On Prevention and Control of an Uncertain Biological Invasion†

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Abstract: This paper examines how optimal prevention and control policies depend on the economic and biological characteristics of a randomly introduced biological invasion where the objective is to minimize the expected social costs from prevention, control, and invasion damages. The results characterize how optimal prevention and control policies vary with the initial invasion size, the invasion growth rate, and the probability distribution of introductions. The paper also examines the conditions under which the optimal policy relies solely on either prevention or control, the conditions under which it is optimal to completely prevent new introductions, and the conditions under which eradication of established invasions is optimal

Key words: invasive species, uncertainty, prevention, control

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The invasion of ecological systems by non-indigenous species is a significant component of global environmental change (Vitousek et. al.) that imposes substantial economic and ecological damages. In the United States alone, the number of harmful invasive species is in the thousands, approximately one-fourth of the value of the country′s agricultural output is lost to non-indigenous plant pests or the costs of controlling them (Simberloff), and the total costs of non-indigenous species have been estimated to be as high as $137 billion per year (Pimentel, et. al.).

Prevention and control are the two basic ways the costs of an invasive species can be reduced. Approximately half of U.S. federal expenditures for invasive species are for prevention activities (National Invasive Species Council). Control of an invasive species after it becomes established may involve significant control costs and pest damages. For example, $5 billion are spent annually on herbicides (Keily, et.al.) while the value of annual crop losses to weeds has been estimated at $20 billion (in 1991 dollars) (AHPIS PPD) with roughly 50-75% of these costs attributed to nonindigenous weed species (OTA). Prevention policy reduces the invasive species damages and the need for control, but prevention is costly, imperfect, and may restrict the flow of beneficial goods and services. Given that prevention and control have different costs and that they target the damages from invasive species in different ways, a fundamental issue in invasive species management is the appropriate balance between prevention and control policy.[1]

The purpose of this paper is to examine how optimal prevention and control policies depend on the economic and biological characteristics of a randomly introduced biological invasion where the objective is to minimize the expected social costs from prevention, control, and invasion damages.[2] At the time prevention and control decisions are made the planner knows the size of the established invasion, y. Depending on the context, the size of an invasion may be the area occupied by the invasive species, the population, or the biomass of the invasive species. If no invasion currently exists then y = 0. Control by chemical, biological, manual, or other means can be used to reduce the size of the existing invasion. A reduced form is used where the reduction in the size of the invasion from all inputs is denoted by a. The size of the invasion that exists after control is x = y-a.

In general, control costs depend on both the amount controlled (the reduction in the size of the invasion) and on the size of the invasion being controlled. In some cases the marginal costs of control vary more with the invasion size than they do with control. For example, historical attempts to eradicate invasive species indicate that it may cost as much to remove the last one to ten percent of an invasion as it does to control the initial ninety to ninety-nine percent (Myers, et. al.). Control costs are denoted by C(a,y). Both total and marginal costs of control are assumed to be increasing a and non-increasing in y. The latter implies that it is less costly to reduce the size of a large invasion by a given amount than it is to reduce the size of a smaller invasion by the same amount. Further, for a given amount of control, the last unit of control is less costly to achieve if the initial invasion is large. These are plausible assumptions when the inputs for control are used in a cost effective way.

Invasive species introductions, ω, occur randomly according to a distribution $F(\omega,\theta)$ with density $f(\omega,\theta)$. Introductions can be reduced through screening and prevention efforts, s. Increases in s could represent more stringent treatment of wood packing materials to prevent the spread of wood boring pests, or more stringent screening of livestock imports for disease. Prevention is scaled so that it achieves a proportional reduction in the random invasive species introduction. A value of s equal to zero is associated with no prevention, while a value of s equal to one is associated with a prevention level high enough to eliminate new introductions. The parameter θ is used to examine how shifts in the distribution of species introductions affects prevention and control policy. The cost of prevention is H(s), where H is an increasing and convex function.

The levels of prevention and control are both chosen before the random introduction is observed. The invasion that exists after control grows at a rate α and the invasion size after the random introduction occurs is $z = \alpha x + (1-s)\omega$. This causes damages D(z), which may be interpreted as the discounted lifetime social costs associated with the invasion size, z, that exists after current prevention and control decisions are made and new invasive species introductions are observed. The damage function D(z) is increasing and convex.

The invasive species management problem is to choose the levels of prevention and control that minimize expected social costs. Formally this problem can be expressed as:

$$\min_{a,s} \quad C(a,y) + H(s) + \int D(\alpha(y-a)+(1-s)\omega)f(\omega,\theta)d\omega$$

subject to: $0 \leq a \leq y$, $0 \leq s \leq 1$. The three cost functions, C, H and D, are all assumed to be twice continuously differentiable.[3] The solutions to this problem will be optimal prevention and control policies, $S(y,\alpha,\theta)$ and $A(y,\alpha,\theta)$, that depend on the size of the existing invasion, the growth rate of the invasion after control, and the probability distribution of introductions. Associated with the optimal control policy is an optimal post-control invasion size $X(y,\alpha,\theta) = y - A(y,\alpha,\theta)$.

Table 1 characterizes how the different possible outcomes for optimal prevention and control depend on marginal costs and damages. When optimal prevention and control policies are interior they satisfy the first order conditions:

$$C_a(a,y) = \alpha E[D_z(\alpha(y-a)+(1-s)\omega)]$$

$$H_s(s) = E[\omega D_z(\alpha(y-a)+(1-s)\omega)].$$

The optimal control balances the marginal costs of control against the expectation of random marginal damages associated with growth in the last unit of the invasion that remains after control. Similarly, optimal prevention balances the marginal costs of prevention against the expectation of random marginal damages weighted by the scale of the random introduction.

The main purpose of this paper is to examine how optimal prevention and control policies vary with the initial invasion size, the invasion growth rate, and the probability distribution of introductions. First, consider how the initial invasion size affects optimal prevention and control.

Proposition 1. *a) The optimal control is nondecreasing in the initial invasion size, i.e.,* $\partial A(y,\alpha,\theta)/\partial y \geq 0$. *b) If marginal control costs are more sensitive to changes in control than to changes in the invasion size,* $C_{aa} + C_{ay} \geq 0$, *then the optimal post-control invasion size is larger and satisfies* $1 \geq \partial X(y,\alpha,\theta)/\partial y \geq 0$. *In addition,* $\partial S(y,\alpha,\theta)/\partial y \geq 0$ *so that prevention increases with the initial invasion size. c) If marginal control costs are more sensitive to changes in the invasion size than to changes in control,* $C_{aa} + C_{ay} \leq 0$, *then the opposite is true for interior optimal policies. If the optimal policy is interior then* $\partial X(y,\alpha,\theta)/\partial y \leq 0$ *and* $\partial S(y,\alpha,\theta)/\partial y \leq 0$ *so the optimal post-control invasion size is smaller and prevention is less when the initial invasion size is larger.*

The intuition behind these results is as follows. An increase in the initial size of the established invasion reduces marginal control costs and increases expected marginal damages. The optimal policy compensates for this by increasing control, thereby raising marginal control costs and reducing expected marginal damages. This establishes part (a). Now suppose the optimal control increases by more than the change in the size of the invasion. This reduces the post-control invasion size and expected marginal damages. But when marginal control costs are more sensitive to control than to the size of the invasion, such a policy also increases the marginal costs of control. This cannot be optimal since it creates a wedge between expected marginal damages and the marginal costs of control. As a consequence, control must increase less than the change in invasion size when $C_{aa} + C_{ay} \geq 0$. This establishes part (b). A similar argument implies that control must increase by more than the change in the invasion size when $C_{aa} + C_{ay} \leq 0$ and the optimal control is strictly positive.

Parts (a) and (b) have obvious implications for policy. The policy implications of part (c) are worth noting. In an intertemporal setting they imply that when control costs are very sensitive to changes in the invasion size, periodic control may be an optimal policy and optimally managed invasions may follow cycles (Olson and Roy 2004). In addition, because a larger invasion lowers the marginal cost of control, it is optimal to shift policy from prevention to control as the invasion size increases.

Next, consider how differences in the invasion growth rate affect prevention and control.

Proposition 2. *a) The optimal control is non-decreasing in the initial growth rate. b) The optimal post-control invasion size is non-increasing in the invasion growth rate. c) The optimal prevention is non-decreasing in the invasion growth rate.*

The intuition and policy implications of these results is straight-forward. Each unit of control yields a greater reduction in expected marginal damages when the invasion growth rate is higher. As a consequence, the incentives for control increase with the invasion growth rate. This, in turn, stimulates more prevention since the two polices act as substitutes to reduce damages.

Finally, let us consider how the probability distribution of introductions affects optimal policy for prevention and control. Suppose that increases in θ are associated with a shift in the distribution that satisfies monotone likelihood ratio dominance (MLR). Formally, this equivalent to f_θ/f increasing in ω. MLR dominance implies first order stochastic dominance ($-F_\theta \leq 0$), so intuitively, the probability that invasive species introductions are greater than any given threshold increases as θ increases. MLR dominance also has the stronger implication that, for all possible introductions, the likelihood of a larger introduction increases more than the likelihood of a smaller introduction. In a portfolio choice model with a single risky asset, Milgrom shows that MLR dominance always increases the demand for a risky asset. For more general univariate choice problems, Ormiston and Schlee demonstrate that MLR shifts in distribution have the same effect on optimal choices as an increase in risk aversion.

The invasive species management problem of this paper has the characteristic that species introductions are like a risky asset, but with two policy instruments the conclusions drawn from a simple portfolio choice problem may be affected by interactions between policies. The marginal benefit from an increase in control depends only on the expectation of random marginal damages (weighted by the growth rate), while the marginal benefit from an increase in prevention depends on the expectation of random marginal damages, the expected introduction rate and the covariance between introductions and damages. To gain a better understanding of how these interactions between uncertainty, prevention and control affect policy it is useful to compare the results to two cases. The first is the response of prevention and control to a deterministic increase in the introduction rate.

Proposition 3. *Assume the introduction* ω *is deterministic. Then* $\partial S/\partial\omega \geq 0$. *Further, if* $H_{ss}(1\text{-}s)/H_s \geq 1$ *then* $\partial A/\partial\omega \geq 0$.

The second case for comparison is the response of one policy to a shift in the distribution when the other policy is held fixed.

Proposition 4. *a) If control is fixed then* $\partial S/\partial\theta \geq 0$. *b) If prevention is fixed then* $\partial A/\partial\theta \geq 0$.

This result subsumes the special case where the introduction of invasive species is deterministic and only one policy is available.

When policy includes both prevention and control the planner's attitudes toward risk play an important role in determining the response of policy to changes in the distribution of introductions.

Proposition 5. *a) If* D_{zz}/D_z *is decreasing in z then* $\partial S/\partial\theta \geq 0$. *b) If* $\omega D_{zz}/D_z$ *is decreasing in* ω *then* $\partial A/\partial\theta \geq 0$.

Prevention policy is strengthened in response to an MLR shift in the distribution of introductions when absolute aversion to risk is increasing, where risk aversion is interpreted in the normal utility-theoretic sense and utility is the negative of damages. An increase in the likelihood of a larger introductions leads to an increase in the absolute amount of prevention. When the elasticity of marginal damage with respect to new introductions is decreasing, marginal damages become less sensitive to introductions as θ increases. This causes policy to shift toward greater control.

To conclude, we offer some observations on the effect of an increase in risk or the variability of the distribution of introductions as measured by second order stochastic dominance. For example, one can think of an increase in risk as a mean preserving spread in the distribution. Suppose that marginal damages are convex. For given levels of prevention and control, an increase in the variability of introductions increases the marginal benefits from prevention and control. This, in turn, implies that emphasis on at least one of the policies increases in response to greater uncertainty. If the marginal damage function is concave, the opposite is true under certain additional restrictions. If marginal damages are constant then the economic benefits from prevention and control depend only on the expected introduction rate. The broad conclusion is that the curvature of the marginal damage function plays an important role in determining the qualitative effects of changes in the variability of invasive species introductions. This means that decision makers need to be informed about the curvature of the marginal damage function (the third derivative of the damage function) in order to evaluate how increases in risk affect prevention and control policy.

Table 1 - Sufficient conditions for various policy outcomes

s a	No control, a=0	Positive control, 0<a<y	Immediate eradication, a=y
No prevention, s=0	$C_a(0,y) > \alpha ED_z(\alpha y+\omega)$ $H_s(0) > E\omega D_z(\alpha y+\omega)$	$C_a(0,y) < \alpha ED_z(\alpha y+\omega)$ $C_a(y,y) > \alpha ED_z(\omega)$ $H_s(0) > E\omega D_z(\alpha(y-a)+\omega)$	$C_a(y,y) < \alpha ED_z(\alpha y+\omega)$ $H_s(0) > E\omega D_z(\omega)$
Positive prevention, 0<s<1	$C_a(0,y) > \alpha ED_z(\alpha y+(1-s)\omega)$ $H_s(0) < E\omega D_z(\alpha y+\omega)$ $H_s(1) > D_z(\alpha y)E\omega$	$C_a(0,y) < \alpha D_z(\alpha y)$, $C_a(y,y) > \alpha ED_z(\omega)$ $H_s(0) < E\omega D_z(\omega)$, $H_s(1) > D_z(\alpha y)E\omega$	$C_a(y,y) < \alpha ED_z(\alpha y+(1-s)\omega)$ $H_s(0) < E\omega D_z(\omega)$ $H_s(1) > D_z(0)E\omega$
Complete prevention, s=1	$C_a(0,y) > \alpha D_z(\alpha y)$ $H_s(1) < D_z(\alpha y)E\omega$	$C_a(0,y) < \alpha D_z(\alpha y)$ $C_a(y,y) > \alpha D_z(0)$ $H_s(1) < D_z(\alpha(y-a))E\omega$	$C_a(y,y) < \alpha D_z(0)$ $H_s(1) < D_z(0)E\omega$

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Endnotes

1. Agricultural economists have long been concerned about problems of pest management. The early literature is reviewed by Shoemaker. It focuses on issues such as pesticide resistance and intra-seasonal management. The more recent literature on the economics of invasive species examines other important aspects of the problem (see the references in Olson and Roy (2002).

2. Proofs of all propositions are omitted due to space limitations.

3. Subscripts are used to denote partial derivatives as in $C_a(a,y) = \partial C(a,y)/\partial a$ and $C_{ay}(a,y) = \partial^2 C(a,y)/\partial a \partial y$.