag{5}$$

The indirect utility function is obtained by substituting the demand functions (3) and (4) into the utility functions to get

$$V(p, E) = E + \frac{1-\gamma}{\gamma} \int_{i=1}^{n} p(i)^{\frac{\gamma}{\gamma-1}} di \tag{6}$$

Indirect utility is an increasing function of wage income and the number of nursery product bundles n available on the market. The latter result implies that increasing the broad selection of plant taxa available to the representative consumer increases his or her welfare. The indirect utility is decreasing in product prices. Given that the price of existing assortments of the nursery product remains constant, the same level of expenditure spread over more bundles increases consumer utility. These results for the indirect utility function conform to the standard outcome of models that assume more conventional Dixit-Stiglitz preferences for a differentiated product (Baldwin et al 2003).

Horticultural Firms and Industry

We assume that the horticultural industry consists of n nursery firms, and each firm produces its own selection of plants targeted to a specific consumer market in a given location.[2] We treat each bundle of plants sold by each nursery, *i*, as if it were a single commodity, or product, with its

[2] We assume only one nursery firm per bundle, which is standard in the monopolistic competition literature (Baldwin et al, 2003). Suppose there is a firm already producing a bundle of nursery plants i, and another firm contemplating entering the market. If the entrant produces exactly bundle i, then the two firms will split the profit. The profit earned by the entrant will be below those that she could earn by producing a unique bundle. Given the assumption that it costs the same to produce each bundle, no entrant will find it profitable to produce an existing bundle.

quantity denoted by $q(i)$. However, two different nursery firms will not offer the same bundle of plants for sale in their respective markets. This allows each firm to sell its own differentiated mix of plants, and thus can act in the short run as a monopolist in its own market segment that is determined by locations. But in the long-run each nursery firm's profits are driven to zero by free market entry and exit.

The production process of each firm uses labor as the variable input and a fixed cost input. There is a one-time fixed cost (in labor-equivalent units) of importing a new exotic plant species, k, which is part of the overall fixed costs of the nursery firm, i.e. $k \in F(i)$. This assumption also implies that the unique bundle of plants, $q(i)$, sold by each nursery i will contain plants either based on propagating exotic plant material or exotic plants itself (Avent 2003).

The demand function faced by each individual nursery firm is given by equation (5). The firm's objective function is to maximize revenue $p(i)q(i)$, minus costs of production which include the variable and fixed costs. For each nursery, production of $q(i)$ units of each assortment of plants requires a unit cost of $w(aq(i)) + wF(i)$, where $F(i)$ comprises the fixed labor cost (i.e. the fixed labor and imported material costs, in labor equivalent units), w is the wage rate and a is the marginal labor requirement. The representative firm's profit function is

$$q(i)^{\gamma-1}q(i) - w\left(a\,q(i) + F(i)\right) \tag{7}$$

In the short-run the firm maximizes profit or minimizes the variable costs by choosing optimal $q(i)$ which yields the following first order condition

$$\gamma q(i)^{\gamma-1} - wa = 0 \tag{8}$$

Substituting p for q gives

$$p(i) = \frac{1}{\gamma}aw \tag{9}$$

This is the profit maximizing price that the firm charges on its sales in the local market. The optimal price is a constant mark-up over marginal cost, which is determined by the constant own price elasticity of substitution, and the variable cost parameters.

From equation (9)

$$(p(i) - aw) = \frac{1}{\gamma} aw - aw$$

$$(p(i) - aw) q(i) = \left(\frac{1}{\gamma} - 1 \right) aw q(i) \tag{10}$$

In the long-run free-entry and exit leads to zero profit condition, which implies that

$$(p(i) - aw) q(i) = wF(i)$$

$$\left(\frac{1}{\gamma} - 1 \right) awq(i) = wF(i) \tag{11}$$

The output bundle per each firm is given by

$$q(i) = \frac{\gamma}{1-\gamma} \frac{F(i)}{a} \tag{12}$$

The equilibrium output of the firm depends on the parameters of the demand function, the presence of substitutes, and the ratio of fixed to variable costs. If the nursery firm is faced with high fixed costs and the existence of close substitute, it would have to propagate stock and sell more output in order to break even.

Note that condition (12) indicates that equilibrium output of each firm is a function of three parameters. Two of these parameters (γ, a) are assumed to be the same across all firms and local markets of the North American industry. However, the third parameter $F(i)$ we have assumed so far to be the fixed cost of each individual nursery firm. In addition, following a standard assumption in the monopolistic competition literature (e.g., see Baldwin et al. 2003; Matsuyama 1995), we assume that equilibrium output of each firm must satisfy a resource constraint, which we suggest must be the same for all nursery firms operating in a large “political jurisdiction” of markets, such as each state in the United States or province in Canada. Denoting each jurisdiction as j, we define the resource constraint for all the nurseries $n(j)$ in a single jurisdiction as

$$L(j) = \int_{i=1}^{n(j)} \left(aq(i) + F(i) \right) di \tag{13}$$

where $L(j)$ is the total industry resources or total labor available in each jurisdiction (i.e. state or province), and it comprises both the aggregate variable labor input and fixed labor, which includes the one-time fixed cost of importing a new exotic plant species expressed in labor equivalent units. Therefore, the total number of firms in each jurisdiction is limited by the scarcity of the factors required for production of the differentiated products.

We now make the simplifying assumption that the fixed cost is likely to be approximately the same for all nursery firms in all jurisdictions, i.e. $F(i) = F$.[3] It follows from (12) that the equilibrium output of each firm is a function of constant parameters (γ, *a*, *F*) that are the same across all nurseries of the horticultural industry, and thus equilibrium output scale is the same for all firms. That is, in (12) and (13) we can denote $q(i) = q$, even though the bundle of plants produced by each firm in the state or province will contain different plant varieties in the long-run. Given that equilibrium output and fixed costs are the same for all *n*(*j*) nursery firms in a jurisdiction, the industry resource constraint (13) simplifies to $L(j) = n(j)(aq + F)$.

The long run number of nursery firms in each jurisdiction, $n^p(j)$, can be derived from inserting the equilibrium output (12) into the resource constraint (13) and rearranging

$$L(j) = n(j)\left(F + \frac{a\gamma F}{(1-\gamma)a}\right)$$

$$n^p(j) = \frac{(1-\gamma)L(j)}{F} \tag{14}$$

The privately optimal number of nursery firms established in each jurisdiction *j* in the long run depends on the degree of substitution between different bundles of plants offered by various nursery firms and fixed costs. The number of nurseries established is also proportional to the total resource supply available in each jurisdiction, *L*(*j*). As fixed costs are lowered within the industry, or the amount of labor employed rises, the long-run equilibrium number of nursery firms established in each jurisdiction, $n^p(j)$, is expected to rise.

[3] Fixed costs of horticultural nursery firms, as approximated by fixed labor resources per firm, appear to display little variation across these jurisdictions over significant periods of time. See, for example, Tables 1 and 3, and Statistics Canada (1997-2006); USDC (1982 and 1991); USDA (2001).

We can also use the resource constraint (13) to derive the long run and short run profit functions of the representative nursery firm in each jurisdiction *j*.[4] For notational convenience, we choose units of measurement to normalize the wage rate, $w = 1$. Recall from the derivation of the long-run equilibrium (11), the zero profit condition requires that net operating revenues of each firm must cover its fixed costs, and this condition can now be written as $\left(p - aw\right)q = F$. However in the short-run, each individual firm profit is positive and is equal to net operating profits only. Denoting short-run profits by π^s, for the representative nursery in each jurisdiction it is simply

$$\pi^s = \left(p - a\right)q\left(j\right). \tag{15}$$

By substituting the resource constraint equation (13) into this short-run profit condition, we can express the representative nurseries short-run profits as a function of the total number of nurseries *n*(*j*) established in each jurisdiction

$$\pi^s\left(n\left(j\right)\right) = \left(p - a\right)q\left(j\right) = \left(\frac{1}{\gamma} - 1\right)a\, q\left(j\right) = \left(\frac{a}{\gamma} - a\right)\frac{L\left(j\right) - n\left(j\right)F}{an\left(j\right)}$$

$$\pi^s\left(n\left(j\right)\right) = \frac{1-\gamma}{\gamma}\left(\frac{L\left(j\right)}{n\left(j\right)} - F\right), \qquad \partial\pi^s / \partial n\left(j\right) < 0. \tag{16}$$

The short-run profits to an individual nursery firm in each jurisdiction are a decreasing function of $n\left(j\right)$. Entry of new nursery firms reduces the profits of incumbent firms. The entry process is expected to continue as long as the gross profits exceed the fixed costs, i.e. $\pi^s\left(n\left(j\right)\right) - F > 0$. The latter is, of course, the long-run profit function of the representative nursery, and thus using (16) it can be written as

[4] Note that the simplified resource constraint $L\left(j\right) = n\left(j\right)\left(aq + F\right)$ holds in both the short run and the long run. It necessarily applies in the long run because of the zero-profit and full-employment conditions of monopolistic competition. In addition, the short-run optimal pricing condition (9) is $p(i) = \frac{1}{\gamma}aw$. However, by definition (5) for the inverse demand, we know that $p(i) = q(i)^{\gamma-1}$. Therefore substituting (5) into (9) and rearranging, we get $q(i) = \left[\frac{aw}{\gamma}\right]^{1/\gamma-1}$. Assuming that all relevant parameters on the right-hand side are the same across firms in each jurisdiction, it follows that $q(i) = q(j)$ in the short run, and thus (13) applies but in the form $L\left(j\right) = n\left(j\right)\left(aq\left(j\right) + F\right)$, which is the version of the resource use constraint used to derive (16).

$$\pi\left(n\left(j\right)\right)=\pi\left(n\left(j\right)\right)^{s}-F=\frac{1-\gamma}{\gamma}\left(\frac{L\left(j\right)}{n\left(j\right)}\right)-\frac{F}{\gamma}\;. \tag{17}$$

In the long-run equilibrium, the profits for all nurseries in all jurisdictions will vanish and (17) will equal zero. Two outcomes immediately follow. First, setting (17) equal to zero and rearranging confirms the long-run equilibrium condition (14) for the privately optimal number of nurseries established in each jurisdiction, $n^{p}\left(j\right)$. Second, if this zero profit condition holds for all nurseries across all 1,…*J* jurisdictions, then we also have an expression for the long-run privately optimal number of nurseries n^p established by the entire horticultural industry; i.e. from (14)

$$n^{p}=\sum_{j=1}^{J}n^{p}\left(j\right)=(1-\gamma)\frac{\sum_{j=1}^{J}L\left(j\right)}{F}\;. \tag{14'}$$

Finally, note that when the number of nurseries in the entire horticultural industry reaches n^p, industry profits are zero, thus satisfying the long-run equilibrium condition.

Social Welfare

In the absence of a plant invasion, societal welfare is composed of the consumer surplus from the consumers' preference for more selections of the nursery good, and the horticultural industry's profits, or producer surplus. We assume that the government, represented by a social planner, would seek to choose the number of nurseries established by the industry to maximize social welfare, which is the sum of consumer and producer surplus across all markets and jurisdictions.

From (4), (5) and (6) the consumer surplus is given by

$$S(n)=\left(\frac{1-\gamma}{\gamma}\right)nq^{\gamma}=\left(\frac{1-\gamma}{\gamma}\right)\left(\frac{a}{\gamma}\right)^{\frac{\gamma}{\gamma-1}}n=Dn \tag{18}$$

Notice that since in the short run price is a fixed mark up of variable costs, then output is determined by parameters, i.e. $q=\left(a/\gamma\right)^{\frac{1}{\gamma-1}}$, so D is essentially a parameter. Aggregate consumer surplus is therefore proportionate to the total number of industry nurseries operating in the market. Denoting $\Pi(n)$ as aggregate industry profit as a function of the number of nurseries established, social welfare is given by sum of consumer and producer surplus

$$W(n) = Dn + \Pi(n), \quad \Pi(n^p) = 0, \;\; \Pi' > 0, \;\; \Pi'' < 0 \tag{19}$$

From our discussion of the long-run equilibrium condition of the horticultural industry and firms, it follows that aggregate industry profits must equal zero when the number of nurseries reach n^p. In addition, the necessary and sufficient conditions for social welfare to have a maximum, is that the profit function must be concave. In the absence of any consideration of the risks and damages of a potential plant invasion, the social planner would choose the socially optimal number of nurseries, n^s, that would maximize consumer and producer surplus, which from (19) satisfies the condition $D + \Pi'(n^s) = 0$. It is unlikely that n^s chosen by the social planner would be the same as the privately optimal number of nurseries n^p established by the industry under the zero-profit condition (14').

Risk of Invasion

However, it is unlikely that the social planner would consider only $W(n)$ to determine the socially optimal number of nurseries. The exotic plant species inputs used in nursery production may escape at some future time, become successfully established in the host natural environment, and cause significant economic and ecological damages. As noted earlier, this cost is not accounted for in the private nursery industry's decisions to establish additional nurseries in new locations and markets; therefore, there is a need for a regulatory framework that internalizes the externality and limits the private number of nursery firms to socially optimal levels. This social regulatory framework must balance the consumer and producer surplus benefits from establishing new nursery firms with the expected social costs from the risk of a potentially harmful plant invasion. To incorporate the risk of invasion in the model, we utilize a hazard rate function (Reed and Heras 1992, Knowler and Barbier 2005).[5]

[5] To simplify the mathematical analysis, we assume that sales of nursery products cease at the onset of successful invasion; i.e., we assume that sales of the offending exotics is immediately terminated by the regulatory authority when it becomes invasive at time τ. Reed (1988) shows that, mathematically, changing such an assumption to allow for the underlying activity to occur after τ would not alter the model's outcome significantly. Thus, our model is also likely to be consistent with the more realistic situation in which nursery firms continue to propagate and make sales of nursery products after an invasion occurs

A hazard rate is characterized as the probability that the plant invasion occurs at any time given that it has not yet invaded at that time, and can be expressed as the following

$$h(t) = \lim_{\Delta t \to 0} \left\{ \mathrm{P}(\text{plants invade in } (t,\ t+\Delta t] \,|\, \text{plants has not invaded by } t) / \Delta t \right\}$$

It is assumed that the hazard h at time t depends on the number or nurseries, n ,established by the horticultural industry, the plant attributes, a_k , of the exotic species, as well as time t [6]

$$h(t) = \varphi\left(n(t), a_k\right) \qquad \text{where } \varphi_n > 0 . \tag{20}$$

As each nursery firm is located in a unique jurisdiction serving the local market, it is reasonable to assume that these sites serve as point dispersal sources for the exotic plant species. This implies that the probability of invasion positively depends on the number of nursery firms n established by the industry. The characteristics of the exotic species, such as its flowering, germination and reproduction attributes, may also influence the success rate at which the exotic plants invade the environment (Rejmánek and Richardson 1996, Reichard and Hamilton 1997, Pheloung et al. 1999).

Risk of invasion can also be expressed in another form as a survival function, which is the probability that the exotic plant species does not invade up to time t , and is given by the following function

$$S(t) = \exp\left\{ -\int_0^t h(z)\, dz \right\} \tag{21}$$

The growth in area invaded by the exotic plant species is assumed to follow a logistic growth function as given by

$$\dot{A} = rA\left(1 - \frac{A}{K}\right) \tag{22}$$

where A is total area invaded, r is the intrinsic rate of growth in the area invaded by the exotic plant species and K is the carrying capacity of the area that could be invaded.[7]

[6] We assume that all sales of the invasive species cease at the time τ, when it is identified as being invasive.

[7] Shigesada and Kawasaki (1997) use the logistic function to describe the population or area invaded for a number of invasive species, including plants, that reproduce and this seems a reasonable assumption here. Barbier and Knowler (1996) cite evidence supporting that the area invaded by purple loosestrife and other invasive herbaceous plants in North America conform to logistic growth.

At some future time τ , when invasion occurs, damages of magnitude $G(A(\tau))$ are realized. These 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 using the instantaneous discount rate δ , the present value of these losses, G, is

$$G(\tau) = \int_{\tau}^{\infty} e^{-\delta(t-\tau)} cA(t)dt \; . \tag{23}$$

The social planner maximizes the expected present value of welfare by taking into account consumer surplus, producer surplus and the expected present value of damages. The expected net present value of social welfare up to the time of invasion is given by

$$J = E\left\{\int_0^{\tau} W\left(n\left(t\right)\right)e^{-\delta t}dt - G\left(A(\tau)\right)e^{-\delta\tau}\right\} \tag{24}$$

where the expectation is taken with respect to the random variable τ . The control variable for the social planner is the number of nursery firms $n(t)$. The objective function (24) is maximized subject to the dynamic state constraint equation (22) and the non-negativity condition $n \geq 0$.

Following Reed and Heras (1992), this stochastic optimization problem is solved by transforming it into a deterministic optimal control problem. This is done by introducing a new state variable $y(t)$

$$y(t) = -\log S(t) \tag{25}$$

Then, the dynamics of the variable y are given by;

$$\dot{y} = \varphi(n, a_k, t): \quad y(0) = 0 \tag{26}$$

Solving for the expectation operator in equation (24) yields the following equation

$$J = \int_0^{\infty} e^{-\delta t - y(t)} \left[W\left(n(t)\right) + \delta G\left(A(\tau)\right)\right] dt + G\left(A(0)\right). \tag{27}$$

The stochastic problem has been transformed into a standard deterministic optimal control problem equation (27), similar to one that arises when there is no risk of invasion, except the inclusion of a new steady state variable $y(t)$ related to the survival function, and an adjustment to the benefit flow (Reed and Heras 1992). The variable $y(t)$ operates like a premium added to the discount rate δ . The positive term δG is the annualized value of damages from invasion.

The welfare planner maximizes equation (27) subject to the dynamic constraint equation (26). The term $G(A(0))$ is a constant and can be dropped from the optimization problem. The problem is solved using the standard maximum principle and employing the following conditional current value Hamiltonian $\tilde{H}$ (while omitting the time arguments), $\tilde{H} = W(n) + \delta G + \lambda\varphi$. The conditional current value Hamiltonian is actually the standard current value Hamiltonian divided by the survival probability $e^{-y(t)}$. The co-state variable λ is the current shadow price divided by the survival probability. The first order conditions for this problem are

$$\frac{\partial \tilde{H}}{\partial n} = 0 \quad : \qquad \Pi'(n) + D + \lambda\varphi_n = 0 \tag{28}$$

$$-\frac{\partial \tilde{H}}{\partial y} = \dot{\rho} - (\delta + \dot{y})\lambda \quad : \quad \Pi(n) + Dn + \delta G = \dot{\lambda} - [\delta + \varphi]\lambda \tag{29}$$

$$\frac{\partial \tilde{H}}{\partial \rho} = \varphi \tag{30}$$

$$\lim_{t\to\infty} \lambda(t)n(t) = 0 .$$

Equation (28) states that the marginal social benefit from an additional nursery firm should equal the value of the marginal hazard rate. The co-state variable λ is the shadow value of damages from an additional nursery at time t, conditional on the exotic plant species having not yet invaded. In the long–run equilibrium, $\dot{\lambda} = 0$, and solving for the value of λ in equation (29) that satisfies this equilibrium we obtain

$$\frac{\Pi(n) + Dn + \delta G}{[\delta + \varphi]} = -\lambda . \tag{31}$$

Substituting (31) into (28) yields:

$$D + \Pi'(n) - \frac{\varphi_n}{\delta + \varphi}\left[\Pi(n) + Dn + \delta G\right] = 0$$

$$\text{or } \; S'(n) + \Pi'(n) - \frac{\varphi_n}{\delta + \varphi}\left[\Pi(n) + S(n) + \delta G\right] = 0 \tag{32}$$

Equation (32) is the socially optimal long-run condition for establishing another nursery in the industry. In equilibrium, the contribution of a new nursery to consumer surplus and industry profits, $S'(n) + \Pi'(n) = D + \Pi'(n)$, must equal the expected marginal social costs of this extra nursery, $\frac{\varphi_n}{\delta+\varphi}\left[\Pi\left(n\right)+S\left(n\right)+\delta G\right]$. These social costs consist of the increased likelihood of invasion due to an additional nursery, φ_n, multiplied by the penalty if the invasion occurs. The latter penalty includes the loss in profits and consumer surplus due to suspension of sales of the exotic plant species, $\Pi\left(n\right)+S\left(n\right)$, plus the annualized value of damages from the invasion, δG. These social costs are converted into a present value using an effective discount rate, $\delta+\varphi$, which comprises the social discount rate plus a risk premium represented by the hazard rate function.

Note that, if the social planner ignores the risks and consequent damages from invasion, i.e. treats the second expression on the left-hand side of (32) as zero, then we obtain the original long-run socially optimal condition from solely maximizing *W*(*n*), i.e. $D+\Pi'\left(n^s\right)=0$. As we have indicated above, in this situation the planner would choose n^s socially optimal nurseries. In contrast from equations (14') and (19), the privately optimal zero-profit condition is simply $\Pi(n^p)=0$. The private industry ignores both consumer surplus and the social costs of a potential invasion, and thus will establish n^p nurseries, ensuring in the long run that the last nursery drives industry and each nursery's profits to zero. Denoting n^* as the socially optimal number of long-run nurseries that satisfies the social planner's condition (32), because of the inclusion of the risk of invasion and its potential damages in this condition, it follows that it is unlikely that n^* will be equal to either n^s or n^p.

By re-arranging (32), it is possible to get an expression of the socially optimal number of nursery firms n^* in the long-run

$$n^*=\left(\frac{\Pi'\left(n\right)+D}{D}\right)\frac{\delta+\varphi}{\varphi_n}-\frac{\Pi\left(n\right)+\delta G}{D} \qquad (33)$$

The expression confirms that, when regulating the number of nurseries established by the horticultural industry in the long run, the social planner takes into account the expected social cost of accidental invasion associated with an additional nursery firm established at a new location as well as consumer surplus. Condition (33) suggests that the socially optimal number of nurseries is likely to be lower if the increased likelihood of invasion due to an additional nursery, φ_n, and the annualized value of damages from the invasion, δG, are high. In contrast, if the effective discount rate $\delta + \varphi$ is large, then the socially optimal number of nurseries is likely to be bigger. Because of these countervailing effects, it is difficult to determine *a priori* whether the long-run socially optimal number of nurseries, n^*, will be less than the privately optimal number of nurseries, n^p or the "myopic" social welfare-maximizing level of nurseries, n^s. But in general, if the risk of an invasion from establishing additional nurseries is high and the potential damages of the invasion are large, then one would expect $n^* < n^p$ and $n^* < n^s$.

Conditions (32) and (33) imply that there is scope for employing a tax on the nursery industry to internalize the expected social cost of accidental invasion associated with establishing new nursery firms. From (32), we calculate this tax, χ, as

$$\chi = \left(\Pi'\left(n\right) + D\right)\frac{\delta + \varphi}{\varphi_n} - \delta G - Dn. \tag{34}$$

Note that this tax is a "net tax". It includes the optimal tax to internalize the increased hazard associated with the risk of invasion as the industry expands its nurseries, $\left(\Pi'\left(n\right) + D\right)\frac{\delta + \varphi}{\varphi_n} - \delta G$. However, the tax must be adjusted for consumer surplus, Dn, generated by the industry. Once the optimal tax is imposed on the industry, its long-run profit condition becomes

$$\Pi(n) - \chi = 0, \tag{35}$$

which when re-arranged will yield both equilibrium condition (32) and the socially optimal nurseries, n^*, as governed by (33). Note as well that in the absence of the tax, the horticultural industry will simply establish its long-run privately optimal number of nurseries n^p, i.e. (35) becomes $\Pi(n^p) = 0$.

Given the construction of our model, the optimal tax or fee imposed on the industry, χ, is not an output tax *per se*. Instead, it is a license fee paid by the industry, or equivalently, an optimal fee $x^* = \chi/n^*$ paid by each firm. There are two reasons why such a license fee rather than an output tax is optimal in our model. First, as can be seen from (20), the hazard rate function, i.e. the probability that the plant invasion occurs at any time given that it has not yet invaded at that time, increases with the establishment of an additional nursery by the industry. Thus, the risk of an invasion is more related to the presence of another nursery rather than the size of output from that nursery. Second, the reason that the latter condition holds is apparent from the equilibrium conditions (12) and (14'); in the long run, industry output is just qn^p, and we have shown that n^p is determined by the industry's zero-profit condition $\Pi(n^p) = 0$. That is, we obtain the standard outcome for a monopolistically competitive industry that the equilibrium output of an individual firm is constant whereas equilibrium industry output expands only if more nursery firms are established in a new location, which is of course governed by both each firm's as well as the industry's profit function.[8]

Empirical Estimation of the Horticultural Industry Profit Function for US and Canada

In this section, we use the results derived from our monopolistic competition model of the horticultural industry to estimate nursery profits of a representative firm as a function of the number of nurseries established by the industry. The estimation is necessary to determine a key parameter, γ, required to simulate the socially optimal number of nurseries and the tax imposed on the industry. Following an approach similar to Panzar and Ross (1987), we use the representative firm's short-run profit (16) as a structural econometric equation to estimate the individual firm's profit function. Thus, we estimate the relationship between profits and the number of nurseries, fixed labor resources and total labor resources, as given by

$$\pi_{jt} = b_o + b_1\left(\frac{L_{jt}}{n_{jt}} - F_{jt}\right) + \varepsilon_{jt}, \quad j = 1,...J, \quad b_1 = (1-\gamma)/\gamma. \tag{36}$$

This estimated relationship is a reciprocal median function in n_{jt}; that is, an increase in the total number of nurseries established in a jurisdiction *j* at time *t* reduces the short-run profit for each individual nursery in that jurisdiction. Note that $b_1 > 0$ also implies that i) an increase in fixed resource requirements, F_{jt}, reduces the individual firm's short run profits; ii) an increase in the total labor resources available to the industry in that jurisdiction, L_{jt}, would increase the nursery firm's short run profits.

[8]Of course, it follows that, if for whatever reason the monopolistically competitive industry expands its equilibrium number of nurseries total industry output qn^p will increase. But to accommodate additional nurseries, they have to be established in new locations (markets). Again, this supports our assumption that the likelihood of an accidental invasion occurring is associated with an additional nursery firm establishing at a new location rather than increased output per firm at existing locations.

Equation (36) was estimated separately for the horticultural industry in the United States and Canada at the appropriate jurisdiction level for which data were available. For the United States, the estimation was conducted using panel data for all 50 states covering periods 1979, 1988 and 1998 based on the *Census of Horticultural Specialties* conducted for these years (USDC 1982 and 1991; USDA 2001). For Canada, the estimation was conducted using panel data for five regional groupings of provinces, the Atlantic provinces, Quebec, Ontario, the Prairie provinces and British Columbia, from 1997 to 2006.

In both estimations, the profit per nursery firm π_{jt}, was created by subtracting variable expenses, which include labor and input expenses, from the region's total sales, and dividing the result by the number of nursery firms in a jurisdiction, n_{jt}. In the analysis for Canada, the nursery plants that were included in the dataset are annual and perennial plants whose end purpose is as ornaments or functional ranging from woody plants (e.g. shrubs, rose brushes) to bedding plants and outdoor flowers (Statistics Canada 1997-2006). For the United States, the set of nursery plant species used in the estimation of a representative profit function include major categories of plants, such as deciduous shades and flowering trees, coniferous and broadleaf evergreens, shrubs, bushes, ground covers, fruit and nut trees, grapevines, small fruit plants and vines (USDC 1982 1991, USDA 1998).

Equation (36) applied to profit and input panel data for the horticultural industry in the United States and Canada. In both analyses, profit per nursery π_{jt}, is represented by the nursery firm's annual profit. The explanatory variables used are n_{jt}, the total number of nursery firms in a jurisdiction, L_{jt}, the total labor resources available in the jurisdiction, and F_{jt}, the number of fixed labor resources required per each nursery firm. L_{jt} is measured as the total number of employees of all nurseries in a jurisdiction, while F_{jt} is measured as the total number of full-time employees per nursery firm, which following (16) is the average across all firms in a jurisdiction. Equation (36) was also.

Tables 1 and 2 provide summary statistics for the relevant variables for the estimation applied to the US horticultural industry. Across all three years, the average number of nursery firms operating in each state is 161, and across all 50 states the average number of nurseries is 8,050. The average total labor resources available per state are 18,745, and the average fixed component of labor per firm per state is 6 (see Table 1). The annual net profit per firm per state is $21,788. For the Canadian horticultural industry, the average number of nursery firms per province grouping for all ten years is 269, and across all provinces the total number of nurseries is 1,345 (see Table 2). The average total labor resource available in each region is 2,776 persons, and the fixed component of labor per firm is given by 4 units. The annual average net profit per nursery firm is C$101,994.

Tables 3 and 4 display the least squares, fixed effects and random effects results of the two-way panel analysis for the US and Canadian horticultural industry, respectively. The F-test, likelihood ratio test and Lagrange Multiplier (LM) tests are highly significant for both the US and Canadian regressions, implying that the least squares regression model with a single constant is inappropriate for the data. The Hausman test based on the difference between the fixed and random effects specification is 0.44 for the US and 0.30 for Canada, and neither statistic is significant. The test therefore fails to reject the hypothesis that individual effects are uncorrelated with other regressors. The random effects specification is preferred to fixed effects model. The preferred regressions confirm that $b_1 > 0$. Thus one cannot reject the hypothesis that profits per nursery firm are positively related to total resources available and negatively related to the total number of firms established by the industry.

The random effects estimation for the US yields a value for γ of 0.7757, which is relatively close to one. This implies that the bundles of nursery products offered to the market by different nursery firms are close substitutes, suggesting less differentiation between nursery products in the US markets. In comparison, the estimate of γ for Canada is 0.1154, which is relatively close to zero and indicates that the various selections of products offered by different nurseries are not close substitutes. Therefore we can conclude that there is more differentiation in nursery products for the Canada market compared to the US market. The elasticity of substitution $\sigma = 1/(1-\gamma)$ for Canada is 1.134, lower than that of the US which is 4.458, implying that the economies of scale in the Canadian nursery industry are stronger than that of the US nursery industry.

Estimation of the Hazard Function and Damage Costs

Following Knowler and Barbier (2005), we assume that the hazard function (20) that represents the accidental risk of invasion associated with the commercial plant industry importing exotic plant has similarities to a standard duration model, where the "spell" is the number of periods after introduction of the species without invasion taking place. It is also assumed that the hazard at any time *t* is a function of several covariates a_k representing various plant characteristic attributes, which include leaf type, type of reproduction, length of flowering period, number of regions already invaded by plant. The hazard function is also likely to be affected by the time-varying number of nurseries established $n(t)$. We therefore represent the hazard function as

$$h(t) = \varphi\left(n(t), a_k\right) = \varphi(a_k)\, f\left(n(t)\right). \qquad (37)$$

The function $\varphi\left(n(t), a_k\right)$ is assumed to be a product of two functions, $\varphi(a_k)$ and $f\left(n(t)\right)$, implying that the underlying "hazard rate" associated with the inherent invasiveness of an exotic plant is distinguished from the influence of the nursery firms on the overall likelihood that a new exotic plant species will become invasive. As outlined earlier, nursery firms that sell the new species act as potential dispersal sites, as do plantings in their customers' gardens, and thus serve to "scale" the likelihood that an invasion will occur as the industry established more nurseries in new locations.

The component of the hazard function – the hazard rate - which represents the likelihood that the new exotic species will invade during the current time interval given that it has not invaded previously, is determined by plant characteristic attributes, $\varphi(a_k)$. We estimate this hazard rate assuming that its functional form is exponential, which is a restricted version of the standard Weibull hazard rate.[9] We test to see whether the exponential hazard rate is a valid representation of the Weibull hazard.

[9] The two models are expressed as follows: (a) the Weibull hazard function $h = \varphi p\left(\varphi t\right)^{p-1}$ and (b) the exponential hazard function $h = \varphi$. Note that if *p=1* then the Weibull function converges to the exponential hazard rate. See Kiefer (1988) for further discussion of different duration models and their relationships.

Recall that the assumption underlying our analysis is that the new exotic plant imported by the horticultural industry is a herbaceous species. We therefore apply our estimation of $\varphi(a_k)$ to herbaceous species potentially supplied by the horticultural industry. Modeling of the probability of plants becoming invasive required a sample of both invasive and non-invasive species that have been introduced to North America. Since species may not begin to invade for some time after introduction, we selected species that have been established for some time without invading as the "non-invaders". In effect, the duration data series for these species are truncated, since we do not know if or when the "non-invaders" might become invasive. We selected taxonomic, eco-geographic, and biological traits describing the species in our samples based on numerous studies of the traits associated with invasive and non-invasive plants (e.g., Rejmánek and Richardson 1996, Reichard and Hamilton 1997, Pheloung et al. 1999). Since the data set was not randomly selected from the population of all introduced horticultural herbaceous plant species in North America, we may face sample selection problems. Further, there were many variables in the data set which we could not include in the analysis because of a high rate of missing data. Further details concerning the selection of herbaceous species and traits are provided in the appendix.

The herbaceous species data set contained 110 observations initially but four observations were removed because of missing variable values, leaving 106 usable observations for the analysis. Of these 106 herbaceous species observations, 77 (72.6%) were for invasive species and 29 (27.4%) were non-invasive species.[10] The appendix provides a description of the plant characteristic variables used in the herbaceous species hazard analysis.

The regression results for the Weibull and exponential hazard rate estimations of $\varphi(a_k)$ are shown in Table 5. As explained in the appendix, models are presented using the individual covariates and, secondly, using the factor scores from a principle components analysis (PCA). The individual covariates model was rejected, as the coefficient of only one plant characteristic variable (global) proved to be significant. However, the PCA revealed that four factor score components explain 66.4% of the total variation (see Table A.2). FS1 (continents, global and

[10]Interestingly, the invasive herbaceous species seem to have been more studied than non-invasives, so that there is more readily available information on the former. Thus, our data sets do not contain as many non-invasive observations as we might have liked but this is unavoidable.

polyploidy) explains 19.9% of the total variance. FS2 (abiotic and annual) explains 17.6% of the total variance. FS3 (flower) explains 15.8% of the total variance. FS4 (selfcomp and germno) explains 13.2% of the total variance. As shown in Table 5, when the Weibull and exponential hazard rates were estimated employing these factor score components as explanatory variables, the coefficients of all but FS4 were significant.

In a test for heterogeneity in the Weibull model, we found the theta parameter to be very low ($\theta = 0.000246$). The low value of the theta parameter implies that heterogeneity is not a significant problem in the regressions and can be ignored (Greene 1990, p. 724). In addition, the estimate of the *p* parameter in the Weibull model is close to 1.0, suggesting that the exponential hazard estimation is a good approximation of the standard Weibull hazard rate, which greatly improves the tractability of our empirical model. For an exponential model, the effect of the vector factor score covariates, $\mathbf{x_i}$, on the hazard rate is defined as $\varphi = e^{-\beta x_i}$. Table 5 computes an estimate of φ based on the mean values of the covariates, which in all regressions is 0.005. This suggests that for a newly imported exotic herbaceous species, assuming that "on average" it shares the typical plant characteristics of herbaceous species previously introduced in North America, the probability that the new exotic species will invade during the current time interval given that it has not invaded before is 0.005. However, when the factor scores corresponding to the plant characteristics of purple loosestrife are employed, then the estimated hazard rate becomes $\varphi = e^{-\beta x_i} = e^{-4.706} = 0.009041$. As expected, a newly imported plant with the characteristics of purple loosestrife appears substantially more invasive than the average herbaceous species imported into North America.

The full hazard function relationship (37) also includes an additional influence of the number of nurseries established by the horticultural industry $f\left(n(t)\right)$. As noted above, the effect of this influence is to "scale" the estimated underlying hazard rate attributable to plant characteristics $\varphi(a_k)$, due to the total number of nursery firms in the industry that sell the potentially invasive species. We assume that this scaling effect is a simple proportional relationship

$$f(n(t)) = fn\left(t\right), \tag{38}$$

where f is the constant determining the number of nursery firms that causes the scaling effect to occur. For example, we assume a value of $f = 0.02$ in North America, which implies that $fn = 1$ when 50 nurseries are present; consequently, more than 50 firms augment the scaling effect but less than 50 diminish it.

Finally, we match the hazard function properties of the representative exotic imported plant species with the likely damages associated with a known herbaceous species invader. We use estimates of the damages inflicted by purple loosestrife for the costs associated with a successful new herbaceous species invasion.

As indicated in our model (see equation (23) above), assuming that the invasive species invades at time τ, the present value of damages or losses from a successful invasion is given by $G(\tau)$. As we noted in the introduction, the losses associated with purple loosestrife are extensive and include the reduced palatability of hay, reduction in water flow in irrigation systems, and decreased waterfowl viewing and hunting opportunities. To calculate the present value of economic loss, we note that estimated damage from purple loosestrife in the US is about $45 million dollars per year (ATTRA 1996). As outlined in the introduction, the total area invaded in the United States is estimated at 131,152 ha, and therefore the annual cost of purple loosestrife in the US is about $340 per ha. Assuming a carrying capacity of 500,000 ha, solving for the area invaded in the growth in the dynamic area equation (22) yields

$$A(t) = \frac{KA(\tau)}{A(\tau) + \left[\frac{K - A(\tau)}{A(\tau)}\right] e^{-r^A(t-\tau)}} \tag{39}$$

where the initial area invaded $A(\tau)$ is set at 1ha. Assuming that purple loosestrife had a long gestation period in which invasion into the natural environment occurred in the 1900s, we can solve for the intrinsic growth rate r^A from equation (39) to get 0.11. [11] From equation (23), the present value of damages become

[11] $131\,152 = \frac{500\ 000}{1 + \left[\frac{500\ 000 - 1}{1}\right] e^{-103 r^A}}$, $r^A = 0.11193$

$$G(\tau) = c\int_{\tau}^{\infty} \frac{Ke^{-\delta(t-\tau)}}{A(\tau) + \left[\frac{K - A(\tau)}{A(\tau)}\right] e^{-r^A(t-\tau)}} dt \tag{40}$$

Solving equation (40) gives an estimate of \$13.8 million as the present value of damages from purple loosestrife in the US, measured from the date of its establishment as an invader (τ).[12] We use this estimate as a proxy for damages from a newly introduced herbaceous plant species.

Simulation of Socially Optimal Nurseries and Taxes

In our theoretical model, equations (33) and (34) determine the long-run socially optimal number of nurseries and tax. Finding explicit solutions for these equations involves substituting in the relevant parameters that we have estimated or assumed so far. However, we must also specify a functional form for the aggregate industry profit function $\Pi(n)$. A function that fits the properties of $\Pi(n)$ as stated in (19) is

$$\Pi(n) = B\left(n^p - n\right)n, \qquad B = r\frac{1-\gamma}{\gamma}, \tag{41}$$

where *r* is a parameter of adjustment. It can be easily confirmed that the properties $\Pi\left(n^p\right) = 0,\ \Pi' > 0,\ \Pi'' < 0$ are all satisfied by (41).

Condition (33) can now be rewritten as

$$n^* = \frac{\left[B\left(n^p - 2n^*\right) + D\right]}{D}\left(\frac{\delta}{\varphi f} + n^*\right) - \frac{\left[B\left(n^p - n^*\right)n^* + \delta G\right]}{D}, \tag{33'}$$

which yields the quadratic equation $Bn^{*2} + \left[\frac{2B\delta}{\varphi f}\right]n^* + \delta\left[G - \frac{Bn^p + D}{\varphi f}\right] = 0$ and the corresponding solution

12 $G(\tau) = 340\int_{100}^{\infty} \frac{500\ 000e^{-0.05(t-100)}}{1 + \left[500\ 000 - 1\right]e^{-0.11193(t-100)}} dt = 13,747,663$

$$n^* = \frac{-\left[\frac{2B\delta}{\varphi f}\right] \pm \sqrt{\left[\frac{2B\delta}{\varphi f}\right]^2 - 4B\delta\left[G - \frac{Bn^p + D}{\varphi f}\right]}}{2B}. \tag{42}$$

From (34), the corresponding optimal tax (annual license fee) for the industry is

$$\chi = \left[\left(B\left(n^p - 2n^*\right) + D\right)\left(\frac{\delta}{\varphi f} + n^*\right) - \delta G\right] - Dn^*. \tag{43}$$

Table 6 lists the specific ecological and economic parameters for the United States and Canada used in equations (42) and (43) to calculate the optimal number of nurseries and the associated tax. Most of these estimates have been discussed previously; for example, our hazard rate formula (37) is now $h\left(a_k, n\right) = \varphi\left(a_k\right) f(n) = \varphi fn$. From the US horticultural industry summary data (see Table 1), estimates of total resources and the fixed resources for the three years of data are L = 937,250 and F = 6. For Canada, across all ten years, L = 13,880 and F = 4. Since profits of the industry are denoted in $1,000 (or C$1,000) units, our estimate of $G(\tau)$ is also in the same units, and apply to both US and Canada. We use an exchange rate of $1 = C$1.06 to convert US damage estimates into Canadian prices.

Equations (42) and (43) for the socially optimal number of nurseries and tax assume that sales of the newly imported exotic species, or plants based on propagating the species contribute 100% to the profits of horticultural nurseries. In practice, however, nursery firms sell a mixture of both native and exotic nursery products as a single bundle. Therefore it is not likely that all firm profits come from a single plant species, or even multiple plants that are propagated from the exotic plant's material. It is fairly straightforward to adjust equations (42) and (43) to allow for each nursery obtaining only a share of its profits from the new exotic plant.[13] Our simulation results for the United States and Canada are depicted in Table 7. We simulate the socially

[13]Letting $0 < \omega \le 1$ represent the share of profits obtained from sale of the exotic plant and $x = \chi/n$ the per nursery tax, then industry profits net of the tax should be $\Pi\left(n\right) - \omega xn = B\left(n^p - n\right)n - \omega xn$. In the long run, the industry will expand its nurseries until its profits net of tax are equal to zero, and the equilibrium number of nurseries will be $n^* = n^p - \frac{\omega x}{B}$. The per firm tax is ωx, and the industry tax is $\omega xn^* = \omega x\left(n^p - \frac{\omega x}{B}\right)$. Note that when $\omega = 0$, $n^* = n^p$ and when $\omega = 1$, $\Pi\left(n\right) - xn = \Pi\left(n\right) - \chi$ as in (35).

optimal number of nurseries and annual firm tax $x = \chi / n^*$ as the share of profits from sales of the new exotic plant increases from 1% to 100%. As this share of profit rises, the socially optimal number of nurseries falls and the optimal tax (license fee) increases.

For the United States, depending on the profit share of the new exotic species, the socially optimal number of nurseries lies between 4,000 and 35,000 firms. The firm tax is as low as $45 per year, in the case of a 1% profit share, and reaches around $4,500 per year if the profit share of the exotic species is 100%. For Canada, the socially optimal number of nurseries range from between 900 and just over 3,000 firms. The firm tax is C$49 per year in the 1% profit share case, and is nearly C$5,000 per year in the 100% profit share case.

In Table 7, for both the United States and Canada, each simulation of the long-run socially optimal number of nurseries, n^*, is compared to the social-welfare maximizing level of nurseries, n^s, the privately optimal level of nurseries, n^p, as well the actual number of nursery firms n, as reported in the current industry survey data. Recall that n^s is the solution to the first-order condition $D + \Pi'\left(n^s\right) = 0$ for maximizing (19), and based on the parameter values in Table 6, is equal to 44,244 for the United States and 3,086 for Canada. For the United States, the survey data suggests that there are currently 8,050 nurseries, and for Canada 1,345 nurseries (see Tables 1 and 3). For the US, the long-run private optimal number of nursery firms is obtained by substituting the relevant parameter values from Table 6 in equation (14) to yield 35,035 firms

$$n^{*p} = \left(1-\gamma\right)(L/F) = (1-0.775713)(937250/6) = 35035$$

Similarly, for Canada the long-run private optimal number of nursery firms is obtained from equation (14) to yield 3,070 firms per year

$$n^{*p} = \left(1-\gamma\right)(L/F) = (1-0.115377)(13880/4) = 3070$$

Thus, the long-run privately optimal number of nursery firms in the US is just over 4 times the current number, whereas for Canada it is less than 2.5 times the current number of nurseries.[14]

[14]This outcome is relatively common for a monopolistically competitive industry. In such an industry, if firms currently make substantial profits, then more firms will enter the industry until in the long run industry profits are zero. Tables 1 and 3 indicate that on average current nurseries in Canada and the United States do make sizable profits, which suggests that the long run number of nurseries, n^p, is likely to be significantly larger than the current number, n. Using a different monopolistically competitive model of the horticultural nursery industry than the one developed here, Knowler and Barbier (2005) estimate the privately optimal number of nurseries in the United States in the long run to be 36,226.

Table 7 shows that, as expected, n^* converges to the privately optimal number of nurseries n^p as the contribution to profits attributed to the newly imported species, and thus the optimal firm tax assessed, declines toward zero. However, as long as there is still a risk of potential invasion, n^* is always less than n^s, although in the case of Canada, n^* and n^s are also likely to converge as the profit share of the exotic species approaches 1% or less. In all simulations for the United States and Canada, except for the case of a 100% profit share, the socially optimal number of nurseries n^* always exceeds the current number of nursery operations *n*.

These simulations for the North American horticultural nursery industry for introducing a new herbaceous plant species suggest that the results are highly sensitive to the share of the exotic plant sales in final profits. Careful consideration must be given to this profit share before designing any tax policy to discourage the introduction of a potentially invasive exotic plant species by the North American horticultural nursery industry. The design of the optimal tax (annual license fee) policy must take into account the implications of the tax on consumer surplus, producer surplus and the risks and potential damages associated with any likely invasion. Although these factors appear to be difficult to measure, our simulations show that such an analysis can be conducted. In addition, there are two additional advantages from such a tax policy.

First, as Table 7 indicates, as long as the profit share of the newly introduced plant is known, it is possible to construct a differentiated tax structure and such differentiations should be optimal to introduce. For example, as shown in the table, for a US nursery that obtains sales from the exotic plant or plants based on its propagation that contribute only 10% to overall profits, the optimal annual fee should be $446, whereas a firm with imported plant sales contributing to 75% of profits should pay around $3,350 per year. For two similar Canadian firms, the tax should be around C$490 and $3,680, respectively.

An additional advantage that such an annual license fee would have compared to other policy options for controlling accidental introduction of invasive herbaceous plants by the horticultural nursery industry is that such a fee would provide funds for combating the various social damages associated with such an invasion. For example, we calculated the present value of the damages inflicted by purple loosestrife to be $13.8 million in the United States, which results in an annualized value of $690,000 for a new herbaceous plant species invasion using a social discount rate of 5%. Based on our simulations, an annual license fee in the US would raise anywhere from $1.6 to $44 million, depending on the share of the exotic species sales in industry profits. Such annual revenues would not only cover the costs of annualized damages but also fund screening programs for all newly introduced species, education and scientific research on plant invasives, and eradication of past woody species invasion. Similarly, in Canada, the annual fee revenues would amount to C$150,000 to C$5.4 million.

Conclusion

We developed a general monopolistic competition framework to model the commercial decision by the horticultural nursery industry to sell plants at different locations by establishing additional nurseries. We conducted an econometric estimation of the representative firm's profit function, and estimated hazard rates for the risk of invasion. We combined the profit function estimates and the hazard rate estimates to carry out simulations of the potential trade-offs between the commercial profits from the nursery industry and expected social damages from the risk of invasion on the industry importing a new exotic plant species. We modeled the damages based on a known herbaceous invasive plant species, purple loosestrife. We used these simulations to estimate the optimal tax per nursery, in the form of an annual license fee, and the post-tax number of socially optimal nurseries established by the industry. The simulations were performed for both the US and Canadian horticultural nursery industries.

The simulations produced similar relative outcomes, in terms of taxes and the socially optimal number of nurseries, for the United States and Canada. All outcomes from the simulations show that, as the share of the exotic plant sales in total profits increases, the size of the tax (annual license fee) rises and the socially optimal number of nurseries falls. To show such effects explicitly, we conducted our simulations over six levels of profitability share associated with the exotic plant species, ranging from 1% to 100% of nursery firm profits.

Thus, our simulations of the optimal tax (i.e. annual license fee) and number of nurseries based on an accidental plant invasion suggest that the results are highly sensitive to the share of the exotic plant sales in final profits. If this share is large, then the sale of the newly introduced species in new locations through establishing additional nurseries in Canada and the United States needs to be discouraged, and the resulting annual fee to internalize the risk and associated damages from a potential invasion should be set higher. On the other hand, if the new species is not significant to overall sales and profits, then a smaller fee is required to restrict the number of nurseries selling the potentially invasive species. Given that the magnitude of the license fee is highly sensitive to the profit share, careful consideration must be given to determining this share before imposing such a fee on the North American horticultural industry. This would appear to be particularly important in the United States, as our simulations show that a high license fee to control for the risks and damages of a potential invasion would reduce the number of nurseries significantly.

However, two important advantages of an annual license fee compared to other policy options is that, first, the license fee can be adjusted optimally to the share of profits earned by each firm from sales of the new exotic plant., and second, the fee could be employed not only to cover the costs of damages but also to fund screening programs for all newly introduced species, education and scientific research on plant invasives, and eradication of past plant invasions. For example, we estimate that the annual revenues could range from $1.6 to $44 million in the United States (C$150,000 to C$5.4 million in Canada), depending on the share of the exotic species sales in industry profits.

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Table 1: Summary statistics for the horticultural industry in the United States

	1978	**1987**	**1998**
Average number of firms per state	166	140	176
Total labor resources (L) per state	31,612	13,965	10,658
Fixed labor resources per firm (F) per state	8	4	5
Average profit per firm ($000) per state	30.31	15.06	20

Source: USDC (1982) and (1991); USDA (2001).

Table 2: Summary statistics for the horticultural industry of Canada

Year	Average number of firms/region	Total labor resources (L)/ region	Fixed labor resources (F)/firm	Average profit (C$000)/ firm
1997	312	2,599	2	56.019
1998	274	2,565	3	68.604
1999	252	2,182	3	78.424
2000	252	2,676	3	111.836
2001	229	2,635	3	127.841
2002	320	3,094	4	100.286
2003	327	3,212	5	945.552
2004	249	3,019	6	123.607
2005	237	2,967	7	111.557
2006	226	2,812	7	147.213

Notes: The five regional groupings of provinces are the Atlantic provinces, Quebec, Ontario, the Prairie provinces and British Columbia.

Source: Statistics Canada (1997-2006).

Table 3: Panel analysis of the profit function for US, 1978, 1987 and 1998

Explanatory variables	Dependent variable: profit ($000) per nursery Parameter estimates[a] OLS[b] model (N=150)	Fixed Effects Model (N=150)	Random Effects Model (N=150)
Constant	-20.476	9.5695	-2.864
	(-1.472)	(0.415)	(-0.162)
b_1	0.4954	0.1435	0.2891
	(3.867)**	(0.559)	(2.187)**
Estimated γ	0.6687	0.8745	0.7757
F-test for pooled model	2.254**		
Likelihood ratio	118.832**		
Breusch-Pagan(LM) test	11.24**		
Hausman Test	0.44		
Adjusted R^2	0.3683		

Notes: [a] *N* is for total number of observations; t-ratios are indicated in parentheses.
**significant at 99% level, *significant at 95% level.

Table 4: Panel analysis of the profit function for Canada, 1997-2004

Explanatory variables	Dependent variable: profit (C$000) per nursery Parameter estimate[a] OLS model (N=50)	Fixed Effects Model (N=50)	Random Effects Model (N=50)
Constant	82.272	48.229	55.440
	(2.084)*	(2.131)*	(2.499)**
b_1	3.2482	8.8548	7.6672
	(0.522)	(2.412)*	(2.591)**
Estimated γ	0.2354	0.1015	0.1154
F- test for pooled model	26.727**		
Breusch-Pagan (LM) test	136.79**		
Hausman Test	0.30		
Adjusted R^2	0.8809		

Notes: [a] *N* is for total number of observations; t-ratios are indicated in parentheses.
**significant at 99% level, *significant at 95% level

Table 5: Regression results for herbaceous species using PCA hazard model

Variable	**All Covariates**				**Only Significant Covariates (if any)**			
	Weibull		**Exponential**		**Weibull**		**Exponential**	
	Coefficient	*P value*	*Coefficient*	*P value*	*Coefficient*	*P value*	*Coefficient*	*P value*
ONE	5.300	0.000	5.315	0.000	5.299	0.000	5.313	0.000
FS1	**-0.221**	**0.054**	**-0.252**	**0.067**	**-0.221**	**0.054**	**-0.251**	**0.067**
FS2	**0.256**	**0.014**	**0.279**	**0.023**	**0.256**	**0.014**	**0.278**	**0.023**
FS3	**-0.254**	**0.010**	**-0.275**	**0.021**	**-0.257**	**0.009**	**-0.278**	**0.020**
FS4	-0.014	0.896	-0.023	0.861				
N	106		106		106		106	
Phi	0.005		0.005		0.005		0.005	
p parameter	1.144		1.000		1.145		1.000	
Log likelihood	-140.298		-141.199		-140.307		-141.217	

Table 6: Parameters used in the analysis of a newly introduced herbaceous plant species

Variable	Parameters	
	United States	Canada
F	6	4
L	937,250	13,880
δ	0.05	0.05
$b_1 = \frac{1-\gamma}{\gamma}$	0.2891	7.667
γ	0.7757	0.1154
a	0.3	0.2
$G(\tau)$	13,800	14,634
$\varphi(a_k)$	0.009041	0.009041
f	0.02	0.02
r	0.0005	0.0003

Table 7: Simulations of the socially optimal tax and number of nurseries selling a new exotic herbaceous plant species in North America

Share of π:	***1%***	***10%***	***25%***	***50%***	***75%***	***100%***
United States						
Nurseries, n^*	34,727	31,949	27,319	19,603	11,886	4,170
Firm tax ($/year)	45	446	1,116	2,231	3,347	4,462
n^*/n^s	78%	72%	62%	44%	27%	9%
n^*/n^p	99%	91%	78%	56%	34%	12%
n^*/n	431%	397%	339%	244%	148%	52%
Canada						
Nurseries, n^*	3,048	2,856	2,536	2,002	1,468	934
Firm tax (C$/year)	49	491	1,228	2,456	3,684	4,913
n^*/n^s	99%	93%	82%	65%	48%	30%
n^*/n^p	99%	93%	83%	65%	48%	30%
n^*/n	227%	212%	189%	149%	109%	69%

Notes: n^* is the social optimal number of nurseries taking into account the risk and damages of a potential invasion, n^s is the number of nurseries that maximizes social welfare (producer and consumer surplus) but ignores the risk and damages of a potential invasion, n^p is the long-run private optimum number of nursery firms, and n is the actual number of nursery firms reported in industry data. For the United States, n^s = 44,244, n^p = 35,035 and n = 8,050; for Canada, n^s=3,086, n^p = 3,070 and n =1,345.

APPENDIX: Ecological Analysis of Invasive Herbaceous Plant Attributes

In developing our ecological data for the hazard modeling, we considered herbaceous species potentially supplied by the horticultural industry. Modeling of the probability of plants becoming invasive required a sample of both invasive and non-invasive species. Invasive species are defined for the purpose of the empirical modeling as those species not native to North America that develop self-sustaining populations outside of cultivation. Non-invasive plants are not native to North America that have not established outside of cultivation to a noticeable degree. A stratified sample of herbaceous species was selected among annual, biennial, and perennial species. The species were identified through lists of herbaceous species invading North America and verified using the United States Department of Agriculture's PLANTS database.[15]

Since species may not begin to invade for some time after introduction, we selected species that have been established for some time without invading as the "non-invaders". We selected the North American herbaceous non-invaders from garden books published prior to 1950. Only true species and not cultivated varieties were used. Cultivated varieties may not reproduce from seeds and that would affect their invasive ability.

We selected taxonomic, eco-geographic, and biological traits describing the species in our samples based on numerous studies of the traits associated with invasive and non-invasive plants (e.g., Rejmánek and Richardson 1996, Reichard and Hamilton 1997, Pheloung et al. 1999). We explored published work on each species through several databases, including Agricola, BIOSIS, Web of Science, Science Direct, and Google. We read the publications identified through abstracts as having pertinent information and the scoring of the traits for each species was entered into an Excel spreadsheet using these publications.

Since the data set was not randomly selected from the population of all introduced horticultural herbaceous plant species in North America, we may face sample selection problems for two reasons. First, since invasive species are more of a public concern than noninvasive species, more information is available about dates of introduction and plant characteristics for invasive

[15] http://plants.usda.gov/.

species. Our sample therefore consists of more invasive species than non-invasive species, even though in the population of introduced plant species, invasive species are a minority. Second, invasive species may have been included for study because known invaders may possess characteristics which make them more noticeable, not more invasive. It is possible that some species have become invasive, but because they do not cause noticeable damage to humans, or the plants themselves are not very noticeable, the species may have thus far gone undetected. We do not attempt to deal with these sampling issues here but recognize that they may be important.

Further, there were many variables in the data set which we could not include in the analysis because of a high rate of missing data. Some of these variables, such as seed production, may have explanatory power but could not be analyzed. When the number of missing observations was less than 5% of the data, we assigned the average value for the variable to these missing values. This method reduces the variance and, consequently, the reliability of the p-values for the estimated coefficients. Table A.1 provides a description of the variables used for the herbaceous species analyses. The herbaceous species data set contained 110 observations initially but four observations were removed because of missing variable values, leaving 106 usable observations for the analysis. Of these 106 herbaceous species observations, 77 (72.6%) were for invasive species and 29 (27.4%) were non-invasive species.

We estimated the hazard rate using both the standard Weibull and exponential hazard function, which are common functional forms in the duration model literature (Keifer, 1988). The two models are expressed as follows: (a) the Weibull hazard function $h = \varphi p \left(\varphi t\right)^{p-1}$, and (b) the exponential hazard function $h = \varphi$. Note that if p=1 then the Weibull function converges to the exponential hazard rate. The standard Weibull and exponential hazard functions were estimated first by employing each of the explanatory variables listed in Table A.1 as individual covariates. However, these estimations proved unsatisfactory as the coefficient of only one variable (global) proved to be significant. We next conducted a Principle Component Analysis (PCA) to determine likely "grouping" of the plant characteristic variables in Table A.1 into factor scores. A PCA explains the variance-covariance structure of a dataset through a few linear combinations of the original variables where the objectives are data reduction and interpreting, and where the components can be used to account for the variability (Sabatini 2005).

A Z-score was first computed for each plant characteristic variable in Table A.1 to standardize the variables and to allow for them all to be on the same scale. Z-scores are the number of standard deviations from the mean in a normal distribution in increments of $1/100^{th}$ of a standard deviation (Bernard 2006, p. 171). Cronbach's Alpha test (CA = 0.26) confirmed the reliability and internal consistency of the data. The Kaiser-Meyer-Olkin Measure of Sampling Adequacy was moderately high (0.44), indicating that a PCA might be useful with the herbaceous species data set. The Measures of Sampling Adequacy were above 0.4, with the exception of selfcomp (0.365), indicating that the variables tend to fit with the structure of the other variables. There are no strong correlations between the variables. The extraction values were above 0.4, indicating that each variable tends to fit well with the PCA factor solution.

The PCA was conducted using the Varimax rotation with Kaiser Normalization, which means that only factors with eigenvalues above 1 were retained (StatSoft, 2003). The outcome and resulting factor score groupings are indicated in Table A.2. The PCA included 106 observations. Four factor score components, highlighted in gray, explain 66.4% of the total variation. FS1 (continents, global and polyploi) explains 19.9% of the total variance. This factor includes variables that describe a potential broad environmental tolerance. Species which occur across a large native geographic range have been correlated with invasive ability (Rejmánek 1996, Reichard 1997). They may be genetically diverse or phenotypically plastic in order to survive under diverse conditions. Similarly, species that invade a large number of bioregions likely have invasive ability, which they demonstrate by repeatedly invading when introduced (Reichard and Hamilton 1997). Polyploidy confers a number of possible advantages that may increase invasive ability, such as faster growth and possible resistance to some herbivores (Levin 1983). FS2 (abiotic and annual) explains 17.6% of the total variance. Annuals generally do not put resources into production of fruit types intended to attract animal dispersers. They typically produce large numbers of small seeds in dry fruits. FS3 (flower) explains 15.8% of the total variance. Species with a long flowering time have been correlated with invasive ability (Perrins et al 1992, Reichard 1997). FS4 (selfcomp and germno) explains 13.2% of the total variance. Both of these variables reflect that successful invaders must be able flexible in order to reproduce. Self-compatibility allows sexual reproduction to occur when a single plant is reproductively isolated from potential pollen sources (Rambuda and Johnson 2004). In addition, many species have physiological and/or mechanical dormancy which must be overcome before germination. Those which do not require cold or warm temperatures, physical disruption of the seed coat, or other pregermination needs are able to germinate in a wide variety of locations (Reichard 1997).

The Weibull and exponential hazard models were then estimated for the 106 herbaceous species observations using these four factor score components. The results are depicted in Table 5, and explained in the text.

Table A.1: Variables for herbaceous species hazard analysis

Variable	**Definition**	**Mean**	**Minimum**	**Maximum**
continents	Number of continents covered by native range	2	1	4
global	Number of global bioregions already invaded	5	0	24
annual	Plant form is annual	0.3	0	1
flower	Length of the flowering time in weeks	14.4	8	45
selfcompatible	Flowers are selfcompatible	0.67	0	1
polyploidy	Has more than two sets of chromosomes per nucleus	0.6	0	1
abiotic	Fruit is dispersed abiotically (otherwise dispersed biotically)	0.85	0	1
germno	Has no specific germination requirements	0.48	0	1

Table A.2: Rotated component matrix for PCA of herbaceous plant characteristic variables

	Component			
	FS1	FS2	FS3	FS4
Zscore: continents	.759	-.113	-.101	-.052
Zscore: global	.668	-.043	.547	-.025
Zscore: polyploi	.597	.240	-.121	.212
Zscore: abiotic	.147	.734	-.108	.037
Zscore: annual	-.216	.643	.464	.151
Zscore: flower	-.088	-.039	.841	.035
Zscore: selfcomp	.009	.209	-.035	.869
Zscore: germno	-.136	.501	-.231	-.617

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
FS: Factor score.