Resource Exploitation, Biodiversity and Ecological Events

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by

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Abstract: We study the management of a natural resource that supports ecological systems as well as human needs. The reduction in the resource base poses a threat of occurrence of catastrophic ecological events, such as the sudden collapse of the natural habitat, that lead to severe loss of biodiversity. The event occurrence conditions involve uncertainty of various types, and the distinction among these types affects the optimal exploitation policies. When uncertainty is due to our ignorance of some aspects of the underlying ecology, the isolated equilibrium states characterizing optimal exploitation for many renewable resource problems become equilibrium intervals, giving rise to hysteresis phenomena. Events triggered by genuinely stochastic environmental conditions maintain the structure of isolated equilibria, but the presence of event uncertainty shifts these equilibrium states relative to their position under certainty.

Keywords: ecological systems; resource management; event uncertainty; biodiversity; extinction

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1. Introduction

We study the management of a natural resource that serves a dual purpose: first, it supplies inputs for human production activities and is therefore being exploited for beneficial use, however defined; second, it supports the existence of other species. Large-scale exploitation competes with the needs of the wildlife populations and, unless controlled, can severely degrade the ecological conditions and lead to species extinction and biodiversity loss. Examples for such conflicts abound, including: (i) water diversions for irrigation, industrial or domestic use reduce in-stream flows that support the existence of various fish populations; (ii) reclamation of swamps and wetlands that serve as habitat for local plant, bird and animal populations and as a "rest area" for migrating birds; (iii) deforestation reduces the living territory of a large number of species; and (iv) airborne industrial pollution falls as acid rain on lakes and rivers and interferes with systems of freshwater ecology. In these examples the affected species may not contribute directly to human well being but their diminution or extinction entails a loss due to use and nonuse values as well as the loss of option for future benefits such as the development of new medicines (about half of medicine prescriptions originate from organisms found in the wild [Littell 1992, Bird 1991]).

The global deforestation example illuminates the issue under consideration. Until recently, a rainforest area about the size of England was cleared each year (Hartwick, 1992), leading to the extinction of numerous species (Colinvaux 1989). The biodiversity loss process often takes the form of a sudden collapse of the ecological system, inflicting a heavy damage and affecting the nature of future exploitation regimes. This is so because ecological systems are inherently complex and their highly nonlinear dynamics give rise to instabilities and sensitivity to threshold levels of essential supplies. Moreover, ecological systems are often vulnerable to environmental events, such as forest fires, disease outbreaks, or invading populations, which are genuinely stochastic in nature. We refer to the occurrence of a sudden system collapse as an ecological event.

When the biodiversity loss process is gradual and can be monitored and controlled by adjusting exploitation rates, and/or when it involves a discrete ecological event whose occurrence conditions are a-priori known, it is relatively simple to avoid the damage by ensuring that the event will never occur. Often, however, the conditions that trigger ecological events involve uncertainty and the corresponding management problems should be modeled as such. The present study characterizes optimal resource exploitation policies under risk of occurrence of various types of events.

Impacts of event uncertainty on resource exploitation policies have been studied in a variety of situations, including pollution-induced events (Cropper, 1976, Clarke and Reed, 1994, Tsur and Zemel, 1996, 1998b, Aronsson et al., 1998), forest fires (Reed, 1984, Yin and Newman, 1996), species extinction (Reed, 1989, Tsur and Zemel, 1994), seawater intrusion into coastal aquifers (Tsur and Zemel, 1995), and political crises (Long, 1975, Tsur and Zemel, 1998a). Occurrence risk typically leads to prudence and conservation, but in some cases has the opposite effect, encouraging aggressive extraction policies in order to derive maximal benefit prior to occurrence (Clarke and Reed, 1994).

Tsur and Zemel (1998b, 2004) trace these apparently conflicting results to different assumptions concerning the event occurrence conditions and the ensuing damage they inflict. An important distinction relates to the type of uncertainty. An event is called endogenous if its occurrence is determined solely by the resource exploitation policy, although the exact threshold level at which the event is triggered is not a-priori known. This type of uncertainty is due to our partial ignorance of the occurrence conditions and allows to avoid the occurrence risk altogether by keeping the resource stock at or above its current state. Exogenous events, on the other hand, are triggered under environmental circumstances that are genuinely stochastic and cannot be fully controlled by the resource managers. With this type of events, no exploitation policy is completely safe although the managers can affect the occurrence hazard by adjusting the stock of the essential resource.

We show that the endogenous-exogenous distinction bears important implications for optimal exploitation policies and alters properties that are considered standard. For example, the optimal stock processes of renewable resources typically approach isolated equilibrium (steady) states. This feature, it turns out, no longer holds under endogenous event uncertainty: the equilibrium point expands into an equilibrium interval whose size depends on the expected loss, and the eventual steady state is determined by the initial stock. Endogenous events, thus, can be the source of hysteresis phenomena. In contrast, exogenous events maintain the structure of isolated equilibria and the effect of event uncertainty is manifest via the shift it induces on these equilibrium states.

2. Certain Events

We consider the management of some environmental resource that is essential to the survival of an ecological system (or of a key species thereof) and at the same time provides an important production factor for anthropogenic activity. The stock S of the resource can denote the area of uncultivated land of potential agricultural use, the water level at some lake or stream or the level of cleanliness (measured e.g. by the ph level of a water resource affected by acid rain or by industrial effluents). Without human interference, the stock dynamics is determined by the natural regeneration rate

$G(S)$ (corresponding to the recharge of the water resource or to the decay rate of the pollution stock). The functional form of G depends on the particular resource under consideration, but we assume the existence of some upper bound $\bar{S}$ for the stock, corresponding to the lake's holding capacity or to the natural cleanliness level, so that $G(\bar{S}) = 0$ and $G'(\bar{S}) \leq 0$. With x_t representing the rate of resource use (extraction), the resource stock evolves with time according to

$$dS_t / dt \equiv \dot{S}_t = G(S_t) - x_t . \tag{2.1}$$

Extraction activities can have several consequences. First, they give rise to a benefit flow (from the use of land and water or from the economic activities that produce the pollutants) at the rate $Y(x)$, where Y is increasing and strictly concave with $Y(0) = 0$. Second, they bear the cost $C(S)x$ of extracting at the rate x while the stock level is S, where the unit cost $C(S)$ is nonincreasing and convex. In addition, reducing the stock level entails damage to the ecological system that depends on the same resource for its livelihood. The latter damage flows at the rate $D(S)$, where the decreasing damage function D is normalized at $D(\bar{S}) = 0$. The instantaneous net benefit is then given by $Y(x) - C(S)x - D(S)$. Finally, reducing the stock below some (possibly a-priori unknown) threshold level can trigger the sudden collapse of the ecological system, inflicting a heavy penalty in terms of biodiversity loss and affecting the nature of future exploitation regime. We begin by considering the reference problem of optimal extraction when the conditions under which such catastrophic events occur are known, and proceed to study the effects of uncertainty under various scenarios regarding their occurrence conditions.

Suppose that driving the stock to some critical level S_c triggers the occurrence of some catastrophic event, e.g., a major loss of biodiversity due to habitat destruction which entails a penalty $\psi > 0$ and prohibits any further decrease of the resource stock. The corresponding post-event value is $\phi(S_c) = W(S_c) - \psi$, where

$$W(S) = [Y(G(S)) - C(S)G(S) - D(S)]/r \tag{2.2}$$

is the steady state value derived from keeping the extraction rate at the natural regeneration rate $R(S)$ and r is the rate of discount. The post-event value ϕ, thus, accounts both for the fact that the stock cannot be further decreased (to avoid further damage) and for the catastrophic loss. Let T denote the event occurrence time ($T = \infty$ if the stock never shrinks to trigger the event at S_c).

The management problem when the critical stock is known with certainty is specified as

$$V^c(S_0) = Max_{\{T,x_t\}} \int_0^T [Y(x_t) - C(S_t)x_t - D(S_t)]e^{-rt}dt + e^{-rT}\phi(S_T) \tag{2.3}$$

subject to (2.1), $x_t \geq 0$; $S_t \geq 0$; $S_T = S_c$ and $S_0 > S_c$ given. Optimal processes associated with the certainty problem (2.3) are indicated with a c superscript. The event occurrence is evidently undesirable, since just above S_c it is preferable to extract at the regeneration rate and enjoy the benefit flow $rW(S_c)$ associated with it rather than trigger the event and bear the penalty ψ. Thus, the event should be avoided, $S_t^c > S_c$ for all t and $T = \infty$. It follows that the certainty problem can be formulated as

$$V^c(S_0) = Max_{\{x_t\}} \int_0^\infty [Y(x_t) - C(S_t)x_t - D(x_t)]e^{-rt}dt \tag{2.4}$$

subject to (2.1), $x_t \geq 0$; $S_t > S_c$ and S_0 given. Thus, the effect of the certain event enters only via the lower bound on the stock level. This simple problem is akin to standard resource management problems and can be treated by a variety of optimization methods (see, e.g., Tsur and Graham-Tomasi, 1991; Tsur and Zemel, 1994, 1995, 2004). Here, we briefly review the main properties of the optimal plan.

We note first that because problem (2.4) is autonomous (time enters explicitly only through the discount factor) the optimal stock process S_t^c evolves monotonically in time. The property is based on the observation that if the process reaches the same state at two different times, then the planner faces the same optimization problem at both times. This rules out the possibility of a local maximum for the process, because the conflicting decisions to increase the stock (before the maximum) and decrease it (after the maximum) are taken at the same stock levels. Similar considerations exclude a local minimum. Since S_t^c is bounded in $[S_c, \bar{S}]$ it must approach a steady state in this interval. Using the variational method of Tsur and Zemel (2001), possible steady states are located by means of a simple function $L(S)$ of the state variable, denoted the evolution function, which measures the deviation of the objective of (2.4) from $W(S)$ due to small variations from the steady state policy $x = G(S)$ (see below). In particular, an internal state $S \in (S_c, \bar{S})$ can qualify as an optimal steady state only if it is a root of L, i.e. $L(S) = 0$, while the corners S_c or $\bar{S}$ can be optimal steady states only if $L(S_c) \leq 0$ or $L(\bar{S}) \geq 0$, respectively.

For the case at hand, the evolution function corresponding to (2.4) is given by

$$L(S) = (r - G'(S))\left\{\frac{-C'(S)G(S) - D'(S)}{r - G'(S)} - [Y'(G(S)) - C(S)]\right\}. \tag{2.5}$$

When $Y'(0) < C(\bar{S})$, exploitation is never profitable. In this case $L(\bar{S}) > 0$ and the unexploited stock eventually settles at the capacity level $\bar{S}$. The condition for the corner solution $L(S_c) < 0$ is obtained from (2.5) in a similar manner. Suppose that $L(S)$ has a unique root $\hat{S}^c$ in $[S_c, \bar{S}]$ (multiple roots are discussed in Tsur and Zemel 2001). In this case, $\hat{S}^c$ is the unique steady state to which the optimal stock process S_t^c converges monotonically from any initial state.

The vanishing of the evolution function at an internal steady state represents the tradeoffs associated with resource exploitation. If a steady state is optimal, then moving to a steady state nearby must inflict a loss. Consider a variation on the steady state policy $x = G(\hat{S}^c)$ in which exploitation is increased during a short (infinitesimal) time period dt by a small (infinitesimal) rate dx above $G(\hat{S}^c)$ and retains the regeneration rate thereafter. This policy yields the additional benefit $(Y'(G(\hat{S}^c)) - C(\hat{S}^c))dxdt$, but decreases the stock by $dS = -dxdt$, which, in turn, increases the damage by $D'(\hat{S}^c)dS$, the unit extraction cost by $C'(\hat{S}^c)dS$ and the extraction cost by $G(\hat{S}^c)C'(\hat{S}^c)dS$. The present value of this permanent flow of added costs is given by $[D'(\hat{S}^c) + G(\hat{S}^c)C'(\hat{S}^c)]dS/(r - G'(\hat{S}^c))$. (The effective discount rate equals the market rate r minus the marginal regeneration rate G' because reducing the stock by a marginal unit and depositing the proceeds at the bank the resource owner gains the market interest rate r plus the additional regeneration rate $-G'$, see Pindyck 1984). At the root of L, these marginal benefit and cost just balance, yielding an optimal equilibrium state.

While the discussion above implies that the stock process must approach $\hat{S}^c$, the time to enter the steady state remains a free choice variable. Using the conditions for an optimal entry time, one finds that the optimal extraction rate x_t^c smoothly approaches the steady state regeneration rate $G(\hat{S}^c)$ and the approach of S_t^c towards the steady state $\hat{S}^c$ is asymptotic, i.e., the optimal stock process will not reach the steady state at a finite time. These properties, as well as the procedure to obtain the full time trajectory of the optimal plan are explained in Tsur and Zemel (2004).

The results obtained for an internal steady state do not depend on the critical state, nor on the penalty inflicted by the event, because the latter enters the certainty problem only via the constraint $S_t > S_c$ which is not binding when the root of L lies above the critical state. However, with $S_c > \hat{S}^c$ the function $L(S)$ is negative in the feasible interval $[S_c, \bar{S}]$, hence no internal steady state can be optimal. The only remaining possibility is the critical level S_c, because the negative value of $L(S_c)$ does not exclude this corner state. The optimal stock process S_t^c, then, converges monotonically and asymptotically to a steady state at S_c. By keeping the process above the path it would follow if the state constraint $S_t > S_c$ could be ignored, the threat of occurrence imposes prudence and a lower rate of extraction.

In this formulation the event is never triggered and the exact value of the penalty is irrelevant (so long as it is positive). This result is due to the requirement that the post-event stock is not allowed to decrease below the critical level. Indeed, this requirement can be relaxed whenever the penalty is sufficiently large to deter the managers from triggering the event in any case. The lack of sensitivity of the optimal policy to the details of the catastrophic event is evidently due to the ability to avoid the event occurrence altogether. This may not be feasible (or optimal) when the critical stock level is not a-priory known. The optimal policy may, in this case, lead to unintentional occurrence, whose exact consequences must be accounted for in advance. We turn, in the following section, to analyze the effect of uncertain catastrophic events on resource management policies.

3. Uncertain Events

Often the conditions that lead to the event occurrence are imperfectly known and may be subject to environmental uncertainty outside the planner's control. In some cases the critical level is a priori unknown, to be revealed only by the event occurrence. Alternatively, the event may be triggered at any time by external effects (such as unfavorable weather conditions or the outburst of a disease). Since the resilience of the ecological system depends on the current resource stock, the occurrence probability also depends on this state. We refer to the former type of uncertainty—that due to the planner's ignorance regarding the conditions that trigger the event—as endogenous uncertainty (signifying that the event occurrence is solely due to the exploitation decisions) and to the latter as exogenous uncertainty. It turns out that the optimal policies under the two types of uncertainty are quite different. These policies are characterized below.

3.1. Endogenous events: Such events occur as soon as the resource stock reaches some critical level S_c, which is imperfectly known. The uncertainty regarding the occurrence conditions, thus, is entirely due to our ignorance concerning the critical level rather than to the influence of exogenous environmental effects. Let $F(S) = Pr\{S_c \leq S\}$ and $f(S) = dF/dS$ be the probability distribution and the probability density associated with the critical level S_c. The hazard function, measuring the conditional density of occurrence due to a small stock decrease given that the event has not occurred by the time the state S was reached, is defined by

$$h(S) = f(S)/F(S). \tag{3.1}$$

We assume that $h(S)$ does not vanish in the relevant range, hence no state below the initial stock can be considered a-priori safe.

The distribution of S_c induces a distribution on the event occurrence time T, as derived below. Upon occurrence, the penalty ψ is inflicted and a further decrease in stock is forbidden, leaving the post-event value $\phi(S) = W(S) - \psi$. Given that the event has not occurred by the initial time, i.e., that $T > 0$, we seek the extraction plan that maximizes the expected benefit

$$V^{en}(S_0) = Max_{\{x_t\}} E_T \left\{ \int_0^T [Y(x_t) - C(S_t)x_t - D(S_t)]e^{-rt}dt + e^{-rT}\phi(S_T) \middle| T > 0 \right\} \quad (3.2)$$

subject to (2.1), $x_t \geq 0$; $S_t \geq 0$ and S_0 given, where E_T represents expectation with respect to the distribution of T. Optimal processes corresponding to the endogenous uncertainty problem (3.2) are denoted by the superscript *en*.

As the stock process evolves in time, the managers' assessment of the distributions of S_c and T can be modified since at time t they know that S_c must lie below $\tilde{S}_t = Min_{0 \leq \tau \leq t}\{S_\tau\}$ (otherwise the event would have occurred at some time prior to t). Thus, the expected benefit in the objective of (3.2) involves $\tilde{S}_t$, i.e., the entire history up to time t, complicating the optimization task. The evaluation of the expectation in (3.2) is simplified when the stock process evolves monotonically in time, in which case $\tilde{S}_t = S_0$ if the process is nondecreasing (and no information relevant to the distribution of S_c is revealed), or $\tilde{S}_t = S_t$ if the process is nonincreasing (and all the relevant information is given by the current stock S_t). It turns out that the optimal stock process S_t^{en} evolves monotonically in time (Tsur and Zemel, 1994). This property extends the reasoning of the certainty case above: If the process reaches the same state at two different times, and no new information on the critical level has been revealed during that period, then the planner faces the same optimization problem at both times. This rules out the possibility of a local maximum for the process, because $\tilde{S}_t$ remains constant around the maximum, yet the conflicting decisions to increase the stock (before the maximum) and decrease it (after the maximum) are taken at the same stock levels. A local minimum can also be ruled out even though the decreasing process modifies $\tilde{S}_t$ and adds information on S_c. However, it cannot be optimal to decrease the stock under occurrence risk (prior to reaching the minimum) and then increase it with no occurrence risk (after the minimum), from the same state.

For nondecreasing stock processes it is known in advance that the event will never occur and the uncertainty problem (3.2) reduces to the certainty problem (2.4). When the stock process decreases, the distribution of T is obtained from the distribution of S_c as follows:

$$1 - F_T(t) \equiv \Pr\{T > t | T > 0\} = \Pr\{S_c < S_t | S_c < S_0\} = F(S_t)/F(S_0). \tag{3.3}$$

The corresponding density and hazard-rate functions are also expressed in terms of the distribution of the critical stock:

$$\begin{aligned} &\text{(a)}\quad f_T(t) = dF_T(t)/dt = f(S_t)[x_t - G(S_t)]/F(S_0), \\ &\text{(b)}\quad h_T(t) = \frac{f_T(t)}{1 - F_T(t)} = h(S_t)[x_t - G(S_t)]. \end{aligned} \tag{3.4}$$

Let $I(\cdot)$ denote the indicator function that obtains the value one when its argument is true and zero otherwise. Writing the objective of (3.2) as

$E_T\left\{\int_0^\infty [Y(x_t) - C(S_t)x_t - D(S_t)]I(T > t)e^{-rt}dt + e^{-rT}\phi(S_T) \middle| T > 0\right\}$, we evaluate the expectation of the first term observing that $E_T\{I(T > t)|T > 0\} = 1 - F_T(t) = F(S_t)/F(S_0)$. The expectation of the second term is obtained, using (3.4), as

$\int_0^\infty f_T(t)\phi(S_t)e^{-rt}dt = \int_0^\infty f(S_t)[x_t - G(S_t)]\frac{\phi(S_t)}{F(S_0)}e^{-rt}dt$. Collecting the terms and using (3.1)-(3.3), the expectation in (3.2) for *decreasing* processes is evaluated to give

$$V^{aux}(S_0) = \\ Max_{\{x_t\}}\left\{\int_0^\infty \{Y(x_t) - C(S_t)x_t - D(S_t) + h(S_t)[x_t - G(S_t)]\phi(S_t)\}\frac{F(S_t)}{F(S_0)}e^{-rt}dt\right\} \tag{3.5}$$

subject to (2.1), $x_t \geq 0$; $S_t \geq \hat{S}^{ne}$ and S_0 given. The allocation problem for which (3.5) is the objective is referred to as the *auxiliary* problem, and optimal processes corresponding to this problem are denoted by the superscript *aux*.

The auxiliary problem could be defined for all stock levels in $[0, \overline{S}]$. However, we show below that this problem is relevant for the formulation of the uncertainty problem (3.2) only for stock levels above the root $\hat{S}^c$ of $L(S)$, hence $\hat{S}^c$ replaces the depletion level (S=0) as the lowest feasible stock for (3.5). Formulated as an autonomous problem, the auxiliary problem also obtains an optimal stock process that evolves monotonically with time. Notice that at this stage it is not clear whether the uncertainty problem (3.2) reduces to the certainty problem or to the auxiliary problem, since it is not a priori known whether S_t^{en} decreases with time. We shall return to this question soon after the optimal auxiliary processes are characterized.

The evolution function corresponding to the auxiliary problem (3.5) is given by (Tsur and Zemel, 2004)

$$L^{aux}(S) = [L(S) + h(S) r\psi] F(S)/F(S_0). \tag{3.6}$$

In (3.6), $L(S)$ is the evolution function for the certainty problem, defined in (2.3), and $h(S)$ is the hazard function defined in (3.1). Occurrence of the event inflicts an instantaneous penalty ψ (or equivalently, a permanent loss flow at the rate $r\psi$) that could have been avoided by keeping the stock at the level S. The second term in the square brackets of (3.6) gives the expected loss due to an infinitesimal decrease in stock. Moreover, this term is positive at the lower bound $\hat{S}^c$, whereas $L(\hat{S}^c) = 0$, hence $L^{aux}(\hat{S}^c) > 0$, implying that $\hat{S}^c$ cannot be an optimal equilibrium for the auxiliary problem.

The eventual steady state depends on the magnitude of the expected loss: for moderate losses, L^{aux} vanishes at some stock level $\hat{S}^{aux}$ in the interval $(\hat{S}^c, \bar{S})$. We assume that the root $\hat{S}^{aux}$ is unique. Higher expected losses ensure that $L^{aux} > 0$ throughout, leaving only the corner state $\hat{S}^{aux} = \bar{S}$ as a potential steady state. The optimal stock process S_t^{aux} converges monotonically to $\hat{S}^{aux}$ from any initial state in $[\hat{S}^c, \bar{S}]$.

In order to characterize the optimal extraction plan for the endogenous uncertainty problem (3.2), we compare the trajectories of the auxiliary problem with those obtained with the certainty problem corresponding to $S_c \le 0$ (the latter can be referred to as the 'non-event' problem because the event cannot be triggered; see Tsur and Zemel 2004):

(i) When $S_0 < \hat{S}^c$, the optimal certainty stock process S_t^c increases in time. With event risk, it is possible to secure the certainty value by applying the certainty policy, since an endogenous event can occur only when the stock decreases. The introduction of occurrence risk cannot increase the value function, hence S_t^{en} must increase. This implies that the uncertainty and certainty processes coincide, $S_t^{en} = S_t^c$ for all t, and increase monotonically towards the steady state $\hat{S}^c$.

(ii) When $S_0 > \hat{S}^{aux} > \hat{S}^c$, both S_t^c and S_t^{aux} decrease in time. If S_t^{en} is increasing, it must coincide with the certainty process S_t^c, contradicting the decreasing trend of the latter. A similar argument rules out a steady state policy. Thus, S_t^{en} must decrease, coinciding with the auxiliary process S_t^{aux} and converging with it to the auxiliary steady state $\hat{S}^{aux}$.

(iii) When $\hat{S}^{aux} \geq S_0 \geq \hat{S}^c$, the certainty stock process S_t^c decreases (or remains constant if $S_0 = \hat{S}^c$) and the auxiliary stock process S_t^{aux} increases (or remains constant if $S_0 = \hat{S}^{aux}$). If S_t^{en} increases, it must coincide with S_t^c, and if it decreases it must coincide with S_t^{aux}, leading to a contradiction in both cases. The only remaining possibility is to follow the steady state policy $S_t^{en} = S_0$ at all *t*.

To sum:

(a) S_t^{en} increases at stock levels below $\hat{S}^c$.

(b) S_t^{en} decreases at stock levels above $\hat{S}^{aux}$.

(c) All stock levels in $[\hat{S}^c, \hat{S}^{aux}]$ are equilibrium states of S_t^{en}.

The equilibrium interval is unique to optimal stock processes under endogenous uncertainty. Its boundary points attract any process initiated outside the interval while processes initiated within it must remain constant. This feature is evidently related to the splitting of the endogenous uncertainty problem into two distinct optimization problems depending on the initial trend of the optimal stock process. At $\hat{S}^{aux}$, the expected loss due to occurrence is so large that entering the interval cannot be optimal even if under certainty extracting above the regeneration rate would yield a higher benefit. Within the equilibrium interval it is possible to eliminate the occurrence risk altogether by not reducing the stock below its current level. As we shall see below, this possibility is not available under exogenous uncertainty, hence the corresponding management problem does not give rise to equilibrium intervals.

Endogenous uncertainty, then, implies more conservative extraction than the certainty policy for any initial stock above $\hat{S}^c$. Observe that the steady state $\hat{S}^{aux}$ is a *planned* equilibrium level. In actual realizations, the process may be interrupted by the event at a higher stock level and the *actual* equilibrium level in such cases will be the occurrence state S_c.

A feature similar to both the certainty and endogenous uncertainty processes is the smooth transition to the steady states. When the initial stock is outside the equilibrium interval, the condition for an optimal entry time to the steady state implies that extraction converges smoothly to the recharge rate and the planned steady state will not be entered at a finite time. It follows that when the critical level actually lies below $\hat{S}^{aux}$, uncertainty will never be resolved and the planner will never know that the adopted policy of approaching $\hat{S}^{aux}$ is indeed safe. Of course, in the less fortunate case in which the critical level lies above the steady state, the event will occur, resolving uncertainty at a finite time.

3.2 Exogenous events: Ecological events that are triggered by environmental conditions beyond the planers' control are called exogenous. The current resource stock level can affect the *hazard* of immediate occurrence through its effect on the resilience of the ecological system, but the collapse event is triggered by stochastic changes in exogenous conditions. This type of event uncertainty was introduced by Cropper (1976) and analyzed by Clarke and Reed (1994), Tsur and Zemel (1998b, 2004) and Aronsson et al. (1998) in the contexts of nuclear waste control, environmental pollution and groundwater resource management. Here we consider the implications for biodiversity conservation. Under exogenous uncertainty, the fact that a certain stock level has been reached in the past without triggering the event does not rule out occurrence at the same stock level sometime in the future, as the exogenous conditions may turn out to be less favorable. Therefore, the mechanism that gives rise to the equilibrium interval under endogenous uncertainty does not work here.

As above, the post-event value is denoted by $\phi(S)$. The expected value from an extraction plan that can be interrupted by an event at time T is again given by the objective of (3.2), but for exogenous events the probability distribution of T, $F(t) = \Pr\{T \le t\}$, is defined in terms of a stock-dependent hazard rate $h(S)$

$$h(S_t) = f(t)/[1-F(t)] = -d\{log[1-F(t)]\}/dt, \tag{3.7}$$

as

$$F(t) = 1 - exp[-\int_0^t h(S_\tau)d\tau]. \tag{3.8}$$

We assume that no stock level is completely safe, hence $h(S)$ does not vanish and the integral in (3.8) diverges for any feasible process as $t \to \infty$. We further assume that $h(S)$ is decreasing, i.e., increasing the stock improves conditions for the ecological system and reduces the hazard for environmental collapse.

Using (3.8) to evaluate the expected value derived from any feasible process we obtain the exogenous uncertainty problem:

$$V^{ex}(S_0) = \underset{\{x_t\}}{Max} \int_0^\infty h(S_T)exp[-\int_0^T h(S_t)dt]\{\int_0^T [Y(x_t) - C(S_t)x_t - D(S_t)]e^{-rt}dt + e^{-rT}\phi(S_T)\}dT \tag{3.9}$$

subject to (2.1), $x_t \ge 0$; $S_t \ge 0$ and S_0 given. Unlike the auxiliary problem (3.5) used above to characterize the optimal policy under endogenous events, (3.9) provides the correct formulation for the exogenous uncertainty problem regardless of whether the stock process decreases or increases.

To characterize the steady state, we need to specify the value $W^{ex}(S)$ associated with the steady state policy $x^{ex} = G(S)$. Exogenous events may interrupt this policy, hence $W^{ex}(S)$ differs from the value function $W(S)$ of (2.5) obtained from the steady state policy under certainty or endogenous uncertainty. Under the steady state policy, (3.8) reduces to the exponential distribution $F(t) = 1 - exp[-h(S)t]$, yielding the expected value

$$W^{ex}(S) = W(S) - [W(S) - \phi(S)]h(S)/[r+h(S)]. \tag{3.10}$$

where the second term represents the expected loss over an infinite time horizon. The explicit time dependence of the distribution $F(t)$ of (3.8) does not allow presenting the optimization problem (3.9) in an autonomous form. Nevertheless, the argument for the monotonic behavior of the optimal stock process S_t^{ex} holds, and the associated evolution function can be derived (see Tsur and Zemel, 1998b), yielding

$$L^{ex}(S) = L(S) + d\{[\phi(S) - W(S)]rh(S)/[r+h(S)]\}/dS. \tag{3.11}$$

When the event corresponds to species extinction, it can occur only once since the loss is irreversible. If a further reduction in stock is forbidden, the post-event value is again specified as $\phi(S) = W(S) - \psi$, and the second term of (3.11) simplifies to $-\psi h'(S)r^2/[r+h(S)]^2$. For decreasing hazard functions this term is positive and $L^{ex}(S) > L(S)$. Since $L(S)$ is positive below $\hat{S}^c$, so must $L^{ex}(S)$ be, precluding any steady state below $\hat{S}^c$. Thus, the root $\hat{S}^{ex}$ of $L^{ex}(S)$ must lie above the nonevent equilibrium, implying that the extraction policy is more conservative than its nonevent counterpart.

Biodiversity conservation considerations enter via the second term of (3.11) which measures the marginal expected loss due to a small decrease in the resource stock. The latter implies a higher occurrence risk, which in turn calls for more prudent extraction policy. Indeed, if the hazard is state-independent, the second term of (3.11) vanishes, implying that the evolution functions of the certainty and exogenous uncertain event problems are the same and so are their steady states. In this case, extraction activities have no effect on the expected loss hence the tradeoffs that determine the optimal equilibrium need not account for the penalty, no matter how large it may be. For a decreasing hazard, however, the degree of prudence (as measured by the difference $\hat{S}^{ex} - \hat{S}^{c}$ between the equilibrium states) increases with the penalty ψ.

The requirement that the stock must not be reduced following occurrence can be relaxed. For this situation, the post-event value changes to $\phi(S) = V^c(S) - \psi$, yielding a somewhat more complex expression for the evolution function, but the prudence property $\hat{S}^{ex} > \hat{S}^{c}$ remains valid (Tsur and Zemel, 1998b).

Another interesting situation involving exogenous events arises when the ecological damage can be fixed (at the cost ψ) following occurrence. For example, the extinct population may not be endemic to the inflicted region and can be restored by importing individuals from unaffected habitats. Under this scenario, event occurrence inflicts the penalty but does not affect the hazard of future events. The post-event policy, then, is to remain at the steady state and receive the post-event value $W^{ex}(S) - \psi$. Using $F(t) = 1 - exp[-h(S)t]$ for recurrent events yields the expected steady state value $W^{ex}(S) = W(S) - [W(S) - W^{ex}(S) + \psi]h(S)/[r+h(S)]$. Solving for $W^{ex}(S)$, we find $W^{ex}(S) = W(S) - \psi h(S)/r$, reducing (3.11) to

$$L^{ex}(S) = L(S) - d[\psi h(S)]/dS. \tag{3.12}$$

When the penalty itself depends on the stock, its policy implications become more involved. Of particular interest is the case of *increasing* $\psi(S)$ and constant hazard, for which (3.12) implies more vigorous extraction. This situation corresponds to the irreversible catastrophic events of Clarke and Reed (1994), which give rise to extraction policies that are less prudent than their certainty counterparts.

The results presented in this section highlight the sensitivity of the optimal uncertainty processes to the details of an interrupting event. The type of uncertainty determines the equilibrium structure: endogenous uncertainty gives rise to equilibrium intervals while exogenous uncertainty implies isolated equilibrium states. In most cases, the expected event loss encourages conservation (more prudent extraction policies), but the opposite behavior can also be obtained.

4. Concluding comments

Renewable resources are typically considered in the context of their potential contribution to human activities but they also support ecological needs that are often overlooked. This work examines the implications of threats of ecological events for the management of renewable resources. The occurrence of an ecological event inflicts a penalty and changes the management regime. Unlike other sources of uncertainty (time-varying costs and demand, stochastic regeneration processes, etc.) which allow to update the extraction policy along the process and respond to changing conditions, event uncertainty is resolved by occurrence, when policy changes are no longer useful. Thus, the expected loss must be fully accounted for prior to the event occurrence, with significant changes to the optimal exploitation rules.

We distinguish between two types of events that differ in the conditions that trigger their occurrence. An endogenous event occurs when the resource stock crosses an uncertain threshold level, while exogenous events are triggered by coincidental environmental conditions. We find that the optimal exploitation policies are sensitive to the type of the threatening events. Under endogenous uncertain events, the optimal stock process approaches the nearest edge of an equilibrium interval, or remains constant if the initial stock lies inside the equilibrium interval. The eventual equilibrium stock depends on the initial conditions. This phenomenon is familiar from the theory of irreversible investments under uncertainty, and is referred to as 'hysteresis'. In contrast, the equilibrium states under exogenous uncertain events are singletons that attract the optimal processes from any initial stock. The shift of these equilibrium states relative to their certainty counterparts is due to the marginal expected loss associated with the events and serves as a measure of how much prudence it implies.

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