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Integrated Prevention and Control of Invasive Species

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Abstract: An emerging problem for environmental policy is how to design efficient strategies for the prevention and control of invasive species. However, the literature has mostly focused either on pre-introduction prevention or post-introduction control of an invasive. The benefits of prevention cannot be understood or estimated without knowing the costs of post-introduction control. This paper provides an integrated framework where optimal prevention is combined with optimal pest removal.

Keywords: Invasive species, pest control, optimal prevention

1. Introduction:

Forest resources, especially tropical forests, are at risk of invasion by exotic species, often of an irreversible nature. An emerging problem for environmental policy is how to design efficient strategies for the prevention and control of invasive species. However, most of the literature has focused either on pre-introduction prevention or post-introduction control (see e.g., Carter et al., 2004; Eiswerth and Johnson, 2002; Horan et al., 2002; Kaiser and Roumasset, 2004; Olson 2004; Olson and Roy, 2002; Settle and Shogren, 2002; Perrings and Dalmazzone, 2000). However, the benefits of prevention

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cannot be understood or estimated without knowing the costs of post-introduction control. In order to provide an integrated framework, we solve for optimal prevention in a model with optimal pest removal nested therein.

The problem of an invasive is the problem of a natural resource stock that is introduced in an area, grows, causes damage, and can be partially or wholly removed. It can be imperfectly prevented from entry by appropriate measures. If prevention fails and introduction occurs, the stock can be harvested according to an optimal control program that leads to a steady-state stock level. There may be a critical stock level, above which the stock cannot be appreciably altered by further introduction and, therefore, further prevention is not required.

Optimal management of such a stock would require one to choose an optimal path of control (harvest) to minimize the control costs and the damage from the invasive. Depending on the initial stock level, the cost of control, and the damages from the stock, the optimal path may entail doing nothing (zero control level) and letting the stock grow to its carrying capacity (or natural steady state), eradicating the stock completely (zero stock level), or achieving a steady state with a positive control and stock level. Minimized control and damage costs are obtained from this solution.

Once the control problem has been solved, it needs to be embedded in the optimal prevention problem. Optimal prevention minimizes the expected present value of prevention costs and the minimized control and damage costs determined in the control problem. If the steady-state stock is less than the critical level, then one also needs to take the possibility of further introductions into account.

This paper constructs a model of introduction of an invasive where the probability of introduction depends on prevention efforts or expenditures and uses the above framework to determine the optimal prevention and control strategies.

2. The Model

We first examine the control of an invasive that has already arrived. It can be wholly or partially removed or left alone. The objective of management is to minimize the costs of control and damage from the invasive. To this end, a social planner chooses the optimal harvest path leading to a steady-state population level, which may be zero or greater.

Next, we examine prevention before the introduction of the invasive. Prevention efforts are meant to reduce the probability of an introduction. The costs associated with the optimal control path are the costs resulting from prevention failure. The social planner chooses a prevention level to minimize the expected costs of prevention and prevention failure.

2.1. Optimal Control

When an invasive population is introduced, its stock causes damage and its removal incurs costs. Optimal removal would minimize the present value of damages and control costs. One important feature of invasive control is the search needed to find the invasive before it can be removed. Cost of the search usually depends on the invasive stock. The greater the size of the stock in a particular area, the easier it is to find it and

hence lower the search costs. Therefore, the control costs that include search cost, in addition to the actual cost of removal, depend on stock level at any time. This feature has been ignored in some studies that examine optimal invasive control but assume the control cost depends only on the amount of removal (see, e.g., Eiswerth and Johnson, 2002; Olson and Roy, 2002). Below we present a model in which control costs depend both on stock level and removal amount.

Suppose a certain population of an invasive (N_0) is introduced. Let N_t be the stock of the invasive at time t, g(N_t) be the growth rate of the stock, $D(N_t)$ be the resulting damage at time t, $C(N_t, x_t)$ be the cost of harvesting x_t from the stock, r be the discount rate. Then we maximize the present value of the benefits minus the costs of control and damage as follows:

$$\begin{aligned} &\underset{x_t}{\text{Min}} \quad \text{V}, \quad \text{where V} = \int_0^\infty e^{-rt}\left[D(N_t) + C(N_t, x_t)\right]dt \\ &\text{subject to:} \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{.....(1)} \\ &\dot{N}_t = g(N_t) - x_t, \quad N_0 \text{ given} \\ &0 \le x_t \le N_t, \forall\, t \end{aligned}$$

We assume[1]

$$D \ge 0, D_N > 0, D_{NN} \ge 0, C \ge 0, C_x > 0, C_{xx} \ge 0, C_N < 0, C_{NN} \ge 0, C_{xN} = C_{Nx} \le 0, C_{xx}C_{NN} - \left(C_{Nx}\right)^2 \ge 0, g > 0, g_{NN} > 0$$

...(2)

[1] To avoid notational clutter, the time subscript (t) and function arguments are suppressed in most of this section.

The Maximum principle of Pontryagin et al. (1962) provides the following Hamiltonian and first-order necessary conditions:

$$H = \left[- D(N_t) - C(N_t, x_t) \right] + \lambda_t \left[g(N_t) - x_t \right] \qquad .....(3)$$

$$\frac{\partial H}{\partial x_t} = - C_{x_t}(N_t, x_t) - \lambda_t \leq 0, \qquad \frac{\partial H}{\partial x_t} x_t = 0 \qquad .....(4)$$

$$\frac{\partial H}{\partial N_t} = - D_{N_t}(N_t) - C_{N_t}(N_t, x_t) + \lambda_t g_{N_t}(N_t) = r\lambda_t - \dot{\lambda}_t \qquad .....(5)$$

$$\frac{\partial H}{\partial \lambda_t} = g(N_t) - x_t = \dot{N}_t \qquad .....(6)$$

Manipulation of the above conditions yields the following equation of motion for control:

$$\dot{x}_t = - \frac{1}{(g_N - r)C_{xx}} \left[D_N + C_N + (g_N - r)C_x + (g - x)C_{xN} \right] \qquad .....(7)$$

Equations (6) and (7) specify the necessary conditions for optimal state and control paths over time. Steady state population, N^* and harvest rate, x^*, can be obtained by setting $\dot{x}_t = \dot{N}_t = 0$. The resulting condition is:

$$r \cdot C_x(N^*, x^*) - C_N(N^*, x^*) - g_N(N^*) \cdot C_x(N^*, x^*) = D_N(N^*) \qquad .....(8)$$

This equates the one-period opportunity cost of harvesting a unit of stock (r C_x>0), the cost increase ($-C_N$>0) due to stock reduction by one unit, and the increase (decrease) in cost ($-g_N C_x$) due to the resulting increased (decreased) growth, on the L.H.S. with the resulting benefit of reduced damage (D_N >0) on the R.H.S. Depending on the costs and damages, the value of N^* may be positive or zero (implying that eradication of the invasive is optimal).

The above conditions give us the optimal time paths of N_t and x_t that minimize V. We denote the minimized value of V by V^*. Next, we imbed this optimal control solution in the optimal prevention problem to determine the efficient level of prevention expenditures.

2.2. Optimal Prevention

Let the prevention expenditure in each period be y, and the resulting probability of introduction be *p(y)*. If there is introduction in a period, prevention stops and we control according to the optimal control program derived in the previous section. The control and damage costs, therefore, equal V^*. If there is no introduction, we continue to spend on prevention. The resulting infinite probability tree is given in Figure 1.

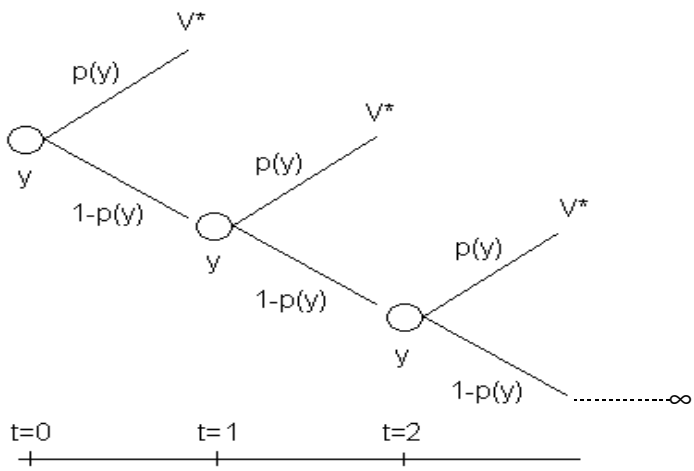

Fig.1: Prevention (y) with given control costs (V^*)

The expected present value of prevention and control costs (including damage) is:

$$W = \left(\frac{p(y)\, V^* + [1+r]\, y}{r + p(y)} \right) \qquad .....(9)$$

We choose y to minimize W. The first-order condition is:

$$\frac{\partial W}{\partial y} = 0 \Rightarrow \frac{\partial}{\partial y}\left[\left(\frac{p(y)\, V^* + [1+r]\, y}{r + p(y)} \right) \right] = 0 \qquad .....(10)$$

This gives us the following condition[2] for optimal y:

[2] For a minimum, we also require $\frac{\partial^2 W}{\partial y^2} > 0$. Some manipulation of this condition in combination with (10) shows that it will be met if $p'' > 0$.

$$(1+r)\left[r+p(y)\right]+\left[r\,V^{*}-(1+r)y\right]\,p'(y)=0 \qquad .....(11)$$

Using the definition of W from (9) and re-arranging, we get:

$$\underbrace{-\frac{p'(y)\,V^{*}}{(1+r)}}_{\text{MB of prevention}}=1+\underbrace{\frac{1}{(1+r)}\frac{\partial}{\partial y}\left\{[1-p(y)]\,W\right\}}_{\text{MC due to increased probability of further prevention and control}} \qquad .....(12)$$

This implies that if the control and damage costs in the case of introduction were large (large V^{*}), optimal prevention expenditures (y) would also be large (ceteris paribus). Similarly, the more sensitive the probability of introduction ($p'(y)$) is to prevention expenditures, the bigger the expenditures. The prevention expenditures would also be bigger, the smaller the interest rate (r) is. We denote the minimized value of W by W^{*}.

2.3. Optimal Eradication

Let N_{min} denote the critical stock level below which further introduction can occur/matter. For simplicity, assume $N_{min} = 1$. Now, if the steady state determined in the optimal control problem above involves eradication of the invasive (i.e., $N^{*} = 0 < N_{min}$), we have to consider prevention and possible repeated eradication. Thus, we have the case where prevention is continuing and whenever it fails, stock eradication takes place at a cost of V^{*}. Let $E = V^{*}$. The problem can then be represented by the infinite probability tree in Fig. 2.

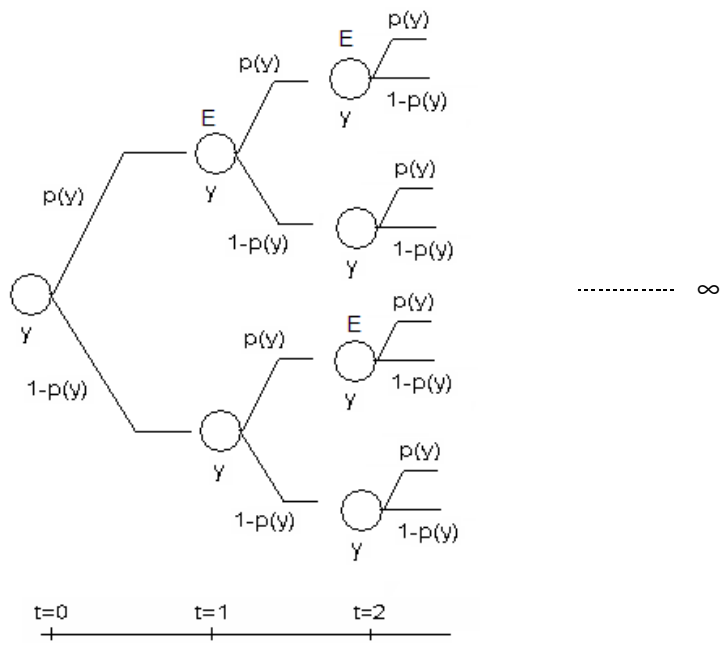

Fig.1: Prevention (y) with repeated eradication costs (E)

The expected present value of prevention and eradication is:

$$Z = \frac{(1+r)y + p(y)E}{r} \qquad .....(13)$$

We choose y to minimize Z. The first-order condition[3] is:

$$\frac{\partial Z}{\partial y} = 0 \Rightarrow \frac{\partial}{\partial y}\left[y + \frac{y + p(y)E}{r(1+r)}\right] = 0 \qquad .....(14)$$

This gives us the following condition for optimal y:

[3] For a minimum, the condition is again $p'' > 0$.

$$-\frac{p'(y)E}{(1+r)} = 1 \qquad .....(15)$$

This implies that as the eradication expenditures (E) become larger, so do the prevention expenditures (y). The prevention expenditures are also larger, the smaller the interest rate (r) is, and the more sensitive the probability of introduction ($p'(y)$) is to prevention expenditures. Let us denote the minimized value of Z by Z^*. This is the cost of prevention and control when the steady-state stock is zero.

An alternative to this outcome is to solve the optimal control problem with a lower limit on stock to prevent it from falling below N_{min}. Denote the resulting steady-state stock level by N^{**} and the new V^* by V^{**}. Replacing V^* by V^{**} in (9), we get a new value of W^* and denote it by W^{**}. If $W^{**} < Z^*$, the restricted optimal control approach to N^{**} is superior to the $N^* = 0$ and the optimal invasive management strategy is the one given in Fig.1 (with V^{**} in place of V^*). If $V^{**} > Z^*$, the strategy of choice is that given in Fig.2.

3. Conclusion

We provide a framework to combine optimal pre-introduction prevention and post-introduction control of invasive species. Optimal prevention depends on the costs that would result when prevention fails to stop an invasion. The costs of prevention failure are the costs of controlling the invasive in an optimal manner, including the damages incurred in the process. For the optimal prevention problem, higher control and/or damage costs required after the species is introduced would result in higher

optimal prevention expenditures. Similarly lower interest rates and greater prevention effectiveness also increase optimal prevention expenditures.

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