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ABSTRACT

In the past two decades, a considerable amount of concern has been expressed in academic and in nonacademic circles about the decline in the world's diverse biological resources. Recently, Swanson (1995b) has suggested that the problem of biodiversity loss is really a problem of regulating the natural habitat conversion process in which naturally existing species have systematically been replaced by human chosen ones. In this way of looking at the problem, a decision maker's central task is to determine the optimal point at which this conversion process should be halted. In this paper, I show how the theory of optimal stopping can be applied to model the biodiversity loss problem as described above. Specifically, I pose the underlying conservation question within the framework of a Markov decision process. I then show how to determine the optimal point at which this conversion process should be halted.

Key words: biodiversity, dynamic, habitat, optimal stopping, stochastic

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1. Introduction

In the last two decades, a considerable amount of concern has been expressed in academic and in nonacademic circles about the loss of diversity in the world's biological resources. As Perrings et al. (1995b) noted, there are many levels at which one can discuss the problem of biodiversity loss. The most popular characterizations have portrayed the problem as essentially one of genetic and species diversity loss. This notwithstanding, a consensus is emerging among economists and ecologists that in thinking about biodiversity loss, the appropriate concept to focus on is not genetic or species diversity, but the notion of ecological resilience.[2] According to this view, biodiversity matters primarily through its role in promoting resilience, ". . . where resilience refers to the amount of disturbance that an ecosystem can sustain before a change in the control or the structure of the ecosystem will occur" (Batabyal 1996a, p. 487).

As a part of this new focus on the diversity of ecological function, Swanson (1995b) has suggested that the global decline in biodiversity is best viewed as a process of natural habitat conversion in which naturally existing species have been systematically replaced by human selected ones. According to Swanson, if we are to ameliorate the problem of biodiversity loss, we need to focus on this "extinction process." In this view of the underlying problem, the central task for a decision maker is to halt this habitat conversion process at an optimally determined point in time.

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[2]For more on this line of thinking, see the papers in Perrings et al. (1995a), and in Swanson (1995a).

In this paper, I shall pursue this way of looking at the biodiversity loss problem. Specifically, I shall cast the underlying conservation question within the context of a Markov decision theoretic framework.[3] I shall then use an optimal stopping rule to provide an answer to the question of when the habitat conversion process should be halted.

The rest of this paper is organized as follows. Section 2 formulates and discusses the theoretical framework in detail. Section 3 offers concluding comments and discusses directions for future research.

2. The Theoretical Framework

My model is based on Ross (1970, pp. 188-190) and on Batabyal (1997b), and the spirit of the analysis is related to that contained in Batabyal (1997a). I shall first describe the infinitesimal look ahead stopping rule (ILASR) and a theorem which provides conditions under which it is optimal to stop using the ILASR. As Ross (1970, p. 188) noted, the ILASR can be thought of as a policy that stops a stochastic process precisely in those states for which stopping immediately yields a higher payoff than waiting an additional time h. Let S be the set of states for which stopping immediately yields a higher payoff than waiting an additional time h. Then it can be shown that

Theorem 1 (Ross 1970, p. 188): If S is closed, i.e., once a stochastic process enters S, the process cannot exit S, then under certain regularity conditions, the ILASR is optimal.

The biodiversity conservation problem can now be cast in a Markov decision theoretic framework. This will then enable me to use Theorem 1 to determine when the habitat conversion process should be halted. I shall model the underlying decision problem as one that is faced by a

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[3]For more on Markov decision processes, see Derman (1970).

national government that is interested in conserving its scarce biological resources.[4] The government solves its problem in a dynamic and stochastic framework. The framework is dynamic because the underlying conservation question involves halting a phenomenon—the conversion of natural habitats—that is taking place over time. The framework is stochastic because the habitat conversion process is stochastic and because the decision to halt this conversion process depends fundamentally on the uncertain availability of information regarding the desirability of such an action.

I assume that this information is produced according to a nonhomogeneous Poisson process $\{I(t):t \geq 0\}$ with a continuous, nonincreasing intensity function $\gamma(t)$. Information is acquired by the government independently, and this information has a common cumulative distribution function $F(\bullet)$ with finite mean. By letting the information acquisition process follow a nonhomogeneous Poisson process, I am leaving open the possibility that it is more likely that information will be received at certain times than at other times. Since it is unlikely that the conversion of natural habitats is taking place uniformly over time, allowing for the above possibility would appear to be necessary. I assume that any information that is not used immediately by the government in deciding whether or not to halt the habitat conversion process can be used subsequently. The specific source of information production is not critical to my analysis. It could be the result of research and development undertaken by the government, or it could be the result of activities undertaken by private agencies. In any event, from the perspective of the government, information is costly to acquire. As such, I shall incorporate this cost in the overall decision problem faced by the government.

Upon acquiring information, the government decides whether to halt the conversion of

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[4]I have posed the decision-making problem at the level of a country. However, a change of scale—to a region within a country or to a region encompassing more than one country—does not affect the analysis qualitatively.

natural habitats or to permit conversion and wait for additional information. Let $\bar{u}(\bullet)$ be the government's utility function. I assume that $\bar{u}(\bullet)$ is a continuous, one-to-one, and strictly monotone function. This utility function maps information about halting conversion to utility from halting conversion. In other words, if $i(t)$ is the information acquired by time t, then $U(t)=\bar{u}\{i(t)\}$ denotes the utility to the government from halting the habitat conversion process. Further, since $\bar{u}(\bullet)$ is a continuous, one-to-one, and strictly monotone transformation of $I(t)$, $\forall t$, it follows that the government's utility $\{U(t):t\geq 0\}$ is itself a nonhomogeneous Poisson process with a continuous and nonincreasing intensity function, say, $\theta(t)$.[5] Further, successive utility realizations are independent, with a cumulative distribution function $G(\bullet)$. This distribution function also has a finite mean.

At any point in time, should the government choose not to halt the conversion process, it incurs benefits and costs. The benefits stem from retaining flexibility. The government leaves open the possibility that more and better information will be received in the future that may call into question the wisdom of a current decision to halt the habitat conversion process. The costs arise from two sources. First, the government has to pay to obtain information about the conversion process. Second, it loses the current utility from halting this conversion process. I shall denote the net benefit per unit of time from not halting the habitat conversion process by B.

The state (see Figure 1) at any time t is denoted by the pair $[t, U(t)]$, where $U(t)$ is the utility that will be received should the government choose to halt the habitat conversion process at time t. The reader should note that with this specification of the state, I have a two-action—halt or do not halt—Markov decision process. If the government halts the habitat conversion process in state

[5]See Wolff (1989, p. 26) for further details.

Step 1

Government's decision problem at time *t*:

Take action I—halt conversion process or

Take action II—do not halt conversion process and wait for time *h*

Step 2

Government's decision is based on a comparison of the payoffs from the two actions

Step 3

Compare U {payoff from action I} with EU {payoff from action II; see eqn. (2)}

Step 4

Halt conversion process iff U $\geq$ EU

Otherwise, wait for additional information

Figure 1. Conceptual Diagram of the Optimal Stopping Approach

$[t, U(t)]$, the government's utility from t onwards will be $U(t)$. On the other hand, if the government chooses not to halt the conversion process and waits for an additional time h, then its expected utility will be

$$\{1 - \int_t^{t+h} \theta(r)dr\} \bullet U + \int_t^{t+h} \theta(r)dr \bullet E[\max(Y, U)] + Bh + o(h). \tag{1}$$

In equation (1), Y is a random variable representing the utility to the government from information received in $[t, t+h]$, and $E[\bullet]$ is the expectation operator.[6] Equation (1) can be simplified to

$$U + \int_t^{t+h} \theta(r)dr \int_U^{\infty} (y-U)dG(y) + Bh + o(h). \tag{2}$$

Intuitively speaking, the government should halt the habitat conversion process upon acquiring information $i(t)$ at time t if and only if the utility from halting, i.e., $U(t)$, exceeds the expected utility given in equation (2) from postponing action and allowing habitat conversion to continue for an additional time h. Alternately put, the habitat conversion process should be halted now if and only if

$$U \geq U + \int_t^{t+h} \theta(r)dr \int_U^{\infty} (y-U)dG(y) + Bh + o(h). \tag{3}$$

Now canceling the common terms on both sides of equation (3), dividing both sides of equation (3) by h, and then letting $h \to 0$ yields

$$0 \geq \theta(t) \int_U^{\infty} (y-U)dG(y) + B. \tag{4}$$

Equation (4) gives us the condition for determining whether the habitat conversion process should

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[6]The $o(h)$ term in equation (1) is a technical requirement that stems from the definition of a nonhomogeneous Poisson process. Specifically, because $\{U(t){:}t \geq 0\}$ is a nonhomogeneous Poisson process, $Prob\{U(t+h) - U(t) = \theta(t)h + o(h)$. See Ross (1996, chapter 2) for further details.

be halted now. From equation (4) I can define the set S, i.e., the set of all states for which halting the habitat conversion process now yields a higher level of utility than permitting habitat conversion to continue for an additional time h. This set is

$$S = \{(t,\ U):\ \theta(t)\int_{U}^{\infty}(y-U)dG(y) \leq -B\}. \tag{5}$$

The reader should note that S is a closed set. This follows from the fact that as t increases, $\theta(t)$ does not increase and the integral in equation (5) does not increase as well. I can now apply Theorem 1, which I stated at the beginning of this section, and conclude that the government should halt the habitat conversion process at time t if and only if the utility from halting the habitat conversion process is $U(t)$, where $U(t)$ solves

$$\theta(t)\int_{U}^{\infty}(y-U)dG(y) = -B. \tag{6}$$

Equations (5) and (6) together tell us that the habitat conversion process should be halted at time t, if, in an expected utility sense, it does not pay the government to wait for information about the consequences of halting the habitat conversion process beyond time t.

2a. An Example[7]

Our government is considering whether or not to halt the habitat conversion process that is at work in this country. As indicated in the previous discussion, this government receives information about the consequences of halting this habitat conversion process at any particular time. Suppose that there are only three states—states 0, 1, and 2—in which the utilities to the government

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[7]This example is adapted from Batabyal (1996b); the government utilities (in dollar terms) have been chosen so as to be consistent with the range mentioned by Simpson, Sedjo, and Reid (1996, p. 164).

(in dollar terms) from halting the habitat conversion process are \$38,000, \$40,000, and \$42,000, respectively. Let the probabilities of obtaining these utilities be $P_0 = 1/2$, $P_1 = 3/8$, and $P_2 = 1/8$, respectively. Further, let B = -\$50 be the net benefit per unit of time from not halting the habitat conversion process. Finally, suppose that the government uses a discount factor of $\beta = 0.99$ in making its decision.

To provide an answer to the "When to halt the habitat conversion process" question, suppose that once a decision to halt the process has been made, the corresponding Markov decision process goes to state infinity and that it stays there indefinitely, accruing a net benefit of B = \$0. Now standard computations tell us that in this example, the government's optimal policy calls for not halting the habitat conversion process when the utility is \$38,000 and halting the conversion process when the utility is either \$40,000 or \$42,000. Further, the government should halt the conversion process in state 1; this decision results in the receipt of utility in the amount of \$40,000.

3. Conclusions

In this paper I modeled the question of biodiversity conservation as an optimal stopping time problem within the context of a Markov decision process. In this context, I provided an answer to the question as to when the habitat conversion process should be halted optimally. This answer involves a comparison of the utility obtainable from halting the habitat conversion process at time t, i.e., $U(t)$, with the expected utility to be obtained by not halting and waiting for new information beyond time t.

The analysis of this paper can be generalized in a number of directions. In what follows, I suggest three possible extensions. First, one can make the net benefit from waiting—the B

term—explicitly stochastic. When this is done, the government's decision will depend on the interaction between this stochastic process and the utility stochastic process.

Second, alternate specifications for the information production function can be analyzed. In this paper, I have provided a rather simple specification in which information is produced in accordance with a nonhomogeneous Poisson process. More general specifications will permit more elaborate analyses of the connections between information production and the optimal time at which the habitat conversion process should be halted.

Finally, one can consider the impact on the optimal time to halt the conversion process when the government uses randomized or nonstationary stopping rules. An analysis of this aspect of the problem will enable us to compare the implications of using alternate stopping rules for the conservation of biodiversity.

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