Economics of Managing Invasive Pest Species: Exclusion and Control

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There has been a surge of interest in improving our understanding of - and our responses to - the economic threats invasive pest species pose to our food and fiber production systems.[1] Much of this interest has been driven by the recent outbreak of foot-and-mouth disease in the United Kingdom and the desire to avoid the economic costs that a similar type of outbreak could inflict on U.S. livestock producers and taxpayers.[2] A second motivation has been the sharp increase in spending by USDA's Animal and Plant Health Inspection Service (APHIS) on emergency programs to eradicate outbreaks of new invasive pests – particularly Karnal bunt, citrus canker, plum pox, and avian influenza. Between 1991 and 1995 expenditures on APHIS's emergency programs averaged about $10.4 million per year. Between 1999 and 2001, these expenditures averaged over $232 million per year.

Invasive pests can be grouped into those that are already present in the U.S. and those that have yet to arrive. [3] An important policy problem then is deciding how to allocate limited invasive species management resources between activities aimed at preventing the arrival of new pests (including additional arrivals of existing pests) and activities aimed at eliminating or reducing the damages done by species that are already here. In this paper we present a dynamic model for managing a generic invasive pest with an uncertain arrival date. We use the model to derive economic properties of the optimal allocation of resources between exclusionary and control measures. Our framework builds on studies by Shogren and by Kaiser and Roumasset.

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[1] By "invasive pest species" we mean non-native species that pose an actual, or a potential, economic threat to some set of crop and livestock producers.
[2] In 1999 and 2000, U.K. slaughtered over 4 million FMD infected cattle, sheep, and pigs. Another 2 million animals were slaughtered to reduce the economic burden on farmers related to restrictions on moving livestock off farms.
[3] By "arrive" we mean, known to exist in either natural or agricultural ecosystems. Arrival can occur through natural or human assisted migration, escape, or intentional introduction. Species that have "arrived" may or may not be

Shogren presents a bioeconomic model for analyzing the risks invasive species pose to the economy and the environment.[4] The problem of managing invasive species, however, combines exclusionary activities before establishment and control activities after establishment, as *ex-ante* measures. Shogren's model, however, cannot distinguish actions taken before and after establishment as distinct economic problems. Kaiser and Roumasset extend Shogren's framework by integrating exclusion and control measures in a potentially cyclical optimal control model for a comprehensive strategy to minimize the social costs associated with invasive species. These authors, however, assume that additional arrivals of a pest after establishment do not affect the total pest population or the magnitude of pest related damages.

Our framework distinguishes between pre- and post-arrival exclusion activities and between post-arrival exclusion and control activities. That is, exclusionary measures – such as trade restrictions, border inspections, and pest eradication programs in foreign countries – occur before and after arrival but are distinct resource allocation decisions. Control measures on the other hand – such as, restrictions on domestic movement of commodities, seizure and destruction of infested or infected commodities, and biological control measures – are only applicable after arrival. We assume that arrival occurs stochastically but the likelihood of arrival can be reduced by the implementation of exclusion activities. Hence, uncertainty enters our framework with respect to the timing of species arrival. Finally, we assume that both the species' population growth rate and the rate of additional – or subsequent - arrivals are known. We use the model to look at the allocation of a budget to control an invasive pest between exclusion and control

considered "established" – meaning having attained a self-sustaining population. For policy purposes, arrival and/or establishment may coincide with when we first become aware that a species poses a serious economic threat.

[4]The models developed by Shogren and by Kaiser and Roumasset consider pre- and post- establishment periods (see footnote 3). While suitable for many invasive pests, this delineation of time is needlessly vague with respect to species that are considered so dangerous that control measures are implemented

measures. More explicitly, we look at the budget allocation for exclusion measures in the periods before and after arrival, and, the budget allocation between control measures and exclusion measures in the period after arrival.

Before developing our model, we note that assuming known rates for population growth (denote this rate as g) and subsequent arrivals (denote this rate as *k*) imposes nothing in the way of restrictions on our model. Specifically, one can think of g and *k* fixed for given levels of relevant biological, environmental, and economic conditions. When one or more of these variables change, then so too may g and/or *k*. In fact, knowing how g and *k* are affected by economic, biological, and environmental factors significantly extends the applicability of our model.

The Model

Let F(t) be the probability that arrival of an invasive species has occurred by time t with $F(t=0) = 0$. The conditional probability of arrival at time t, h(t), which is often called the hazard rate, is the probability that arrival will occur during the next Δt time unit, given that arrival has not occurred at time t. Following Kamien and Schwartz, we incorporate a hazard function into an optimal control framework. Our hazard function is given by:

(1) $$h(t,Q|Z,x) = [\partial F(t)/\partial t] / [1 - F(t)], \quad h(0,Q|Z,x) = 0, \quad \partial h(t,Q|Z,x)/\partial Q < 0,$$

$$\partial^2 h(t,Q|Z,x)/ \partial Q^2 >=< 0,$$

where: $\partial F(t)/\partial t = f(t)$ is the probability density function, Q represents all exclusion measures, Z is the stock of invasive species, $\partial h(t,Q|Z,x)/\partial Z > 0$, and x represents all other variables.

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immediately upon discovery – and hopefully before establishment. Examples include medfly, screw worm, citrus canker, plum pox and foot and mouth disease.

Before arrival, exclusion measures aim to keep our representative pest species out – that is to reduce the hazard rate shown in equation 1. After arrival, exclusion measures aim to reduce or eliminate the incidence of subsequent arrivals. Following Huffaker and Cooper, and Vargas and Ramadan, the change in the pest population, after arrival is given by:

(2) $[\partial Z(t)/\partial t] = g(S)[1+ k(Q)]Z, \qquad (\partial g/\partial S) < 0; \quad (\partial k/\partial Q) < 0,$

where: Z is the pest population, S is control effort, and g and k are as defined above.

The economic objective is to minimize the present value of the expected social costs associated with exclusion and control measures. The dynamic optimization problem is stated as:

(3) $$\text{Max } L = -\int_0^\infty \exp(-rt)\,[(1\text{-}F(t))\,C_1(Q) + F(t)\,(C_2(Q,S) + D(Z))]\delta t,$$

subject to equations (1) and (2),

where: C represents the costs associated with exclusion and/or control measures, subscripts 1 and 2 represent, respectively, before and after arrival, and D is the damage function.

The Hamiltonian equation is given by:

(4) $$H= - e^{-rt}[(1\text{-}F(t))C_1(Q)+F(t)(C_2(Q,S)+D(Z))]+\lambda_1 h(t,Q|Z,x)[1-F(t)]+ \lambda_2\, g(S)[1+k(Q)]Z,$$

where: Q and S are control variables, F and Z are state variables, and λ_1 and λ_2 are costate variables.

The necessary conditions for optimality are:

(5) $$\partial H/\partial Q = - e^{-rt}\,[(1\text{-}F)\,(\partial C_1/\partial Q) + F\,(\partial C_2/\partial Q)] + \lambda_1(1-F(t))(\partial h/\partial Q) + \lambda_2\, g(S)Z(\partial k/\partial Q) = 0,$$

(6) $$\partial H/\partial S = - e^{-rt}\, F(\partial C_2/\partial S) + \lambda_2(1+k)Z(\partial g/\partial S) = 0,$$

(7) $$(\partial \lambda_1/\partial t) = h\lambda_1 - e^{-rt}\,[C_1 - C_2 - D(Z)],$$

(8) $(\partial\lambda_2/\partial t) = e^{-rt} F(\partial D/\partial Z) - g(1+k)\lambda_2$,

(9) $(\partial H/\partial\lambda_1) = h[1–F(t)] = \partial F/\partial t$,

(10) $(\partial H/\partial\lambda_2) = g(1 + k)Z = \partial Z/\partial t$,

(11) $\lim_{t\to\infty} \lambda_1 F(t) = 0$ and $\lim_{t\to\infty} \lambda_2 Z(t) = 0$.

To derive economic properties of the optimal solutions, the first-order differential equations in (7), (8) and (9) are solved and presented as follows:

(12) $\lambda_1 = e^{--rt} (C_1 - C_2 - D(Z)) / (r+h)$,

(13) $\lambda_2 = - e^{-rt} F(t)(\partial D/\partial Z) / [r- g(1+k)]$,

(14) $F(t) = 1 – \exp(-h(t,Q|Z,x))t$,

where: a constant associated with the derivation of equation (13) is assumed to be zero.

Inserting equations 12 and 13 into equation 5, and equation 13 into equation 6 results in, respectively, the following:

(15) $[(1-F) (\partial C_1/\partial Q) + F (\partial C_2/\partial Q)] = (1-F(t))[(C_1 - C_2 - D(Z))(\partial h/\partial Q)] / (r+h)$

$- F(t)[(\partial D/\partial Z)gZ(\partial k/\partial Q) / (r-g(1+k))]$.

(16) $(\partial C_2/\partial S) = - Z(1+k)(\partial g/\partial S))/(r- g(1+k))$.

Equations 15 and 16 have straightforward economic interpretations. Equation 15 states that the expected marginal costs of exclusion measures before and after the first arrival of an invasive species must equal the expected marginal economic benefits resulting from the reductions of the hazard rate and the rate of additional subsequent arrivals. Equation 16 states that the marginal costs of control measures must equal the marginal benefits resulting from the reduction of the species' population growth rate.

Optimal Budget Allocation: Exclusion vs. Control

To develop criteria for evaluating economically efficient budget allocations for exclusionary measures in the pre- and post-arrival periods, we insert equation 14 into equation 3 (the objective function) and integrate. The resulting function is represented by:

(17) $L = [(C_1 - C_2 - D(Z)) / (r+h)] + [(C_2 + D(Z)) / r]$.

The first term of the right-hand side of equation (17) represents the transient costs capitalized at the sum of the rate of time preference (r) and the hazard rate (h). The second term represents costs of both exclusion and control activities capitalized at the rate of time preference for the period after arrival. Equation 17 says that expenditures for invasive species management – that is for exclusion measures - are discounted at a higher rate before arrival (i.e., r+h) than for both exclusion and control measures after arrival (i.e., r). To investigate whether this has any implications for the allocation of invasive pest management resources, we return to equation 15 and separate it into two parts reflecting the periods before and after arrival and differentiate each part with respect to exclusion effort (i.e., Q). We get:

(18) $(\partial C_1/\partial Q) = (C_1 - C_2 - D(Z))(\partial h/\partial Q) / (r+h)$ for $0 \leq t < T$,

(19) $(\partial C_2/\partial Q) = - Z(\partial D/\partial Z)g(\partial k/\partial Q) / (r-g(1+k))$ for $T \leq t < \infty$,

where: T is the time of species initial arrival.

Equation 18 states that before arrival, the marginal costs of exclusion measures are capitalized at the sum of the rate of time preference and the hazard rates for the pre-arrival period. Equation 19 states that after arrival, the marginal costs of exclusion measures are capitalized at the rate of time preference, adjusted by the rate of population growth and the rate of additional subsequent arrivals (equation 19)). Hence, from the standpoint of minimizing the total cost of managing this invasive pest, resources for exclusion activities should put more emphasis on pushing the arrival date further into the future than on preventing additional arrivals once it is already here. For the post-arrival period, however, the optimal allocation of expenditures between exclusion and control measures depends on the relative magnitudes of the marginal impact of control measures on the species population growth rate (equation 16) and the marginal impact of exclusion measures on the rate of new arrivals (equation19).

Comparative Dynamic and Static Analyses

This section conducts a comparative dynamic analysis of λ_1 and λ_2 and a comparative static analysis on T with respect to changes in three variables with important implications for the design of economically efficient invasive pest policies – specifically *g*, *k*, and Z. Mathematically, the costate variable λ_1 measures the marginal contribution of the state variable F(t) to objective function. Similarly, the costate variable λ_2 represents the marginal contribution of the state variable Z(t) to the objective function. From an economic perspective then, these are the shadow costs of, respectively, an increase in the probability of arrival and an increase in the stock of a species that has already arrived. Assuming that arrival of the invasive pest occurs at time t=T, total differentiation of equations 2, 5, and 6 are represented by:

$$(20) \qquad \begin{pmatrix} (1-F)(\partial h/\partial Q) & gZ(\partial k/\partial Q) & re^{-rT}[(1-F)(\partial C_1/\partial Q)+F(\partial C_2/\partial Q)] \\ 0 & Z(1+k)(\partial g/\partial S) & re^{-rT}F(\partial C_2/\partial S) \\ 0 & 0 & (\partial Z/\partial T) \end{pmatrix} \begin{vmatrix} \delta\lambda_1 \\ \delta\lambda_2 \\ \delta T \end{vmatrix}$$

$$
= \begin{vmatrix} -\lambda_2 Z\,(\partial k/\partial Q) & 0 & -\lambda_2 g\,(\partial k/\partial Q) \\ 0 & -\lambda_2 Z\,(\partial g/\partial S) & -\lambda_2(1+k)(\partial g/\partial S) \\ -(\partial Z/\partial g) & -(\partial Z/\partial k) & 1 \end{vmatrix} \begin{vmatrix} \delta g \\ \delta k \\ \delta Z \end{vmatrix}
$$

Equation (20) can be rewritten more compactly as follow:

$$
(20) \quad \begin{vmatrix} \delta\lambda_1 \\ \delta\lambda_2 \\ \delta T \end{vmatrix} = M^{-1} \begin{vmatrix} A11 & A12 & A13 \\ A21 & A22 & A23 \\ A31 & A32 & A33 \end{vmatrix} \begin{vmatrix} \delta g \\ \delta k \\ \delta Z \end{vmatrix},
$$

where, $M = Z(1+k)(1-F)(\partial Z/\partial T)(\partial g/\partial S)(\partial h/\partial Q) < 0$,

$$A11 = -\lambda_2 Z^2(1+k)(\partial \mathbf{g}/\partial S)(\partial k/\partial Q)(\partial Z/\partial T) - re^{-rT}FgZ(\partial Z/\partial g)(\partial C_2/\partial S)(\partial k/\partial Q)$$

$$+ re^{-rT}Z(1+k)(\partial Z/\partial g)(\partial g/\partial S)[(1-F)(\partial C_1/\partial Q)+F(\partial C_2/\partial Q)],$$

$$A21 = re^{-rT}\,F(1-F)(\partial Z/\partial g)(\partial C_2/\partial S)(\partial h/\partial Q),$$

$$A31 = -Z\,(1-F)(1+k)(\partial Z/\partial g)(\partial g/\partial S)(\partial h/\partial Q),$$

$$A12 = \lambda_2 Z^2 g(\partial g/\partial S)(\partial k/\partial Q)(\partial Z/\partial T) - re^{-rT}FgZ(\partial Z/\partial k)(\partial C_2/\partial S)(\partial k/\partial Q)$$

$$+re^{-rT}Z(1+k)(\partial Z/\partial k)(\partial g/\partial S)[(1-F)(\partial C_1/\partial Q)+F(\partial C_2/\partial Q)],$$

$$A22 = -\lambda_2 Z(1-F)(\partial g/\partial S)(\partial Z/\partial T)(\partial h/\partial Q) + re^{-rT}F(1-F)(\partial Z/\partial k)(\partial h/\partial Q)(\partial C_2/\partial S)$$

$$= e^{-rT}F(1-F)(\partial h/\partial Q)\{r(\partial C_2/\partial S)(\partial Z/\partial k) + Z(\partial D/\partial Z)(\partial Z/\partial T)(\partial g/\partial S) / [r-g(1+k)]\},$$

$$A32 = -Z\,(1-F)(1+k)(\partial Z/\partial k)(\partial g/\partial S)\,(\partial h/\partial Q),$$

$A13 = re^{-rT} Fg Z(\partial k/\partial Q)(\partial C_2/\partial S) - re^{-rT} Z(1+k)(\partial g/\partial S)[(1-F)(\partial C_1/\partial Q)+F(\partial C_2/\partial Q)]$,

$A23 = - \lambda_2 (1+k)(1-F)(\partial Z/\partial T)(\partial g/\partial S)(\partial h/\partial Q) - re^{-rT}F(1-F)(\partial h/\partial Q)(\partial C_2/\partial S)$,

$= e^{-rT}F(1-F)(\partial h/\partial Q)\{(\partial D/\partial Z)(\partial g/\partial S)[(1+k)(\partial Z/\partial T) / (r-g(1+k)) - rZ]\}$,

$A33 = Z (1+k)(1-F)(\partial g/\partial S)(\partial h/\partial Q)$.

The comparative dynamic and comparative static results that follow from equation 20 are listed below. Each has an unambiguous sign except for λ_1.

(21) $\partial T/\partial Z = (1/M)Z (1-F)(1+k)(\partial g/\partial S)(\partial h/\partial Q) < 0$,

(22) $\partial T/\partial g = (1/M)\{-Z (1-F)(1+k)(\partial Z/\partial g)(\partial g/\partial S)(\partial h/\partial Q)\} > 0$,

(23) $\partial T/\partial k = (1/M)\{-Z (1-F)(1+k)(\partial Z/\partial k)(\partial g/\partial S) (\partial h/\partial Q)\} > 0$,

(24) $\partial \lambda_2/\partial g = (1/M)re^{-rT} F(1-F)(\partial Z/\partial g)(\partial C_2/\partial S)(\partial h/\partial Q) > 0$,

(25) $\partial \lambda_2/\partial k= (1/M)e^{-rT}F(1-F)(\partial h/\partial Q)\{r(\partial C_2/\partial S)(\partial Z/\partial k)$

$+ Z(\partial D/\partial Z)(\partial Z/\partial T)(\partial g/\partial S) / [r-g(1+k)]\} > 0$,

(26) $\partial \lambda_2 /\partial Z= (1/M)e^{-rT}F(1-F)(\partial h/\partial Q)\{(\partial D/\partial Z)(\partial g/\partial S)[(1+k)(\partial Z/\partial T) / (r-g(1+k)) - rZ]\} > 0$,

(27) $\partial \lambda_1/\partial g= (1/M)\{-\lambda_2 Z^2(1+k)(\partial g/\partial S)(\partial k/\partial Q)(\partial Z/\partial T) - re^{-rT}FgZ(\partial Z/\partial g)(\partial C_2/\partial S)(\partial k/\partial Q)$

$+ re^{-rT}Z(1+k)(\partial Z/\partial g)(\partial g/\partial S)[(1-F)(\partial C_1/\partial Q)+F(\partial C_2/\partial Q)]\} >=< 0$,

(28) $\partial \lambda_1/\partial k = (1/M)\{\lambda_2 Z^2 g(\partial g/\partial S)(\partial k/\partial Q)(\partial Z/\partial T) - re^{-rT}FgZ(\partial Z/\partial k)(\partial C_2/\partial S)(\partial k/\partial Q)$

$+ re^{-rT}Z(1+k)(\partial Z/\partial k)(\partial g/\partial S)[(1-F)(\partial C_1/\partial Q)+F(\partial C_2/\partial Q)]\} >=< 0$,

(29) $\partial \lambda_1 /\partial Z = (1/M)\{re^{-rT} FgZ(\partial k/\partial Q)(\partial C_2/\partial S)$

$- re^{-rT} Z(1+k)(\partial g/\partial S)[(1-F)(\partial C_1/\partial Q)+F(\partial C_2/\partial Q)]\}>=< 0$.

Equation (21) states that arrival time T moves closer to the present as the stock of an invasive pest species increases. This result follows from our population growth function (equation 2) but also makes sense biologically. That is, the probability of a pest arriving in our environment – and for that matter ultimately reaching a self-sustaining population - increases as the number individuals in the initial migration, escape, or introduction increases. Extending the logic to policy responses to invasive pests suggests relatively drastic measures may be justified when isolated occurrences of pests known particularly damaging are found but are not yet numerous enough to be considered established (e.g., screwworm or the prion that causes mad cow disease). Equations 22 and 23 state that the arrival date can be pushed further into the future by increasing measures that reduce either the population growth rate or the rate of new arrivals. Using these relationships along with knowledge of how economic activities, biological factors, environmental conditions affect g and k for different species can suggest where to focus exclusion and control resources.

Equations 24, 25, and 26 describe how the shadow cost of an increase in the stock - or population- of species that are already here changes with changes in, respectively, population growth rate, the rate of new arrivals, and the existing stock of the invasive pest. In each case, the shadow cost associated with an increase in the population rises with an increase in the variable in question (i.e., g, k, or Z). Again, using these relationships along with knowledge of how economic activities, biological factors, environmental conditions affect g, k, and Z for different species can suggest how to allocate exclusion and control resources.

Equations 27, 28, and 29 describe how the shadow cost of an increase in the probability of arrival in the next time period changes with changes in, respectively, population growth rate, the rate of subsequent arrivals, and the initial stock of the invasive pest. The signs of these expressions are all inconclusive, meaning it is not possible to generalize about how this shadow cost will move in response to changes in *g*, *k*, and Z. These could well be anticipated. The costate variable λ_1 measures the marginal contribution of the state variable F(t), which covers the period before arrival, while the characteristics of invasive species cover the period after arrival.

Conclusions

In this paper we have developed a conceptual model for managing resources allocated to the exclusion and control of invasive pest species. We assume that exclusion measures occur through time while control measures are only implemented after a species has been found in the environment. Hence, exclusionary measures before and after arrival are distinct economic decisions, as are exclusion and control measures after arrival.

We assume that arrival occurs stochastically but the probability of arrival is reduced by implementing exclusion activities. For any given application, we assume that both the species' population growth rate and the rate of subsequent arrivals are known. Using comparative dynamic analysis we show 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 generally economically more efficient to spend a larger share of outlays for exclusion activities before a species arrives than after it is known to be here. They also show that outlays should be allocated such that the marginal costs of control measures equal the benefits from the marginal reduction of the population growth rate, and the marginal costs of exclusion measures equal the benefits from the marginal reduction of the rate of subsequent arrivals.

From a policy standpoint, it is important to develop conceptual frameworks for thinking about invasive pests (and invasive species generally). First, as noted in the introduction, the incidence of invasive pest outbreaks and the costs of responding to them have both increased dramatically in the last few years. Hence the need to respond to these pests is increasing rapidly. Second, empirical analysis of invasive pest is often hampered by a lack of data – especially for cases where the pest is not yet present – or a lack of general applicability. That is, many problems related to invasive pests and their possible remedies are very case specific. Conceptual models like ours, then, can help to formalize the process of thinking about invasive pests (and invasive species generally) and help to ensure that policies for prioritizing and addressing invasive pest problems are consistent and make economic sense.

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