Prevention or Control: Optimal Government Policies for Invasive Species Management

C.S. Kim, Ruben N. Lubowski, Jan Lewandrowski, and Mark E. Eisworth

We present a conceptual, but empirically applicable, model for determining the optimal allocation of resources between exclusion and control activities for managing an invasive species with an uncertain discovery time. This model is used to investigate how to allocate limited resources between activities before and after the first discovery of an invasive species and the effects of the characteristics of an invasive species on limited resource allocation. The optimality conditions show that it is economically efficient to spend a larger share of outlays for exclusion activities before, rather than after, a species is first discovered, up to a threshold point. We also find that, after discovery, more exclusionary measures and fewer control measures are optimal, when the pest population is less than a threshold. As the pest population increases beyond this threshold, the exclusionary measures are no longer optimal. Finally, a comparative dynamic analysis indicates that the efficient level of total expenditures on preventive and control measures decreases with the level of the invasive species stock and increases with the intrinsic population growth rate, the rate of additional discoveries avoided, and the maximum possible pest population.

Key Words: invasive species, exclusion, control, eradication, public expenditures

Federal and state agricultural policymakers are increasingly interested in the consequences of alternative policy responses to address the economic and public health threats posed by invasive pest species.[1] Total spending and programs to control outbreaks of invasive pests have increased dramatically over the last decade. The USDA Animal and Plant Health Inspection Service (APHIS) operates a set of emergency programs for the purpose of eradicating new outbreaks of invasive pests, including avian influenza, Karnal bunt, citrus canker, and plum pox. Between 1991 and 1995, these programs numbered one or two per year, with total annual expenditures averaging \$10.4 million. Between 2002 and 2004, the average number of emergency programs increased to eighteen, with total annual expenditures averaging \$298 million (Garrett 2005). An important policy question is how to allocate limited resources between exclusionary activities to prevent the arrival of new invasive pests (including additional arrivals of existing pests) and activities to mitigate damages by species that have already reached the country.

Given the complexity of the problem and the magnitude of adverse ecological and economic impacts, economists have formulated bioeconomic models to understand the economics of invasive species management. Some models focus on just the preventive measures before the first arrival of

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[1] "Invasive pest species" include non-native species posing an actual, or a potential, economic threat to crop or livestock producers.

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an invasive species (Horan et al. 2002), or on the control measures after the species' establishment (Eiswerth and Johnson 2002, Eiswerth and van Kooten 2002, Olson and Roy 2002, Settle and Shogren 2002).[2] Other studies have examined the role of both prevention and control measures (Kaiser and Roumasset 2002, Ranjan, Marshall, and Shortle 2003, Shogren 2000, Olson and Roy 2005).

In Shogren's (2000) formulation, the problem of managing invasive species combines preventive activities (before establishment) and control and exclusionary activities (after establishment), as *ex-ante* measures. As a result, his bioeconomic model does not distinguish actions taken before and after establishment as distinct economic problems. Kaiser and Roumasset (2002) extend this framework by integrating preventive and control measures in a potentially cyclical optimal control model for a comprehensive strategy to minimize the social costs associated with invasive species. Given their assumption that additional pest arrivals after establishment do not affect the total pest population or the magnitude of pest-related damages, however, their analysis cannot provide insights into the role of exclusionary measures after establishment.

Ranjan, Marshall, and Shortle (2003) and Olson and Roy (2005) also extend Shogren's (2000) model by distinguishing preventive measures before a species' (uncertain) arrival date, control measures for the period between the first arrival of the species and its establishment in the country, and control measures during the post-establishment period. These authors assume no additional arrivals of existing pests, and hence no role for further preventive measures, once a species has become established in a country.

We provide a general model that subsumes these previous analyses as special cases and allows for a more comprehensive examination of exclusionary and control measures both before and after the discovery of an invasive species. In particular, our model broadens the analysis of possible actions in the post-discovery period. Shogren (2000) and Kaiser and Roumasset (2002) consider pre- and post-establishment periods. While suitable for many invasive pests, this characterization of time obscures the potential for action after the arrival of a species but before its establishment. This is important for species that are so undesirable that control measures would ideally be implemented immediately upon discovery and prior to establishment.

Our model examines the trade-offs between pre-discovery preventive (exclusionary) activities, post-discovery exclusionary activities, and post-discovery control activities. Exclusionary measures—such as trade restrictions, border inspections, and pest eradication programs in foreign countries—could be implemented both before and after the species has been discovered in the country, but involve distinct resource allocation decisions depending on the information that is available. On the other hand, control measures—such as restrictions on domestic movement of commodities, seizure and destruction of infested or infected commodities, and biological control measures—are applicable only after a pest is known to be present in the country.

The model is used to derive economic properties of the optimal allocation of resources between the different possible sets of preventive and control measures.[3] Our conceptual analysis reveals that it is economically efficient to spend a larger share of outlays for exclusion activities before, rather than after, a species is first discovered, up to a threshold point. This threshold is the point where the marginal net benefits (avoided damages) from expenditures on pre-invasion exclusionary measures no longer exceed the net benefits of expenditures after the first discovery. We also find that, after discovery, exclusionary measures and control measures are competitive, and the marginal costs of the exclusionary measures after the first discovery decline as the size of the pest population increases.

In the spirit of Eiswerth and Johnson (2002) and Olson and Roy (2002, 2005), we also evaluate how the optimal management strategy varies with different characteristics of an invasive species. Our comparative dynamic analysis indicates that the economic benefits resulting from the im-

[2] A species has "arrived" when it is present in either natural or agricultural ecosystems. Arrival can occur through natural or human assisted migration, escape, or intentional introduction. A species is considered "established" when it attains a self-sustaining population.

[3] Given the prominent role of international trade in biological invasions, another set of questions involves the optimal trade policy to address invasive pests (see Costello and McAusland 2003, James and Anderson 1998). In this paper, we consider only optimal resource allocation for invasive species management.

plementation of the preventive and control measures decrease with the level of the invasive species stock and increase with the intrinsic population growth rate and the rate of additional discoveries avoided. Furthermore, the optimal budget allocation for preventive measures increases with the maximum possible size of the infestation.

The Model

We model a regulator's choice between different activities aimed at avoiding or mitigating damages from an invasive species. Uncertainty enters our framework with respect to the timing of the discovery of a species.[4] Uncertainty in previous studies is associated with the timing of the arrival of species (Ranjan, Marshall, and Shortle 2003, Shogren 2000). We distinguish the concepts of "arrival" and "establishment" from the notion of "discovery," the point at which the relevant regulatory authority becomes aware that a species has reached the country. Specifically, we assume that after an alien pest first arrives in the country, there is a period in which it multiplies, disperses, and perhaps becomes established without the policymaker being aware of it. The concept of discovery is important because while a species may be present and spreading, if it is not known to have arrived, policies will focus only on prevention, and control measures will not be undertaken. For instance, by the time that soybean aphid (*Aphis glycines*) was first officially confirmed in the United States in 2000, the species was already established across the Corn Belt and Lake States (North Central Soybean Research Program 2004).

Let $F(t)$ be the probability that discovery of an invasive pest has occurred by time t with $F(t = 0) = 0$. The conditional probability of discovery at time t, $h(t)$, often called the hazard rate, is the probability that discovery will occur during the next Δt time unit, given that discovery has not occurred at time t (see Cox 1972, Kiefer 1988, Rose and Joskow 1990). Following Kamien and Schwartz (1971), we incorporate a hazard function into an optimal control framework.

[4] The concept of an uncertain discovery or terminal date was first explored by Yaari (1965), followed by Kamien and Schwartz (1971), Dasgupta and Heal (1974), and Blanchard (1985).

For simplicity, we treat discovery essentially as a function of the arrival time and do not consider possible policies such as investments in searches and monitoring that could alter the speed of discovery once an alien pest has arrived. Hence, "discovery" in our model can be thought of as referring to "arrival" but with a fixed time lag during which the species population can grow. We assume that the arrival time of an alien species is stochastic but that the likelihood of arrival (and subsequent discovery) can be reduced by the implementation of preventive activities. Our hazard function is expressed as follows:

$$(1) \qquad h(E_b(t)) = \frac{(\partial F(t)/\partial t)}{1 - F(t)}, \quad h(E_b(t=0)) = 0,$$

$$\frac{\partial h(E_b(t))}{\partial E_b} < 0, \quad \frac{\partial h^2(E_b(t))}{\partial^2 E_b} >=< 0,$$

where $\partial F(t)/\partial t = f(t)$ is the probability density function, and $E_b(t)$ represents exclusionary (preventive) measures before the first discovery of invasive species. The hazard rate of discovery is assumed to decline as exclusionary (preventive) measures increase. Equation (1) can be rewritten as a state equation as follows:

$$(1') \qquad \frac{\partial F(t)}{\partial t} = h(E_b(t))[1 - F(t)].$$

Before discovery, an alien pest is not yet known to have arrived, so management efforts are limited to exclusion (preventive) measures to keep it out of the country—that is, to reduce the hazard rate in equation (1). After a species is known to have arrived, the regulator can implement control measures to reduce the domestic population and take exclusionary measures to reduce the incidence of subsequent arrivals. Following Eiswerth and Johnson (2002), Huffaker and Cooper (1995), and Vargas and Ramadan (2000), we use a modified logistic growth function for the pest population. The pest population grows due to intrinsic growth of the species population in the country and also due to additional arrivals, where both sources of growth are affected by management efforts. At discovery, the change in the pest population is[5]

$$(2)\quad \frac{\partial z(t)}{\partial t} = g(Q)[z(t) - F(t)k(E_a(t))] \{1-(1/V)[z(t) - F(t)k(E_a(t))]\},$$

$$\frac{\partial g}{\partial Q} < 0\,,\ \frac{\partial k}{\partial E_a} > 0\,,$$

where $z(t)$ is the pest population in time t; Q is control effort; $g(Q)$ is the species' intrinsic growth rate; E_a represents exclusionary measures after the first discovery of the invasive species; $k(E_a)$ indicates the extent to which subsequent discoveries are avoided (or entrants are eliminated) after the first discovery, with $\partial^2 z(t)/\partial k \partial t < 0$, where $z(t) < F(t)k(E_a) + 0.5V$ and $\partial k/\partial E_a > 0$ so that more additional discoveries are avoided with greater exclusionary effort; and V is the maximum possible pest population. The intrinsic growth rate is assumed to be reduced by the control measures such as genetic modification and pesticide application in case of plant diseases and quarantine for animal diseases to reduce contacts. After discovery, the pest population in the country can thus be reduced through control activities, which reduce the intrinsic growth rate, and/or exclusionary measures, which reduce the rate of additional discoveries.

We assume that both the species' intrinsic growth rate g and the exclusion rate k are known with certainty by the policymaker. However, the additional discovery time is stochastic. Assuming known rates for intrinsic growth and the exclusion rate does not impose restrictions on our model. Specifically, one can think of these rates as fixed for given levels of relevant biological, environmental, and economic conditions. When one or more of these variables change, then g and/or k may also change.

The economic damage (loss in benefits), $-D(z)$, resulting from an invasive species is specified as

[5] An increase in the term $F(t)k(E_a)$ reduces the rate of species population growth. A reviewer correctly pointed out that there will be one response in the species population conditional on discovery and another on non-discovery. However, the resulting decision tree will be too complicated for modeling purposes. Equation (2) provides an approximation.

$$(3)\quad -D(z) = [PS_b(Y(z)) + CS_b(Y(z))] - [PS_a(Y(z)) + CS_a(Y(z))],$$

where PS and CS represent producer surplus and consumer surplus, respectively, Y is commodity output, and subscripts b and a indicate "before" and "after" discovery of an invasive species, respectively. Given the goal of maximizing the present value of expected net economic benefits associated with preventive measures before discovery and with exclusion and control measures after discovery, the objective function facing policymakers is the following:

$$(4)\quad \text{Max } L = \int_0^\infty e^{-rt} \begin{Bmatrix} [1-F(t)][PS_b(Y(z)) \\ +CS_b(Y(z)) - C_b(E_b)] \\ +F(t)[PS_a(Y(z)) \\ +CS_a(Y(z)) - C_a(E_a,Q)] \end{Bmatrix} dt,$$

subject to equations (1′) and (2), where $C_b(E_b)$ is the total cost of the policies (just exclusionary measures) before discovery and $C_a(E_a,Q)$ is the total cost of policies after discovery, including both exclusionary measures and control activities.

Most models presented in earlier studies on invasive pest management are a subset of the objective function in equation (4). When the probability of invasive species discovery (F) equals zero, the objective function (4) reflects only the exclusionary (preventive) measures before the discovery of invasive species as in Horan et al. (2002). When the probability of discovery equals one, the objective function includes the control measures as well as the exclusionary measures after the discovery of the invasive species, similar to the analysis by Olson and Roy (2002).

The Hamiltonian equation is

$$(5)\quad H = e^{-rt} \begin{Bmatrix} [1-F(t)][PS_b(Y(z)) + CS_b(Y(z)) - C_b(E_b)] \\ +F(t)[PS_a(Y(z)) + CS_a(Y(z)) - C_a(E_a,Q)] \end{Bmatrix} + \lambda_1 h(E_b)[1-F(t)] + \lambda_2 g(Q)[z(t) - F(t)k(E_a)] \{1-(1/V)[z(t) - F(t)k(E_a)]\},$$

where E_b, Q, and E_a are control variables, F and z are state variables, and λ_1 and λ_2 are costate (adjoint) variables associated with state variables $F(t)$ and $z(t)$, respectively. The variable λ_1 thus measures the marginal effects of the probability of discovery on the objective function, while λ_2 measures the marginal effects of the stock of an invasive species on the objective function. The necessary conditions for optimality are

$$(6)\quad \frac{\partial H}{\partial E_b} = -e^{-rt}(1-F)\frac{\partial C_b}{\partial E_b} + \lambda_1(1-F)\frac{\partial h}{\partial E_b} = 0\,,$$

$$(7)\quad \frac{\partial H}{\partial Q} = -e^{-rt}F\frac{\partial C_a}{\partial Q} + \frac{\lambda_2}{V}(z-Fk)\left[1-\frac{1}{V}(z-Fk)\right]\frac{\partial g}{\partial Q} = 0,$$

$$(8)\quad \frac{\partial H}{\partial E_a} = -e^{-rt}F\frac{\partial C_a}{\partial E_a} - \lambda_2 Fg\left[1-\frac{2}{V}(z-Fk)\right]\frac{\partial k}{\partial E_a} = 0,$$

where $z(t) < 0.5V + Fk$,

$$(9)\quad \frac{\partial \lambda_1}{\partial t} = -e^{-rt}[D + C_b - C_a] + \lambda_1 h + \lambda_2 gk\left[1-\frac{2}{V}(z-Fk)\right],$$

$$(10)\quad \frac{\partial \lambda_2}{\partial t} = -e^{-rt}F\frac{\partial D}{\partial z} - \lambda_2 g\left[1-\frac{2}{V}(z-Fk)\right],$$

$$(11)\quad \frac{\partial H}{\partial \lambda_1} = h(1-F) = \frac{\partial F}{\partial t}\,,$$

$$(12)\quad \frac{\partial H}{\partial \lambda_2} = g(z-Fk)\left[1-\frac{1}{V}(z-Fk)\right] = \frac{\partial z}{\partial t}\,,$$

and

$$(13)\quad \lim_{t\to\infty}\lambda_1 = 0\,,\ \lim_{t\to\infty}\lambda_2 = 0\,,\ \lim_{t\to\infty}\lambda_1 F = 0\,,\ \lim_{t\to\infty}\lambda_2 z = 0$$

(arguments of each variable omitted hereafter).

The optimality condition (6) indicates that the marginal costs of preventive measures before the first discovery equal the marginal benefits from the reduction in the hazard rate due to these measures. The marginal benefits from a delay in the expected discovery date of the species include the avoided damages as well as the avoided costs of the additional exclusionary and control measures that would have been undertaken after discovery of the species. Equation (7) indicates that at the optimum the marginal costs of control measures equal the marginal benefits resulting from the reduction of the species' intrinsic growth rate. A positive level of control effort could be optimal even if this would fall short of achieving complete eradication. Similarly, the optimality condition in equation (8) requires that the marginal costs of exclusionary measures after the first discovery equal the marginal benefits from the resulting increase in the rate at which additional discoveries are avoided.

It should be noted that an optimal policy after the first discovery will include both the exclusionary measures and the control measures if $z(t) < 0.5V + Fk$, as shown in equations (7) and (8). As the pest population increases so that $z(t) > 0.5V + Fk$, the model allows only control measures to be implemented.

Optimal Budget Allocation

Management Efforts Before Versus After the First Arrival

To evaluate the economically efficient allocation of resources for preventive measures before the first discovery relative to exclusionary and control measures after the discovery, we derive the user costs λ_1 and λ_2 from equations (6) and (7), respectively:

$$(14)\quad \lambda_1 = \frac{e^{-rt}(\partial C_b/\partial E_b)}{\partial h/\partial E_b}\,,$$

$$(15)\quad \lambda_2 = \frac{e^{-rt}F(\partial C_a/\partial Q)}{(z-Fk)\left[1-(1/V)(z-Fk)\right](\partial g/\partial Q)}\,,$$

where $\lambda_1 < 0$ and $\lambda_2 < 0$.

Inserting λ_1 and λ_2 in (14) and (15) into equations (9) and (10), respectively, we obtain

$$(16)\quad \frac{\partial \lambda_1}{\partial t} = -e^{-rt}[D(z) + (1-w^b_{hE_b})C_b - (1-w^a_{kQ})C_a]\,,$$

(17) $$\frac{\partial \lambda_2}{\partial t} = -e^{-rt}\left[F\frac{\partial D}{\partial z} - w^a_{kQ}\right],$$

where $D(z) < 0$ is as defined in equation (3),

$$w^b_{hE_b} = \frac{(\partial C_b/\partial E_b)(E_b/C_b)}{(\partial h/\partial E_b)(E_b/h)},$$

and

$$w^a_{kQ} = \frac{\partial C_a}{\partial Q}\frac{Q}{C_a}\left[\frac{(\partial z'/\partial k)(k/z')}{(\partial z'/\partial Q)(Q/z')}\right],$$

with $z' = \partial z/\partial t$ in equation (2).

Equation (16) indicates that, under the optimal allocation of resources, the rate of change of λ_1, the shadow costs of changing the probability of discovery, equals the present value of the aggregate costs of managing the invasive species, where the costs are weighted in a particular manner. The costs of preventive measures before the first discovery are weighted according to the ratio between the cost elasticity of preventive measures and the hazard rate elasticity of the preventive measures. The costs after the discovery are weighted according to the cost elasticity of control measures and the ratio of the growth rate elasticities of control and exclusionary measures.

Similarly, from equation (17), the rate of change of λ_2, the shadow costs of changing the species population known to be present in the country, must equal the present value of the expected marginal damages less the cost elasticity of adopting control measures adjusted by the ratio between the growth rate elasticity of control and exclusionary measures. These conditions indicate that the slope of $\lambda_1(t)$ is always greater than or equal to the slope of $\lambda_2(t)$ where the equality holds when time approaches infinity to satisfy the transversality condition in equation (13) (Figure 1).

The costate variable λ_1 reflects the instantaneous benefits of adopting the preventive measures before the first discovery of an invasive species. Similarly, the costate variable λ_2 represents the instantaneous expected benefits of adopting control measures after the discovery of an invasive species. λ_1 is greater than λ_2 in absolute value because the benefits of preventing discovery include the avoided costs of controlling the species once it is known to be in the country. Thus, the benefits from a marginal decrease in the probability of discovery must rise at least as fast as the marginal benefits of post-discovery control efforts.

These findings imply that as long as the species is expected to be sufficiently harmful to merit expenditures to keep it out of the country, it is economically efficient to allocate a larger (or equal) share of public expenditures for preventive measures before the first discovery than for exclusionary and control measures after this discovery. If the marginal costs of preventive measures are prohibitively high, however, then it makes sense to wait for the species to be discovered and to allocate all resources to control efforts.

Rewriting equation (16) at a steady state yields an expression for the damages due to the invasive species:

(18) $$-D(z) = (1 - w^b_{hE_b})C_b + (w^a_{kQ} - 1)C_a,$$

where $w^b_{hE_b} < 0$ and $w^a_{kQ} > 0$. Under the optimal policy, the marginal reductions in damages due to expenditures before and after the first discovery, respectively, are

(19a) $$\frac{\partial(-D)}{\partial C_b} = (1 - w^b_{hE_b}),$$

(19b) $$\frac{\partial(-D)}{\partial C_a} = (w^a_{kQ} - 1),$$

where $w^a_{kQ} > 1$. Expenditures should be allocated only if they result in a reduction in damages. Thus,

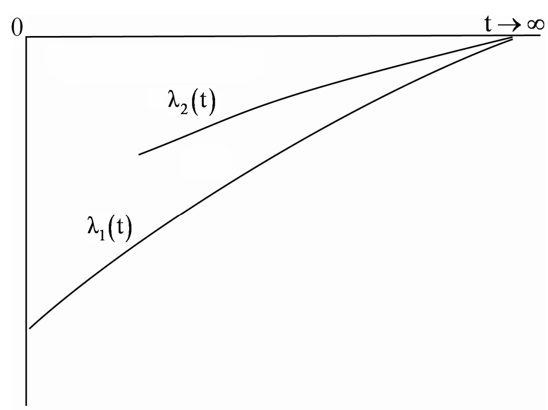

Figure 1. The Costate Variables λ_1 and λ_2

equations (19a) and (19b) indicate that it is economically efficient to allocate resources before the first discovery if $w_{kQ}^{a} > [2+|w_{hE_b}^{b}|]$. This provides a threshold for the use of preventive measures. Up until the point that $w_{kQ}^{a} = [2+|w_{hE_b}^{b}|]$, the optimal policy is to spend at least as much before rather than after the first discovery. If $w_{kQ}^{a} < [2+|w_{hE_b}^{b}|]$, it is optimal to wait and allocate at least as many resources after rather than before the first discovery.

Exclusionary Versus Control Measures After the First Discovery

The limited resources, $C_a(Q,E_a)$, after the first discovery of an invasive species must be allocated between control and exclusionary measures. For a given expenditure at year t, the changes in the costs of the control and exclusionary measures after the first discovery are as follows:

$$(20) \qquad dC_a(Q,E_a) = \frac{\partial C_a}{\partial Q}dQ + \frac{\partial C_a}{\partial E_a}dE_a = 0\,,$$

or

$$(21) \qquad \frac{dQ}{dE_a} = -\frac{\partial C_a/\partial E_a}{\partial C_a/\partial Q}\,,$$

where $z < 0.5V + Fk$.

The marginal costs of the control and exclusionary measures are obtained from the first-order conditions in equations (7) and (8) as follows:

$$(22) \quad \frac{\partial C_a}{\partial Q} = \frac{\lambda_2(z-Fk)[1-(1/V)(z-Fk)](\partial g/\partial Q)}{e^{-rt}F}\,,$$

$$(23) \quad \frac{\partial C_a}{\partial E_a} = \frac{-\lambda_2 Fg[1-(2/V)(z-Fk)](\partial k/\partial E_a)}{e^{-rt}F}\,,$$

where $z < 0.5V + Fk$. Equation (22) states that the present value of the expected marginal costs of the control measures must equal the marginal shadow costs of the control measures. Similarly, equation (23) states that the present value of the expected marginal cost of the exclusionary measures after the first discovery must equal the marginal shadow costs of the exclusionary measures. Equation (23) reveals that the marginal cost of the exclusionary measures after discovery is positive if the population of the invasive species is less than $F(t)k+0.5V$ and is zero when the population level is equal to $F(t)k+0.5V$. This indicates that the marginal cost of the exclusionary measures declines as the population of invasive species increases. The assumption is that exclusionary measures will be more effective when there are more potential entrants to exclude and that this situation will coincide with a high species population in the country. Another interpretation is that additional discoveries, which increase the domestic population, also provide information and experience to the regulator that increase the effectiveness of exclusionary measures.

This result indicates that it is economically efficient to allocate limited management resources more for the exclusionary measures than the control measures, as the population of the species increases up to $z(t) < F(t)k + 0.5V$, when the marginal costs of these measures decline as the population grows. Olson and Roy (2002) similarly found that when the marginal cost declines sharply with the size of invasion, it may be optimal to allow an invasion to grow naturally before it is controlled.

Inserting equations (22) and (23) into equation (21) results in the following:

$$(24) \quad \frac{dQ}{dE_a} = \frac{Fg[1-(2/V)(z-Fk)](\partial k/\partial E_a)}{(z-Fk)[1-(1/V)(z-Fk)](\partial g/\partial Q)}\,,$$

where $dQ/dE_a < 0$ if $Fk < z(t) < Fk + 0.5V$. Equation (24) indicates that the exclusionary and control measures after the first discovery compete for resources when the population of an invasive species is less than $Fk + 0.5V$. As expenditures for exclusionary activities increase, expenditures for control measures decrease, and vice versa. When the population level of an invasive species is small, both the control measures and the exclusionary measures are adopted after the first discovery. As the population grows, additional resources are allocated to exclusionary activities as the marginal costs of these measures decline.[6]

In most cases, the economically efficient policies will involve maintaining a positive level of the invasive species population after the time of

[6] As shown by equation (8), however, exclusionary measures are not permitted in the model structure once the population reaches a critical level of $Fk + 0.5V$.

discovery. If the policy objective is to completely eradicate the species population, exclusionary and control measures must be adopted so that

$$\text{(25)} \qquad \left| \int_0^T \left\{ \frac{\partial^2 z}{\partial E_a \partial t} dE_a + \frac{\partial^2 z}{\partial Q \partial t} dQ \right\} dt \right| \approx z(T),$$

where $(\partial^2 z/\partial E_a \partial t)dE_a < 0$ and $(\partial^2 z/\partial Q\partial t)dQ < 0$. The adoption rates of both exclusion and control measures in equation (25) will usually differ from those presented in equation (24). In equation (25), the policy goal is to reduce the population of invasive species to zero rather than to maximize net social economic benefits.

Comparative Dynamic Analyses

The optimal policy guided by conditions in equations (6) through (12) requires that the marginal benefits resulting from the adoption of preventive measures, exclusionary measures, or control measures increase at the rate of time preference until the marginal benefits resulting from the adoption of policy measures have increased sufficiently to cover their marginal costs. Further insights into the properties of the optimal budget allocation policy are gained through comparative dynamic analyses concerning the effect of an exogenous change in the characteristics of invasive species on the preventive measure E_b before the first discovery of an invasive species, as well as the control measure Q and the exclusionary measures E_a after discovery.

Without well-specified functional forms for E_b, Q, and E_a, the effects of the changing characteristics of the invasive species on these variables are not identifiable. However, we can conduct a comparative dynamic analysis of costate variables λ_1 and λ_2. We examine the impact of changing four variables reflecting characteristics of the invasive species that have important implications for the design of economically efficient invasive pest policies:[7] z, g, k, and V. The costate variable λ_1 measures the marginal contribution of the state variable $F(t)$ to the objective function. Similarly, the costate variable λ_2 represents the marginal contribution of the state variable $z(t)$ to the objective function. Therefore, the costate variables λ_1 and λ_2 represent, respectively, the shadow costs of an increase in the probability of discovery and of an increase in the population of a species that is already known to be present.

Assuming that discovery of the invasive pest occurs at time $t = T$, equations (6) and (7) yield

$$\text{(26)} \qquad \lambda_1(1-F)\frac{\partial h}{\partial E_b} - \lambda_2\left(z - Fk\right)\left(1-W\right)\frac{\partial g}{\partial Q} = e^{-rT}\left(1-F\right)\frac{\partial C_b}{\partial E_b} - e^{-rT}F\frac{\partial C_a}{\partial Q},$$

where $W = (1/V)(z - Fk)$. Similarly, equations (6) and (8) yield

$$\text{(27)} \qquad \lambda_1\left(1-F\right)\frac{\partial h}{\partial E_b} + \lambda_2 Fg\left(1-2W\right)\frac{\partial k}{\partial E_a} = e^{-rT}\left(1-F\right)\frac{\partial C_b}{\partial E_b} - e^{-rT}F\frac{\partial C_a}{\partial E_a}.$$

Total differentiation of equations (26) and (27) yields the following:

$$\text{(28)} \qquad \begin{pmatrix} (1-F)\dfrac{\partial h}{\partial E_b} & -VW(1-W)\dfrac{\partial g}{\partial Q} \\ (1-F)\dfrac{\partial h}{\partial E_b} & Fg(1-2W)\dfrac{\partial k}{\partial E_a} \end{pmatrix} \begin{pmatrix} d\lambda_1 \\ d\lambda_2 \end{pmatrix} = \begin{pmatrix} a11 & a12 & a13 & a14 \\ a21 & a22 & a23 & a24 \end{pmatrix} \begin{pmatrix} dk \\ dg \\ dV \\ dz \end{pmatrix},$$

where

$a11 = -F\lambda_2(1-2W)\partial g/\partial Q$,

$a12 = 0$,

$a13 = \lambda_2 W^2(\partial g/\partial Q)$,

$a14 = \lambda_2(1-2W)\partial g/\partial Q$,

$a21 = (1/V)(-2\lambda_2 F^2 g)\partial k/\partial E_a$,

$a22 = -\lambda_2 F(1-2W)\partial k/\partial E_a$,

[7] A state variable $z(t)$, the rate of subsequent discovery avoided, $k(E_a)$, and the intrinsic growth rate, $g(Q)$ are assumed to be constant at $t = T$.

$$a23 = -(1/V)(2\lambda_2 FgW)\partial k/\partial E_a,$$

$$a24 = (1/V)(2\lambda_2 Fg)\partial k/\partial E_a.$$

Equation (28) can be rewritten more compactly as follows:

$$(29)\begin{pmatrix} d\lambda_1 \\ d\lambda_2 \end{pmatrix} = N^{-1}\begin{pmatrix} A11 & \mathrm{A12} & \mathrm{A13} & \mathrm{A14} \\ A21 & \mathrm{A22} & \mathrm{A23} & \mathrm{A24} \end{pmatrix}\begin{pmatrix} dk \\ dg \\ dV \\ dz \end{pmatrix},$$

where

$$N = (1-F)\frac{\partial h}{\partial E_b}\left[Fg(1-2W)\frac{\partial k}{\partial E_a} + (z - Fk)(1-W)\frac{\partial g}{\partial Q}\right]$$
$$= (1-F)(z-Fk)(1-W)\frac{\partial h}{\partial E_b}\frac{\partial g}{\partial Q}\left(1 + \frac{dQ}{dE_a}\right) > 0,$$

and where $|dQ/dE_a| < 1$, which is positive, and the remaining elements are as defined in the Appendix.

The comparative dynamic results following from equation (29) are listed below. Only equation (31c) has an ambiguous sign.[8]

(30a) $\partial\lambda_1/\partial k < 0,$

(30b) $\partial\lambda_1/\partial g < 0,$

(30c) $\partial\lambda_1/\partial V < 0,$

(30d) $\partial\lambda_1/\partial z > 0,$

(31a) $\partial\lambda_2/\partial k < 0,$

(31b) $\partial\lambda_2/\partial g < 0,$

(31c) $\partial\lambda_2/\partial V >=< 0,$

(31d) $\partial\lambda_2/\partial z > 0,$

where $\lambda_1 < 0$ and $\lambda_2 < 0$, as shown in equations (14) and (15), respectively.

Equations (30a) through (30d), respectively, describe how the shadow costs of changing the probability of discovery evolve with changes in the subsequent discovery avoided, the intrinsic growth rate, the maximum possible pest population, and the population of the invasive species. Similarly, equations (31a) through (31d) describe how the shadow costs of the stock size of an invasive species change as the characteristics of the invasive species change.

The objective function of our model [equation (4)] represents the weighted average of the net social benefits associated with the invasive species management, where a greater weight is assigned to the net social benefits before, rather than after, the first discovery of an invasive species. Increases in the rates of the subsequent discovery avoided, the intrinsic growth rate, and the maximum possible pest population would induce greater adoption of exclusionary and control measures to reduce the social economic damages caused by invasive species. This response, in turn, increases (makes more negative) the shadow costs of both the probability of discovery and the stock size of invasive species. However, once invasive species are actually discovered, increases in the population of invasive species increase the overall costs associated with exclusion and control, reducing (making less negative) the shadow costs of the probability of discovery and the stock size of invasive species.

Equations (30a) and (31a) state that increasing the extent to which discoveries of invasive species are avoided after the first discovery increases (makes more negative) the shadow costs by reducing the marginal costs of the exclusionary measures so that more preventive and exclusionary measures are implemented. Similarly, equations (30b) and (31b) indicate that increasing the rate of intrinsic growth increases (makes more negative) the shadow costs by reducing the marginal costs of the control measures so that more preventive and control measures are implemented. Olson and Roy (2005) similarly found that each unit of control yields a greater reduction in expected marginal damages when the invasion growth rate is higher.

Equation (30c) simply shows that as the maximum potential for pest infestation increases, the shadow costs of the probability of discovery of the invasive species increase (becomes more negative), making it economically efficient to allocate additional resources to preventive measures be-

[8] Eisworth and Johnson (2002) conducted a comparative dynamic analysis using a modified logistic growth function for an invasive species, similar to our growth function in equation (2). They evaluate the effects of the invader's intrinsic growth rate, carrying capacity, and stock level on the optimal level of control measures, but find their results inconclusive in sign.

fore the first discovery. Finally, in equations (30d) and (31d), $\lambda_i(t)$ declines (becomes less negative) with an increase in the known population size of the species after discovery. An increase in the known population of the invasive species decreases net economic benefits, including increasing costs of prevention and control measures. This reduces (makes less negative) the shadow costs of the probability of discovery and of the known population of the invasive species.

These results have several implications for invasive species management policies. First, it is more efficient to increase preventive measures before the first discovery and control and the exclusionary measures after the first discovery, when the intrinsic growth rate and the rate of subsequent discoveries avoided rise. However, it is economically efficient to reduce the implementation of preventive measures before the first discovery and the exclusionary measures and the control measures after the first discovery, as the population of the invasive species increases. (The model structure, however, does not allow exclusion measures once the population reaches $F + 0.5V$.) Finally, the shadow costs of the probability of discovery of invasive species increase (become more negative) as the maximum capacity of infestation increases, so it is more economically efficient to increase the adoption of the preventive measures.

Conclusions

We have presented a conceptual model for managing resources for the exclusion and control of invasive pest species with an uncertain discovery date. In our model, exclusion measures can be implemented at any time while control measures are implemented only after a species has been found in the environment. Exclusionary measures before and after a species is discovered to be present are thus distinct economic decisions, as are exclusion and control measures after the initial discovery. Compared to previous studies, this formulation allows for a more comprehensive analysis of the policy options available before and after discovery of a species.

We assume that subsequent species discovery occurs stochastically. The rate of subsequent discovery avoided, however, can be increased by adopting exclusionary measures. For any given application, we assume that the species' intrinsic growth rate, the rate of subsequent discoveries avoided, and the maximum capacity of infestation are known. A comparative dynamic analysis illustrates how knowledge of these rates, as well as how they are affected by relevant biological, environmental, and economic conditions, can significantly extend the applicability of our model.

The optimal conditions reveal that it is economically efficient to spend a larger share of outlays for management activities before a species is known to have arrived rather than after it has been discovered, up to a threshold point based on the cost-effectiveness of these activities. This is in contrast to the typical pattern of escalating prevention and control policy actions once an outbreak, such as foot-and-mouth or mad cow disease, has been detected. We also show that outlays are most efficient when allocated such that the marginal costs of control measures equal the benefits from the marginal reduction of intrinsic growth rate, and the marginal costs of exclusion measures equal the benefits from the marginal increase in the rate of subsequent discoveries avoided.

Our study indicates that the control measures and the exclusionary measures after the first discovery of an invasive species compete with each other for a share of the total post-discovery measures. The marginal costs of the exclusionary measures decline as the population of invasive species increases. Consequently, it is economically efficient to allocate a larger share of outlays for exclusion, rather than control, as the population increases—up to a threshold point, after which no further exclusionary measures can be implemented.

Results from the comparative dynamic analysis have policy implications. Our analysis suggests that as the level of invasive species stock increases, its shadow costs decline (become less negative), reducing the efficient level of expenditures on exclusion and control activities. As the rate of subsequent discoveries avoided and the rate of intrinsic growth increase, their shadow costs increase (become more negative) and it becomes more efficient to allocate outlays for the preventive measures and the control and exclusionary measures. Similarly, as the maximum capacity of infestation increases, the shadow costs of the probability of discovery of invasive species increase (become more negative), so it is more efficient to spend more outlays for the prevention measures before the first discovery of invasive species. These relationships, along with knowledge of how economic activities, biological factors, and environmental conditions affect z, g, k, and V for different species, can suggest where to focus limited exclusion and control resources.

Conceptual frameworks are important for developing policies to address invasive pests. While there is an increasing need to respond to invasive pests, empirical analyses of invasive pests are often hampered by a lack of data—especially for cases where the pest is not yet present—or a lack of generally applicable protocols. That is, many problems related to invasive pests and their possible remedies are very case-specific. Our conceptual model can help to guide analyses of invasive pests (and invasive species generally) and help inform policies for prioritizing and addressing invasive pest problems that are economically efficient.

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APPENDIX

$$A11 = -\lambda_2 F^2 g(\partial g/\partial Q)(\partial k/\partial E_a)$$
$$[(1-2W)^2 + 2W(1-W)] < 0,$$

where $W = (1/V)(z - Fk)$,

$$A12 = -\lambda_2 F(z - Fk)(1-2W)(1-W)$$
$$(\partial g/\partial Q)(\partial k/\partial E_a) < 0,$$

$$A13 = \lambda_2 Fg(1-2W)W^2(\partial g/\partial Q)(\partial k/\partial E_a)$$
$$-2\lambda_2 FgW^2(1-W)(\partial g/\partial Q)(\partial k/\partial E_a)$$
$$= -\lambda_2 FgW^2(\partial g/\partial Q)(\partial k/\partial E_a) < 0,$$

$$A14 = \lambda_2 Fg(\partial g/\partial Q)(\partial k/\partial E_a)$$
$$[(1-2W)^2 + 2W(1-W)] > 0,$$

$$A21 = \lambda_2 F(1-F)(\partial h/\partial E_b)$$
$$[(1-2W)(\partial g/\partial Q) - (1/V)(2Fg)(\partial k/\partial E_a)] < 0,$$

$$A22 = -\lambda_2 F(1-F)(1-2W)$$
$$(\partial k/\partial E_a)(\partial h/\partial E_b) < 0,$$

$$A23 = -\lambda_2(1-F)W(\partial h/\partial E_b)$$
$$[W(\partial g/\partial Q) + (1/V)(2Fg)(\partial k/\partial E_a)] >=< 0,$$

$$A24 = -\lambda_2(1-F)(\partial h/\partial E_b)$$
$$[(1-2W)(\partial g/\partial Q) - (1/V)(2Fg)(\partial k/\partial E_a)] > 0.$$