Economic Policy for Invasive Species

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Abstract

Biological invasions are classical examples of externalities. The risks and damages from biological invasions are endogenous, depending on how society protects itself from invasions, and how it reacts to them after they occur. This paper analyzes a dynamic model in which society can undertake a flow of expenditures to protect against a biological invasion, which continue until an invasion actually occurs, in which case society can undertake a flow of expenditures to control or reduce the damage. The trade-off between these policies is highlighted by the fact that it is optimal to undertake expenditures to protect against the invasion if and only if the cost of the invasion is large enough. This result holds if the cost of the invasion is known initially either with certainty or only in distribution. No protection is more likely to be optimal the larger is either the natural hazard rate of the invasion or the discount rate.

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1 Introduction

In recent years increasing attention has been paid to the problem of invasive species by environmentalists and policy-makers. An invasive species is one that is introduced and becomes established in an environment in which it is not indigenous. Many of these were introduced for food, fiber, or ornamental purposes, but then escaped into the environment and established themselves. For example, Morse et al. (1995) estimates that over 5000 plant species have escaped and become established in U. S. ecosystems. Many nonindigenous species have provided significant benefits. For example, food crops and livestock such as corn, wheat, poultry, and pigs, account for the vast majority of food provided in the U.S. at a value of roughly \$800 billion per annum (USBC 1998). Moreover, invasions which cause damage have not been that frequent. Conventionally, the 'tens' rule of thumb of biological invasions suggests that only ten per cent of introduced species will become established in the new environment, and that only ten per cent of these will cause harm. A study estimates that only 0.1 per cent of all known plants (between 200 and 250) are exotic pests in agriculture throughout the world (FICMNEW (1998)).

Nevertheless, some of the few that have caused damage have done so in spectacular fashion, resulting in substantial costs in the form of direct damage and abatement or control costs associated with weeds and pests, alterations in ecosystems and the populations dependent upon them, and loss of biodiversity. There are only two estimates of the aggregate cost of invaders at the national level. The U.S. OTA (1993) estimated the damage costs from 79 of the most harmful invasive species over the previous 85 years at \$96,994 million. Pimentel et al. (1999) estimated the annual damage costs from all invasive species at \$122,639 million. For example, Pimentel et al. estimate total costs of \$45 million from purple loosestrife, \$19,000 million from rats, \$5,000 million from zebra mussels, and \$1,100 million from pigeons. Moreover, the problems associated with invasive species are of increasing concern for two other reasons. First, the number of introductions, and thus the potential number of invasions, is increasing due to the increasing level of international trade and travel (Dalmazzone (2000)). Second, the costs of invasions are also increasing due to increases in population density and reductions in biodiversity and habitat conversion (Cohen and Carlton (1998), Rejmanek (1989), and Williamson (1996, 1999)).

Biological invasions are classical examples of externalities, whether they provide benefits or costs. In the case of damaging invasions, external costs are imposed costs on all society, so the control of invasions will be under-provided by markets. This creates an impetus for governmental policy. Recently there has been much activity in developing policy to address the problems associated with these invasions. In 1999, Executive Order 13112 was signed establishing the National Invasive Species Council, tasked with coordination and complementary of Federal activities regarding invasive species. The Council issued the National Invasive Species Management Plan early in 2001 to provide an overall blueprint for Federal action. There are a variety of Federal Laws that address these problems. Some involve efforts to restrict intentional introductions, such as importation of exotic species of flora for ornamental purposes and fauna for sport or biological control purposes, or to limit unintentional introductions of exotic species through shipping or the mail. Others include efforts to control organisms that already have been introduced and proliferated. Similar legislation has been adopted by state governments. For example, California has a comprehensive state-wide program for prevention and control of insect pests, noxious weeds, and plant or animal disease. Florida has a similarly comprehensive program to deal with aquatic and upland plant species, while Montana has such a program, to deal with noxious weeds (see http://www.invasivespecies.gov/).

The purpose of this paper is not to argue that the recent growth of policy is inappropriate or misguided, but instead that this may have overlooked a fundamental trade-off in the types of policies that can be employed to address the costs of harmful invasions. As is evident, the risks and damages from biological invasions are endogenous, depending on how society protects itself from invasions, and how it reacts to them after they occur. Therefore, optimal economic policy for invasive species should recognize the dynamic nature of the problem by explicitly taking into account the trade-off between current expenditures to protect against invasions and future expenditures to control or abate the damages associated with those few harmful invasions.

A dynamic model is constructed in which society can undertake a flow of expenditures intended to protect against a biological invasion. Examples of these include the costs associated with trade regulations to reduce the risk of introduction, such as ballast water exchange requirements for ocean transport ships, or quarantine requirements for importation of flora or fauna. These expenditures continue until an invasion actually occurs, in which case society can undertake a flow of expenditures intended to abate the damage from the invasion. Examples of these include the costs of weeding, spraying, pesticides, or biocontrol agents. The date at which an invasion succeeds is assumed to be an exponentially distributed random variable, with an associated hazard rate that depends on the natural hazard rate and the protection expenditure by society. Greater protection expenditure reduces the probability of an invasion at every date, and thus delays the need to begin damage abatement expenditure. Conversely, lower damage abatement expenditure reduces the incentive for protection expenditure. This approach allows for an analysis of the interaction between these two policies. That is, optimal policy may be to delay the invasion, and its damage abatement cost, as long a possible, or to do nothing to delay it and simply pay the damage abatement costs.

Society is assumed to choose these policies to maximize the present discounted value of the flow of utility from net income (GDP). Using the standard technique of backward induction, I first solve for the optimal post-invasion level of damage abatement flow cost, which determines the total flow cost of the invasion (actual damages plus damage abatement costs). I then solve for the optimal pre-invasion level of protection flow expenditure conditional on this invasion cost. To separate the effects of uncertainty about the timing or the invasion from uncertainty about the magnitude of its damage, I consider two cases. In the first, damages from the invasion are known with certainty at the beginning of the problem. In this case, it is optimal to undertake expenditures to protect against the invasion if and only if the known invasion cost is large enough. If so, then protection expenditure is increasing in this invasion cost, but decreasing in the natural hazard rate and the discount rate. However, as seems intuitively evident, it is not optimal to undertake protection expenditure for any invasion whose cost is not sufficiently large. This is a more likely outcome the larger is either the natural hazard rate, so an invasion is more likely for any level of protection expenditure, or the larger is the discount rate, so society values the future less.

In the second case, the magnitude of invasion damages are uncertain until the invasion has occurred. In this case, it is optimal to undertake expenditures to protect against the invasion if and only if the post-invasion expected utility given the cost of the invasion is small enough. If so, then protection expenditure is again decreasing in the natural hazard rate and the discount rate. Now it is not optimal to undertake protection expenditure for any invasion whose expected damage abatement cost is not sufficiently large, which corresponds to a sufficiently large post-invasion level of expected utility. Again, this outcome is more likely the larger is either the natural hazard rate the discount rate. Interestingly, no protection expenditure can be optimal even when the entire range of potential invasion costs is positive, while positive protection expenditure can be optimal even when expected invasion cost is zero.

The preceding literature on economic policy for invasive species is rather sparse. Shogren (2000) develops a static model of a policy-maker who choose levels of expenditure to mitigate the probability of an invasion and to adapt so as to reduce the damage from an invasion. Because his analysis is static, it assumes these expenditures are both made ex ante, before the invasion occurs. The examples of mitigation he uses, however, include both expenditures made before an invasion to reduce its likelihood and expenditures incurred after an invasion has occurred. The focus of this paper, alternatively, is on the dynamic interaction of expenditure policies undertaken before with those undertaken after an invasion. Knowler and Barbier (2000) develop a dynamic model of a profit-maximizing competitive firm when an invasion affects the population dynamics of the resource it harvest, and tests the model using data for the effects of the invasion of comb jelly effect on the anchovy fishery in the Black Sea. Perrings et al. (2002) argue that control of an invasive species is a weakest-link public good, so the welfare of society is determined by the efforts of the least effective member. They suggest policies to induce changes in behavior to enhance protection against invasions, and the development of international institutions to support the weakest-link members of global society.

Section 2 presents the probabilistic framework for the timing of an invasion. Section 3 analyzes optimal policies when the damages associated with an invasion are certain, while Section 4 analyzes optimal policies when damages are uncertain. Section 5 provides an algebraic example that is used to derive numerical results indicating that all cases discussed can indeed occur. Section 6 concludes.

2 Model

I consider a dynamic model in which the date at which the invasion occurs is uncertain. The government can employ two types of expenditure policies. One is to protect against an invasion by expenditure it undertakes (or mandates others to do) that reduces the likelihood of an invasion. The other is to abate the damage from an invasion by expenditure it undertakes after the invasion occurs. Obviously the timing of these policies is fundamentally different. There is no need to spend to repair damages from an invasion that has not occurred, just as there is no need to spend to protect against an invasion that has already occurred. The analysis that follows explicitly takes this timing into account.

I model the problem as one in which a "social planner" chooses policies to maximize the present discounted value of the country's expected welfare.

Given national income of y, the country's welfare is given by the utility function $U(y)$, where $U'(y) > 0$ and $U''(y) \leq 0$. The marginal utility of income is positive, but not necessarily diminishing. That is, I admit the possibility that the nation is risk-neutral as well as risk-averse. *Ex ante* policy, undertaken to protect against the possibility of an invasion, is assumed to take the form of a constant flow expenditure $p \geq 0$. *Ex post* policy, undertaken to abate the damage from an invasion, is assumed to take the form of a constant flow expenditure k. This expenditure plus the actual damages determine the cost of the invasion c. Thus, flow utility is $U(y - p)$ before the invasion and $U(y - c)$ afterward.

After an invasion occurs, let $d(k)$ be the flow damage that results when a flow expenditure of $k \geq 0$ is made by society to abate (or control) the damage. As noted above, the 'tens' rule says that, in the absence of policy, only one of ten alien species becomes established, and only one of these ten actually causes damage, $d(0) > 0$. The remainder either cause no damage, $d(0) = 0$, or perhaps even provide some benefit, $d(0) < 0$. The total flow cost of the invasion, including damage abatement, is then $d(k) + k$. Obviously, damage abatement expenditure cannot be optimal unless it results in a reduction in the damages, so I assume that the damage function is decreasing initially, $d'(0) < \dot{0}$. That is, $-d'(0)$ is the reduction in damage from the first dollar spent on damage abatement.

If the instantaneous rate of discount is $r > 0$, then the present value of the flow of utility after an invasion, discounted back to the date of the invasion, is

$$D(k; r, y) = \int_0^\infty e^{-rt} U(y - d(k) - k) dt = \frac{U(y - d(k) - k)}{r}. \tag{1}$$

The planner's problem is to choose damage abatement expenditure k to maximize this payoff, $\max_{k \geq 0} D(k; r, y)$. Because $\frac{\partial D}{\partial k} = (1/r)U'(y - d(k) - k)[-d'(k) - 1]$, the first order condition for an interior solution at $k^* > 0$ is $-d'(k^*) = 1$. The next result is immediate.

Theorem 1 *If $-d'(0) > 1$ and $d''(k) > 0$, then the solution to the planner's post-invasion problem is to undertake a flow expenditure $k^* > 0$ to abate the damage from the invasion, where k^* is independent of r and y. However, if $-d'(0) \leq 1$, then no damage abatement expenditure is optimal.*

Proof. Because $\frac{\partial D}{\partial k} = (1/r)U'(y - d(k) - k)[-d'(k) - 1]$, $\frac{\partial D}{\partial k} = 0$ if and only if $d'(k^*) + 1 = 0$. And because $d''(k) > 0$ implies $\frac{\partial^2 D}{\partial k^2} = (1/r)U''(y -$

$d(k) - k)[-d'(k) - 1]^2 + (1/r)U'(y - d(k) - k)[-d''(k)] < 0$, it follows that the unique maximum is at $k^* > 0$ if and only if $\frac{\partial D(0;r,y)}{\partial k} = (1/r)U'(y - d(0))[-d'(0) - 1] > 0$, or $-d'(0) > 1$. The proof is completed by noting that $\frac{\partial^2 D}{\partial k \partial r} = \frac{\partial^2 D}{\partial k \partial y} = 0$ at k^*. ■

This result says that it is optimal to expend resources to try to repair the damage from an invasion only if the first dollar spent flow reduces damages by more than that dollar, $-d'(0) > 1$, so the (total) cost of the invasion declines. In this case, if the damage abatement cost function is convex, $d'' > 0$, abatement spending occurs up to the point where the last dollar spent reduces damage by a dollar.

It is worth noting that, as one expects, this solution also minimizes the cost of an invasion, $c = d(k^*) + k^*$. Note well that there is no presumption that $c > 0$. Indeed, as noted above, it is possible that $d(0) \leq 0$ and $c = d(k^*) + k^* < 0$. This corresponds to a case in which the species that invades is beneficial, as in the case of numerous agricultural crops and many domesticated animals (assuming we assess their impact by including the benefits from their domestication as well as the costs of caused by those which have gone feral). In this case the expenditure k is not a damage abatement cost, but a subsidy chosen to maximize the net benefits of the invasion. It is also possible, of course, that $k^* = 0$, so $c = d(0)$.

In any of these cases, the maximized utility of net income received at every date after an invasion is $U(y - c)$, where $c = d(k^*) + k^*$. The present value of the flow of utility after an invasion, discounted back to the date of the invasion, is then $\int_0^\infty e^{-rt}U(y - c)dt = (1/r)U(y - c)$.

The probability of an invasion is modeled in an explicitly dynamic fashion. I assume that the date $T > 0$ at which an invasion occurs is exponentially distributed with parameter $h > 0$. The probability that an invasion occurs at or before a date t is thus $Pr\{T \leq t\} = 1 - e^{-ht}$, and the probability that an invasion occurs in the instant after t is $Pr\{T \in (t, t + dt)|T > t\} = \frac{he^{-ht}}{e^{-ht}} = h$. That is, h is the hazard rate associated with an invasion. Note that $h > 0$ implies the expected date of an invasion $1/h$ is both positive and finite. That is, this approach allows the possibility that the probability of an invasion cannot be driven to zero, or it is not optimal to do so, in which case the invasion will eventually occur. In this case, the role of policy *ex ante* is to protect again the invasion by delaying it as long as feasible, not to try to make invasion impossible. If p is the constant flow expenditure to protect against an invasion, assume the hazard rate is given by $h(p, n)$, where $h(0, n) = n > 0$, $\frac{\partial h}{\partial p} < 0 < \frac{\partial^2 h}{\partial p^2}$, $\lim_{p \to \infty} h(p, n) \geq 0$, $\frac{\partial h}{\partial n} > 0 > \frac{\partial^2 h}{\partial n^2}$, and $\frac{\partial^2 h}{\partial n \partial p} \geq 0$. If nothing is done, an invasion occurs with the "natural" hazard rate $n > 0$. Otherwise, increasing expenditures reduce the hazard rate at a decreasing rate, thought it cannot be negative.

In addition to this uncertainty about the timing of an invasion, there may also be uncertainty before the invasion occurs regarding the magnitude of the resulting damage, if any. In order to highlight the effects of each type of uncertainty, I proceed by first considering the case where the timing of the invasion is uncertain, but the associated damages are known at the beginning of the problem. I then turn to the case where both the timing of the invasion and the associated damages are uncertain.

3 Policy with Uncertain Timing and Certain Damages

As a benchmark, consider the choice of policy when the damage from an invasion is foreseen with certainty. The present discounted value of the expenditure p per period to protect against an invasion is therefore

$$\begin{aligned} V(p; c, n, r, y) &= \int_0^\infty e^{-rt}[h(p,n)e^{-h(p,n)t}[U(y-c)/r] + e^{-h(p,n)t}U(y-p)]dt \\ &= \frac{U(y-p) + [h(p,n)/r]\,U(y-c)}{r + h(p,n)} \qquad (2) \end{aligned}$$

The social planner's problem is to choose a nonnegative flow expenditure of protection to maximize this payoff, $\max_{p\geq 0} V(p; c, n, r, y)$. The first order condition for an interior solution at $p^* > 0$ can be written as $\upsilon(p^*; c, n, r, y) = 0$ where

$$\upsilon(p; c, n, r, y) = \left(-\frac{\partial h}{\partial p}\right)\left[\frac{U(y-p) - U(y-c)}{r + h(p,n)}\right] - U'(y-p). \qquad (3)$$

The marginal cost of an additional dollar spent on protection is the current loss of the associated marginal utility, $U'(y-p)$. In return, the hazard rate declines and the expected date of the invasion increases, which delays the date at which damage abatement expenditures begin. The first term on the right-hand side of (3) is the expected, hazard-discounted gain in flow utility from delaying the invasion. Thus, when protection expenditure is undertaken, $p^* > 0$, it is increased up to the point where the expected, hazard-discounted benefit of the last dollar spent equals the current marginal utility cost of that dollar. In this case, flow utility before the invasion must exceed that after the invasion, $U(y-p^*) - U(y-c) = \frac{[(r+h(p^*,n))U'(y-p^*)]}{\left(-\frac{\partial h}{\partial p}\right)} > 0$.

Because the marginal utility of income is positive, expenditure on protection before the invasion never exceeds the cost of the invasion, $U(y-p^*) > U(y-c)$ if and only if $p^* < c$.

Theorem 2 *If future damage from an invasion is certain, if* $\frac{\partial v}{\partial p} < 0$*, and if*

$$v(0;c,n,r,y) = \left(-\frac{\partial h(0,n)}{\partial p}\right)\left[\frac{U(y)-U(y-c)}{r+n}\right] - U'(y) > 0, \qquad (4)$$

then the solution to the planner's problem is to undertake a flow expenditure $p^*(c,n,r,y) \in (0,c)$ *to protect against an invasion, where* $p^*(c,n,r,y)$ *is increasing in* c*, but decreasing in* n *and* r*. A change in* y *has an ambiguous effect on* $p^*(c,n,r,y)$*. However, if* (4) *does not hold, then protection expenditure against an invasion is not optimal,* $p^*(c,n,r,y) = 0$*.*

Proof. Because $\frac{\partial V}{\partial p} = \left(-\frac{\partial h}{\partial p}\right)\frac{[U(y-p)-U(y-c)]}{[r+h(p,n)]^2} - \frac{U'(y-p)}{r+h(p,n)} = \frac{v(p;c,n,r,y)}{r+h(p,n)}$ and $\frac{\partial v}{\partial p} < 0$ implies $\frac{\partial^2 V}{\partial p^2} = \frac{\frac{\partial v}{\partial p}(r+h)-v\frac{\partial h}{\partial p}}{(r+h)^2} < 0$ when $v = 0$ (at p^*), $v(0;c,n,r,y) > 0$, or (4), implies an interior solution $p^* > 0$ defined by $v(p^*;c,n,r,y) = 0$ with $\frac{\partial p^*}{\partial x} = -\frac{\frac{\partial v}{\partial x}}{\frac{\partial v}{\partial p}}$ for $x = c,n,r,y$, while $v(0;c,n,r,y) \leq 0$ implies $p^* = 0$. Note that $\frac{\partial v}{\partial c} = \frac{-\frac{\partial h}{\partial p}U'(y-c)}{r+h} > 0$ because $\frac{\partial h}{\partial p} < 0$ and $U' > 0$, while $\frac{\partial v}{\partial r} = -\left(-\frac{\partial h}{\partial p}\right)\frac{[U(y-p^*)-U(y-c)]}{(r+h)^2} < 0$ and $\frac{\partial v}{\partial n} = \left[-\frac{\partial^2 h}{\partial p \partial n}(r+h) + \frac{\partial h}{\partial p}\frac{\partial h}{\partial n}\right]\frac{[U(y-p^*)-U(y-c)]}{(r+h)^2} < 0$ because $U(y-p^*) > U(y-c)$, $\frac{\partial h}{\partial n} > 0$, and $\frac{\partial^2 h}{\partial p \partial n} \geq 0$. Finally, $\frac{\partial v}{\partial y} = \left(-\frac{\partial h}{\partial p}\right)\frac{[U'(y-p^*)-U'(y-c)]}{r+h} - U''(y-c)$ is ambiguous because $p^* < c$ and $U'' \leq 0$ implies $U'(y-p^*) \leq U'(y-c)$. ■

This result simply says that a policy of expenditure to protect against an invasion is optimal if the expected, hazard-discounted benefit of the first dollar spent exceeds the associated loss in marginal utility. In this case, the optimal protection expenditure is greater for more costly invasions. Protection expenditure is also greater when the rate of discount is smaller, because society values the future more and so prefers to delay the invasion longer. However, protection expenditures are smaller for invasions that are more likely to occur because their natural hazard rates are high, and so they are more likely to occur for any level of protection expenditure. Wealthier nations may spend more or less on protection, in general, because the marginal gain from delaying the cost of the invasion and the marginal cost of protection are both smaller for wealthier nations, given risk-aversion. Nevertheless, as is evident from the proof, a change in income has no effect on the optimal protection if the planner is risk-neutral.

Conversely, when the marginal benefit of the first dollar spent is not high enough, no protection should be undertaken. The next result more fully characterizes the conditions under which it is not optimal to protect against an invasion.

Theorem 3 *If future damage from an invasion is certain, and if* $\frac{\partial v}{\partial p} < 0$*, then there exists a unique level of net invasion cost* $c^* > 0$ *such that no invasion protection is optimal for invasion costs less than this,* $p^*(c, n, r, y) = 0$ *for all* $c \leq c^*$*. This critical value of invasion cost is increasing in* r *and* n*, but a change in* y *has an ambiguous effect on it.*

Proof. Note that $\frac{\partial V(0;0,n,r,y)}{\partial p} = \frac{v(0;0,n,r,y)}{r+n} = \left(-\frac{\partial h(0,n)}{\partial p}\right)\frac{[U(y)-U(y)]}{(r+n)^2} - \frac{U'(y)}{r+n} = -\frac{U'(y)}{r+n} < 0$, which implies $p^*(0, n, r, y) = 0$. The result then follows from the fact that $\frac{\partial v}{\partial c} > 0$, which implies the existence of a $c^* > 0$ such that $v(0; c^*, n, r, y) = 0$, $v(0; c, n, r, y) < 0$ for $c < c^*$, and $v(0; c, n, r, y) > 0$ for $c > c^*$, where $\frac{\partial c^*}{\partial x} = -\frac{\frac{\partial v}{\partial x}}{\frac{\partial v}{\partial c}}$ for $x = n, r, y$. Because $v(0; c^*, n, r, y) = 0$ implies $U(y) > U(y - c^*)$, now $\frac{\partial v}{\partial r} = -\left(-\frac{\partial h}{\partial p}\right)\frac{[U(y)-U(y-c^*)]}{(r+h)^2} < 0$, $\frac{\partial v}{\partial n} = \left[-\frac{\partial^2 h}{\partial p \partial n}(r + h) + \frac{\partial h}{\partial p}\frac{\partial h}{\partial n}\right]\frac{[U(y)-U(y-c^*)]}{(r+h)^2} < 0$, and $\frac{\partial v}{\partial y} = \left(-\frac{\partial h}{\partial p}\right)\frac{[U'(y)-U'(y-c^*)]}{r+h} - U''(y - c^*)$ is again ambiguous. ■

It is not surprising, of course, that no protection expenditure is undertaken when the invasion is beneficial and imposes no costs on society. Similarly, it cannot be optimal to spend more on protection than the cost of an invasion. However, it is significant that the optimal policy involves no protection expenditure when the cost of an invasion is not too large. That is, when the timing of the invasion is uncertain, but the magnitude of its damage is certain, it is not optimal to protect against invasions that have small enough costs. The optimality of this non-response to the threat of an invasion is more likely the larger the discount rate, so society values the future less, and the higher the natural hazard rate, so the invasion is more likely for any level of protection expenditure. Again, risk-averse wealthier nations may be more or less likely to choose no protection expenditure because the marginal gain from delaying invasion costs and the marginal cost of protection are both lower in wealthier nations.

4 Policy with Uncertain Timing and Damages

Now assume that the damages from an invasion are learned with certainty at the date the invasion occurs, but that these damages cannot be foreseen (before the invasion). After an invasion occurs, the planner still faces the same optimization problem in section 2. However, before the invasion actually occurs, the cost associated with the invasion, and therefore net flow income, are known only in distribution. In particular, assume the distribution of invasion costs is given by the density $f(c)$.[1]

Because there is no presumption that $c > 0$, the support of f can include negative numbers. However, because c results from an optimization problem with a finite solution, the support of f should be a closed and bounded interval of the form $[a, b] \subset [-y, y]$. Unfortunately, there are no empirical studies that provide estimates of the distribution of damages and benefits from all biological invasions. The understandable concern with addressing those cases that cause serious damages has led to a lack of interest in estimates of the benefits from invasions. For this reason, the analysis is conducted as generally as possible, though emphasis is placed on the cases where on average an invasion results in a net cost.

Given the density $f(c)$, the flow utility from net post-invasion income, expected before the invasion occurs, is

$$E[U(y-c)] = \int_a^b U(y-c)f(c)dc. \tag{5}$$

Before the invasion, the present value of the flow of expected utility after an invasion, discounted back to the date of the invasion, is $\int_0^\infty e^{-rt}EU[y-c]dt = (1/r)E[U(y-c)]$. The present discounted value of the spending p per period to protect against an invasion is now

$$\begin{aligned} W(p;n,r,y) &= \int_0^\infty e^{-rt}[h(p,n)e^{-h(p,n)t}(E[U(y-c)]/r) + e^{-h(p,n)t}U(y-p)]dt \\ &= \frac{U(y-p) + [h(p,n)/r]\, E[U(y-c)]}{r+h(p,n)} \end{aligned} \tag{6}$$

The social planner's problem is to choose a nonnegative cost flow of protection to maximize this payoff, $\max_{p\geq 0} W(p;n,r,y)$. The first order condition for an interior solution at $p^* > 0$ can be written as $\omega(p^*;n,r,y) = 0$

$$\omega(p;n,r,y) = \left(-\frac{\partial h}{\partial p}\right)\left[\frac{U(y-p) - E[U(y-c)]}{r+h(p,n)}\right] - U'(y-p). \tag{7}$$

The interpretation is essentially the same in this case. When protection expenditure against invasion is undertaken, it is increased up to the point

[1] Writing the density of invasion costs in this fashion assumes that the date of the invasion and the magnitude of the damages it causes are independent random variables.

where the expected, discounted benefit of the last dollar spent equals the current marginal utility cost of that dollar. In this case however, the discounted gain in flow utility from delaying the invasion includes expectations over both the invasion date and the cost associated with it. Thus, now one can conclude only that pre-invasion utility of net income exceeds post-invasion expected utility of net income, $U(y-p^*)-E[U(y-c)] = \frac{[r+h(p^*,n)]U'(y-p^*)}{\left(-\frac{\partial h}{\partial p}\right)} > 0$. What this implies about the relative magnitudes of protection expenditure and invasion cost depends on the distribution of the invasion costs and the nature of the utility function.

Theorem 4 *If future damages from an invasion are uncertain, $\frac{\partial \omega}{\partial p} < 0$, and*

$$\left(-\frac{\partial h(0,n)}{\partial p}\right)\left[\frac{U(y)-E[U(y-c)]}{r+n}\right] > U'(y), \tag{8}$$

then the solution to the planner's problem is to undertake a flow expenditure $p^*(n,r,y) > 0$ to protect against an invasion, where $p^*(n,r,y)$ is decreasing in n and r. A change in y has an ambiguous effect on $p^*(n,r,y)$. However, if (8) does not hold, then protection expenditure against an invasion is not optimal, $p^*(n,r,y) = 0$.

Proof. Because $\frac{\partial W}{\partial p} = \left(-\frac{\partial h}{\partial p}\right)\left[\frac{U(y-p)-E[U(y-c)]}{[r+h(p,n)]^2}\right] - \frac{U'(y-p)}{r+h(p,n)} = \frac{\omega(p;n,r,y)}{r+h(p,n)}$ and $\frac{\partial \omega}{\partial p} < 0$ implies $\frac{\partial^2 W}{\partial p^2} = \frac{\frac{\partial \omega}{\partial p}(r+h)-\omega\frac{\partial h}{\partial p}}{(r+h)^2} < 0$ when $\omega = 0$ (at p^*), it follows that $\omega(0;n,r,y) > 0$, or (8), implies an interior solution $p^* > 0$ defined by $\omega(p^*;c,n,r,y) = 0$ with $\frac{\partial p^*}{\partial x} = -\frac{\frac{\partial \omega}{\partial x}}{\frac{\partial \omega}{\partial p}}$ for $x = n,r,y$, while $\omega(0;c,n,r,y) \leq 0$ implies $p^* = 0$. Note that $\frac{\partial \omega}{\partial r} = -\frac{\left(-\frac{\partial h}{\partial p}\right)(U(y-p^*)-E[U(y-c)])}{(r+h)^2} < 0$ and $\frac{\partial \omega}{\partial n} = \frac{\left[-\frac{\partial^2 h}{\partial p \partial n}(r+h)+\frac{\partial h}{\partial p}\frac{\partial h}{\partial n}\right](U(y-p^*)-E[U(y-c)])}{(r+h)^2} < 0$. However, $\frac{\partial \omega}{\partial y} = \left(-\frac{\partial h}{\partial p}\right)\left[\frac{U'(y-p^*)-\frac{\partial E[U(y-c)]}{\partial y}}{r+h}\right] - U''(y-c)$ is ambiguous. ∎

This result simply says that a policy of expenditure to protect against an invasion is optimal when the marginal benefit of the first dollar spent exceeds its cost in terms of marginal utility loss. In this case, the optimal level of protection expenditure is greater when the rate of discount is larger, so society prefers to delay the invasion longer, but smaller for invasions that are more likely to occur, because their hazard rates are greater for any level of protection expenditure. Wealthier nations may spend more or less on protection, in general, because the marginal gain from delaying the cost of the invasion and the marginal cost of protection both decline. Nevertheless, as is evident from the proof, a change in income has no effect on the optimal protection if the planner is risk-neutral.

Again, however, if the marginal benefit of the first dollar spent is not high enough, no protection should be undertaken. The next result more fully characterized the conditions under which it is not optimal to protect against an invasion.

Theorem 5 *If future damages from an invasion are uncertain, and if* $\frac{\partial \omega}{\partial p} < 0$*, then there exists a unique level of post-invasion expected flow utility of net income,* $E[U(y-c)] = u^*$*, such that no invasion protection is optimal for invasions with costs resulting in expected utility above this level,* $p^*(n,r,y) = 0$ *for all* $E[U(y-c)] > u^*$*. Given risk-aversion, this critical level of post-invasion expected utility may be less than that associated with no expected invasion costs, which implies that invasion protection may be optimal,* $p^*(n,r,y) > 0$*, even if expected invasion cost is zero. The critical value of expected post-invasion utility is decreasing in* r *and* n*.*

Proof. Observe that $\frac{\partial W(0;n,r,y)}{\partial p} = \frac{\omega(0;n,r,y)}{r+n} = \left(-\frac{\partial h(0,n)}{\partial p}\right)\frac{(U(y)-E[U(y-c)])}{(r+n)^2} - \frac{U'(y)}{r+n}$, so $\frac{\partial W(0;n,r,y)}{\partial p} = 0$ if and only if $E[U(y-c)] = U(y) - \frac{(r+n)U'(y)}{\left(-\frac{\partial h(0,n)}{\partial p}\right)} = u^*$. Note that $E[U(y-c)]$ can be varied without affecting any other variables, by changing the distribution of invasion costs, for example. In this sense $\omega(0;n,r,y)$ can be viewed as a decreasing function of $E[U(y-c)]$. Thus, $\omega(0;n,r,y) \leq 0$ if $E[U(y-c)] \geq u^*$, in which case $p^*(n,r,y) = 0$. However, $\omega(0;n,r,y) > 0$ if $E[U(y-c)] < u^*$, in which case $p^*(n,r,y) > 0$. Finally, if expected invasion cost is zero, $E[c] = 0$, note that $U'' < 0$ implies $E[U(y-c)] < U(E[y-c]) = U(y-E[c]) = U(y)$. Hence, the first term in $\omega(0;n,r,y)$ can be positive even if $E[c] = 0$, whence it is possible that $\omega(0;n,r,y) > 0$ and $p^*(n,r,y) > 0$. Finally, it follows from the definition of u^* above that $\frac{\partial u^*}{\partial r} = -\frac{U'(y)}{\left(-\frac{\partial h(0,n)}{\partial p}\right)} < 0$ and $\frac{\partial u^*}{\partial n} = -\frac{U'(y)\left[\left(-\frac{\partial h(0,n)}{\partial p}\right)+(r+n)\frac{\partial^2 h(0,n)}{\partial p \partial n}\right]}{\left(-\frac{\partial h(0,n)}{\partial p}\right)^2} < 0$. ■

As shown above in Theorem 2, when invasion damage is certain, no protection expenditure is optimal if the invasion results in no costs, and thus no protection expenditure is optimal even for invasions with small enough costs. However, if damage from an invasion is uncertain, and society is risk-averse, then some protection expenditure may be optimal even when expected invasion cost is zero. This is not surprising, of course, because risk-aversion may induce society to pay a cost to avoid even the fair gamble of an invasion with no expected cost, on average. It is also worth emphasizing, again, that no protection expenditure is optimal, even when expected invasion cost is positive, as long as this expected cost is not too great. As in the case of certain damage, this is more likely to be the case the larger the discount factor or natural hazard rate. An explicit algebraic example is provided in the next section to show that each of these results can occur.

Finally, it is natural to ask how an increase in the risk of damages affects optimal protection policy. This follows immediately from the last result, using the standard Rothschild and Stiglitz (1970, 1971) formulation of increasing risk. That is, given risk-aversion, the expected utility of riskier invasions (with the same mean costs) is lower.

Theorem 6 *An increase in the risk of damages associated with an invasion:*
(i) Increases the likelihood that optimal protection expenditure is positive; and
(ii) Increases the level of optimal protection expenditure when it is positive.

Proof. For concave utility functions, greater risk is equivalent to lower post-invasion expected utility, $E[U(y-c)]$, which in turn implies that (8) is more likely to hold, so some protection expenditure is optimal, $p^*(n,r,y) > 0$. Moreover, in this event it follows from (7) and $\frac{\partial \omega}{\partial p} < 0$ that $p^*(n,r,y)$ increases as $E[U(y-c)]$ declines. ∎

As intuitively expected, greater risk of invasion costs, whatever their mean, leads a risk-averse social planner to spend more to protect against an invasion. It should be noted, however, that even in this case the planner may well simply be delaying the inevitable.

5 An Algebraic Example

In this section an algebraic example with specific utility function and distribution of post-invasion costs is presented to demonstrate some of the preceding results.

Let utility be given by $U(y) = -e^{-\rho y}$, where $\rho > 0$ is a constant (its inverse is the well-known rate of constant relative risk-aversion), and assume the density of invasion costs is uniform, $f(c) = (b-a)^{-1}$. Also let the hazard function be $h(p,n) = n - \frac{mp}{1+p}$, so $\frac{\partial h(0,n)}{\partial p} = -m$. Then $E[c] = \int_a^b \frac{cdc}{(b-a)} = \frac{a+b}{2}$ and

$$E[U(y-c)] = \int_a^b \frac{-e^{-\rho(y-c)}dc}{(b-a)} = \frac{\left[e^{\rho a} - e^{\rho b}\right] e^{-\rho y}}{\rho(b-a)} = \frac{\left[e^{\rho a} - e^{\rho b}\right] U(y)}{\rho\,(b-a)}. \quad (9)$$

Thus, $\frac{\partial W(0;n,r,y)}{\partial p} = \frac{U(y)}{(r+n)^2\rho(b-a)}\left[m\rho(b-a) - m(e^{\rho b} - e^{\rho a}) + (r+n)\rho^2(b-a)\right]$, and so positive protection expenditure is optimal if and only if

$$G(n,r,y,\rho,m,a,b) = m(e^{\rho b} - e^{\rho a}) - \rho(b-a)[m + (r+n)\rho] > 0. \quad (10)$$

It is straightforward to show that $G(.5,.5,y,1,m,0,10) < 0$ for all $m < .00049$ and $y > 0$. This is an interesting example because expected invasion cost is positive, $E[c] > 0$, but no protection expenditure is optimal whenever the initial decline in the hazard rate is not large enough. Indeed, one can see from (10) that $G < 0$ is likely whenever m is small. However, protection expenditure may or may not be optimal when expected invasion cost is zero. For example, assume that $a = -b$, so $E[c] = 0$ and $G(.5,.5,y,1,1,-b,b) = e^b - e^{-b} - 4b$. Then $G(.5,.5,y,1,1,-2,2) = -0.75$, so no protection expenditure is optimal, but $G(.5,.5,y,1,1,-2.5,2.5) = 2.1$, and protection expenditure is undertaken.

Alternatively, in this case the critical value of post-invasion expected utility is

$$u^* = \left[1 - \frac{\rho(r+n)}{m}\right] U(y).$$

Recalling that no protection is optimal for values of expected utility above this level, the likelihood that no protection against an invasion is the appropriate strategy, even when there is uncertainly about the magnitude of the potential damages, *ceteris paribus*, is increasing in the discount rate and the natural hazard rate, but decreasing in the marginal impact of the first dollar spent on protection and the degree of constant relative risk-aversion.

6 Conclusion

This paper has focused on the interaction between policies that society can employ to protect itself from biological invasions. Before an invasion, society can undertake a flow of expenditures intended to protect against the invasion. If an invasion does occur, society can undertake a flow of expenditures intended to abate the damage from the invasion. Greater protection expenditure reduces the probability of an invasion at every date, and thus (in expectation) delays the invasion and its costs. Conversely, lower invasion costs reduce the incentive for protection expenditures. When damages from an invasion are known with certainty, it is optimal to undertake expenditures to protect against the invasion if and only if the known invasion cost is large enough. If so, then protection expenditure is increasing in this invasion cost, but decreasing in the natural hazard rate and the discount rate. However, as seems intuitively evident, it is not optimal to undertake protection expenditure for any invasion whose cost is not sufficiently large. This is a more likely outcome the larger is the natural hazard rate or the discount rate. When the magnitude of invasion damages are uncertain until the invasion has occurred, it is optimal to undertake expenditures to protect against the invasion if and only if the post-invasion expected utility (given optimal damage abatement expenditure) is small enough. Protection expenditure is again decreasing in the natural hazard rate and the discount rate. Now, however, it is not optimal to undertake protection expenditure for any invasion whose expected cost is not sufficiently large, which is more likely the larger is either the natural hazard rate the discount rate. Given this uncertainty about invasion costs, it follows that no protection expenditure can be optimal even when the entire range of potential invasion costs is positive, while positive protection expenditure can be optimal even when expected invasion cost is zero.

Several extensions of the analysis seem interesting. First, this analysis assumes that the date of the invasion and the magnitude of the damages it causes are independent random variables. Although this seems quite reasonable, one can also envision situations in which they are related. For example, one might expect that invasions that are especially damaging would also be very difficult to delay, so one must consider a joint density on the timing and cost of an invasion. Such an extension would allow one to examine the interplay between the correlation between these random variables and the choices of protection and damage abatement expenditures. Shogren (2000), notes that adaptation policies such as crop rotation might affect the magnitude of future damages. Another example is research and development, which can provide improved control techniques and materials. Incorporating the possibility of another such expenditure policy before the invasion is a natural extension that would allow one to consider the trade-off between protection and abatement policies toward biological invasions. Finally, this analysis has assumed only one invasion with characteristics that are well-known, at least in probability. As such, it is best suited to cases of well-known biological invaders, such as problems observed in neighboring regions or encountered and eradicated in the past (but which continue to be a threat). It is at least as important would be to analyze policy to guard against lesser-known potential invaders.

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