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Resource Exploitation, Biodiversity Loss and Ecological Events

by

Yacov Tsur and Amos Zemel

P.O. Box 12, Rehovot 76100

ת.ד. 12, רחובות 76100

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Yacov Tsur[a] and Amos Zemel[b]

Abstract: We study the management of a natural resource that supports ecosystems as well as human needs. The reduction in the resource base introduces 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*. 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 when occurrence conditions are known with certainty.

Keywords: ecosystem; resource management; event uncertainty; biodiversity; extinction

[a]Department of Agricultural Economics and Management, The Hebrew University of Jerusalem, P.O. Box 12, Rehovot, 76100, Israel (tsur@agri.huji.ac.il).

[b]Department of Solar Energy and Environmental Physics, The Jacob Blaustein Institute for Desert Research, Ben Gurion University of the Negev, Sede Boker Campus, 84990, Israel and Department of Industrial Engineering and Management, Ben Gurion University of the Negev, Beer Sheva, 84105, Israel (amos@bgu.ac.il)

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; (iv) intensive pest control may lead to the extinction of the pests' natural predators and eventually to the invasion of an immune pest species which is harder to control; (v) overgrazing reduces soil fertility and the destruction of natural vegetation over vast semi-arid areas in central Asia and sub-Saharan Africa, contributing to the process of desertification; and (vi) airborne industrial pollution falls as acid rain on lakes and rivers and interferes with freshwater ecosystems. In some of 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 (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

ecosystem, inflicting a heavy damage and affecting the nature of future exploitation regimes. This is so because ecosystems are inherently complex and their highly nonlinear dynamics give rise to instabilities and sensitivity to threshold levels of essential supplies. Moreover, ecosystems 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 may also invoke the opposite effect, encouraging aggressive exploitation 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. It 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 by environmental circumstances that are genuinely stochastic and cannot be fully controlled by exploitation decisions. 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 event 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.

In this chapter we avoid detailed exposition and mathematical derivations of optimal policies under uncertainty (these can be found in a number of cited papers, particularly Tsur and Zemel 2001, 2004). Our aim here is to explain the line of

reasoning and present the main results characterizing optimal exploitation policies under threats of ecological events.

2. Ecological setup

We consider the management of some environmental resource that is essential to the survival of an ecosystem (or of a key species thereof) and at the same time is exploited in various production processes. The stock S of the resource can represent the area of uncultivated land of potential agricultural use, the water level at some lake or river or the level of cleanliness (measured e.g. by the ph level of a lake 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 groundwater recharge, to the decay rate of a pollution stock, or to the natural expansion rate of a forest area). 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 resource carrying capacity, such that $G(\bar{S}) = 0$ and $G'(\bar{S}) \leq 0$. With x_t representing the rate of resource exploitation, the resource stock evolves with time according to

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

Exploitation at a rate x entails several consequences. First, it generates a benefit flow at the rate $Y(x)$ (from the use of land, water or timber or from the economic activities that involve the emission of pollutants), where $Y(x)$ is increasing and strictly concave with $Y(0) = 0$. Second, it bears the exploitation cost $C(S)x$, where the unit cost $C(S)$ is nonincreasing and convex. Third, reducing the stock level (by setting $x > G(S)$) entails increasing the damage rate $D(S)$ inflicted upon the ecosystem that depends on the same resource for its livelihood. The damage function

is assumed to decrease with S and is normalized at $D(\bar{S}) = 0$. The net benefit flow is then given by $Y(x) - C(S)x - D(S)$.

Moreover, a decrease in the resource stock S increases the probability of occurrence of an influential event of adverse consequences due to the abrupt collapse of the ecosystem it supports. In some cases the event is triggered when S crosses an a priori unknown critical level, which is revealed only when occurrence actually takes place. Alternatively, the event may be triggered at any time by external effects (such as unfavorable weather conditions or the outburst of some disease). Since the resilience of the ecosystem 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 our 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 are sensitive to the distinction between the two types of uncertainty.

Let T denote the (random) event occurrence time, such that $[0,T]$ and (T,∞) are the *pre-event* and *post-event* periods, respectively. The benefit flow $Y(x) - C(S)x - D(S)$ defined above is the pre-event instantaneous net benefit. Let $\varphi(S_T)$ denote the post-event value at the occurrence time T, consisting of the value generated from the optimal post-event policy (discounted to time T) as well as of the immediate consequences of the event occurrence (see examples below).

An exploitation policy $\{x_t, t \geq 0\}$ gives rise to the resource process $\{S_t, t \geq 0\}$ via (2.1) and generates the expected present value

$$E_T\left\{\int_0^T [Y(x_t) - C(S_t)x_t - D(S_t)]e^{-rt}dt + e^{-rT}\varphi(S_T) \middle| T > 0\right\} \tag{2.2}$$

where E_T denotes expectation with respect to the distribution of T and r is the time rate of discount. The distribution of T and the ensuing conditional expectation depend on the nature of the event and on the exploitation policy. Given the initial stock S_0, we seek the policy that maximizes (2.2). In the next section, we consider the reference case in which the event occurrence conditions are known with certainty and characterize the optimal policy. Uncertain endogenous and exogenous events are studied in Sections 4 and 5, respectively.

3. Certain events

Suppose that driving the stock to some *known* critical level S_c triggers the collapse of the ecosystem and the loss of the species it supports, which entails a penalty $\psi > 0$ and prohibits any further decrease of the resource stock. The corresponding post-event value is $\varphi(S_c) = W(S_c) - \psi$, where

$$W(S) = [Y(G(S)) - C(S)G(S) - D(S)]/r \tag{3.1}$$

is the steady state value derived from keeping the extraction rate at the natural regeneration rate $G(S)$. 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 penalty implied by the loss of biodiversity. Since the event occurs as soon as the stock reaches the critical level S_c, the event occurrence time T is defined by the condition $S_T = S_c$ ($T = \infty$ if the stock is always kept above S_c).

Since T is subject to choice, the conditional expectation in (2.2) can be ignored and the management problem becomes

$$V^c(S_0) = Max_{\{T,x_t\}} \int_0^T [Y(x_t) - C(S_t)x_t - D(S_t)]e^{-rt}dt + e^{-rT}\varphi(S_T) \tag{3.2}$$

subject to (2.1), $x_t \geq 0$; $S_T = S_c$ and $S_0 > S_c$ given. Optimal processes associated with this "certainty" problem 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 $T = \infty$. The certainty problem, thus, can be reformulated as

$$V^c(S_0) = Max_{\{x_t\}} \int_0^\infty [Y(x_t) - C(S_t)x_t - D(x_t)]e^{-rt} dt \tag{3.3}$$

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 (3.3) 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 distinct 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 monotone and 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 (3.3) 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, we find that the evolution function is given by

$$L(S) = (r - G'(S))\left\{\frac{-C'(S)G(S) - D'(S)}{r - G'(S)} - [Y'(G(S)) - C(S)]\right\}. \tag{3.4}$$

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 carrying capacity level $\bar{S}$. The condition for the corner solution $L(S_c) < 0$ is obtained from (3.4) 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. 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 investing the proceeds yields the market interest rate r minus the loss in marginal regeneration $G'(S)$ (see, e.g., 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 is a 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 derived in Tsur and Zemel (2004).

When $L(S)$ obtains a root in $[S_c, \bar{S}]$, the constraint $S_t > S_c$ is never binding and the event has no effect on the optimal policy. 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 no-event optimal (i.e., the optimal policy without the constraint $S_t > S_c$), the event threat 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 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 two sections, to analyze the effect of uncertain catastrophic events on resource management policies.

4. Endogenous Events

Here the critical level S_c is imperfectly known and the uncertainty regarding the occurrence conditions is entirely due to our ignorance concerning the critical level rather than to the influence of exogenous environmental effects. The post-event value is specified, as above, $\varphi(S) = W(S) - \psi$.

Let $F(S) = Pr\{S_c \leq S\}$ and $f(S) = dF/dS$ denote the probability distribution and density functions of the critical level S_c and denote by $q(S)$ 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:

$$q(S) = f(S)/F(S). \tag{4.1}$$

We assume that $q(S)$ 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 in a nontrivial way, which depends on the exploitation policy. To see this notice that as the stock process evolves in time, the distributions of S_c and T are modified since at time t it is known 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 distributions of S_c and T involve $\tilde{S}_t$, i.e., the entire history up to time t, which complicates the evaluation of the conditional expectation in (2.2). The situation is simplified when the stock process S_t evolves monotonically in time, since then $\tilde{S}_t = S_0$ if the process is non-decreasing (and no

information relevant to the distribution of S_c is revealed), or $\tilde{S}_t = S_t$ if the process is non-increasing (and all the relevant information is given by the current stock S_t).

It turns out that the *optimal* stock process evolves monotonically in time. 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 optimal state 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. (See Tsur and Zemel 1994 for a complete proof.)

For a non-decreasing stock process it is known in advance that the event will never occur and the uncertainty problem reduces to the certainty problem (3.3). For non-increasing stock process the distribution of T is obtained from the distribution of S_c as follows:

$$1 - F_T(t) \equiv \Pr\{T > t | T > 0\} = \Pr\{S_c < S_t | S_c < S_0\} = F(S_t)/F(S_0). \tag{4.2}$$

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

$$\begin{aligned} &\text{(a)} \quad f_T(t) = dF_T(t)/dt = f(S_t)[x_t - G(S_t)]/F(S_0), \\ &\text{(b)} \quad h(t) = \frac{f_T(t)}{1 - F_T(t)} = q(S_t)[x_t - G(S_t)]. \end{aligned} \tag{4.3}$$

Let $I(\cdot)$ denote the indicator function that obtains the value one when its argument is true and zero otherwise. For non-increasing state process, the conditional expectation (2.2) can be expressed as

$$E_T\left\{\int_0^\infty [Y(x_t)-C(S_t)x_t-D(S_t)]I(T>t)e^{-rt}dt+e^{-rT}\varphi(S_T)\middle|T>0\right\}.$$

Notice that $E_T\{I(T > t)|T > 0\} = 1 - F_T(t) = F(S_t)/F(S_0)$ and, using (4.3), the expectation of the second term gives

$\int_0^\infty f_T(t)\varphi(S_t)e^{-rt}dt=\int_0^\infty f(S_t)[x_t-G(S_t)]\dfrac{\varphi(S_t)}{F(S_0)}e^{-rt}dt$. For non-increasing state processes the management problem becomes

$$V^{aux}(S_0)=$$
$$\max_{\{x_t\}}\left\{\int_0^\infty\{Y(x_t)-C(S_t)x_t-D(S_t)+q(S_t)[x_t-G(S_t)]\varphi(S_t)\}\frac{F(S_t)}{F(S_0)}e^{-rt}dt\right\} \tag{4.4}$$

subject to (2.1), $x_t \geq 0$ and S_0 given. This problem is referred to as the *auxiliary* problem and the associated optimal processes are denoted by the superscript *aux*. Since we show below that the auxiliary problem is relevant for the formulation of the uncertain-endogenous-event problem only for stock levels above the root $\hat{S}^c$ of $L(S)$, we complement the constraints of (4.4) by the requirement $S_t^{aux} \geq \hat{S}^c$.

Formulated as an autonomous problem, the auxiliary problem also gives rise to an optimal stock process that evolves monotonically in time. Notice that at this stage it is not clear whether the uncertainty problem at hand reduces to the certainty problem or to the auxiliary problem, since it is not a priori known whether the optimal stock process decreases with time. We shall return to this question after the optimal auxiliary processes are characterized.

The evolution function corresponding to the auxiliary problem (4.4) is given by (Tsur and Zemel, 2004)

$$L^{aux}(S) = [L(S) + q(S)r\psi]F(S)/F(S_0). \tag{4.5}$$

In (4.5), $L(S)$ is the evolution function for the certainty problem, defined in (3.2), and $q(S)$ is defined in (4.1). The event inflicts an instantaneous penalty ψ (or equivalently, a permanent loss flow at the rate $r\psi$) that could have been avoided by the safe policy of keeping the stock at the level S. The second term in the square brackets of (4.5) gives the expected loss due to an infinitesimal decrease in stock. Moreover, $L^{aux}(\hat{S}^c) > 0$ at the lower bound $\hat{S}^c$ (since $L(\hat{S}^c) = 0$ and $q(\hat{S}^c)r\psi > 0$), 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 $L^{aux}(S) > 0$ for all $S \in (\hat{S}^c, \bar{S})$, leaving only the corner state $\hat{S}^{aux} = \bar{S}$ as a potential steady state. Thus, 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 process S_t^{en} under endogenous uncertain events, we compare the trajectories of the auxiliary problem with those obtained with the certainty problem corresponding to $S_c = 0$ (the latter can be referred to as the 'non-event' problem because the event cannot be triggered; see Tsur and Zemel 2004). The following characterization holds:

(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 uncertain endogenous events. 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 intertemporal exploitation problem to 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 for uncertain exogenous events and the corresponding management problem does not give rise to equilibrium intervals.

Endogenous uncertain events imply more conservative exploitation as compared with the certainty case. 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 realized occurrence state S_c.

A feature similar to both the certain event and the endogenous uncertain event cases 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 at finite time with the inflicted damage.

5. Exogenous events

Ecological events that are triggered by environmental conditions beyond the planners' control are termed 'exogenous'. Changing the resource stock level can modify the *hazard* of immediate occurrence through the effect of the stock on the resilience of the ecosystem, but the collapse event is triggered by stochastic changes

in exogenous conditions. This type of event uncertainty has been applied for the modeling of a variety of resource-related situations, including nuclear waste control (Cropper 1976, Aronsson et al. 1998), environmental pollution (Clarke and Reed 1994, Tsur and Zemel 1998b) and groundwater resource management (Tsur and Zemel 2004). Here we consider the implications for biodiversity conservation. Under exogenous event 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 $\varphi(S)$ and the expected present value of an exploitation policy that can be interrupted by an event at time T is given in (2.2). The probability distribution of T, $F(t) = Pr\{T \leq t\}$, is defined in terms of a stock-dependent hazard rate function $h(S)$ satisfying

$$h(S_t) = f(t)/[1-F(t)] = -d\{log[1-F(t)]\}/dt, \tag{5.1}$$

such that

$$F(t) = 1- exp[-\Omega(t)] \text{ and } f(t) = h(S_t)exp[-\Omega(t)], \tag{5.2}$$

where

$$\Omega(t) = \int_0^t h(S_\tau)d\tau \,. \tag{5.3}$$

With a state-dependent hazard rate, the quantity $h(S_t)dt$ measures the conditional probability that the event will occur during $(t,t+dt)$ given that it has not occurred by time t when the stock level is S_t.

We assume that no stock level is completely safe, hence $h(S)$ does not vanish and $\Omega(t)$ diverges for any feasible stock process as $t \to \infty$. We further assume that $h(S)$

is decreasing, because a shrinking stock deteriorates the ecosystem conditions and increases the hazard for environmental collapse.

Given the distribution of T, (2.2) is evaluated by

$$E_T\left\{\int_0^T [Y(x_t)-C(S_t)x_t-D(S_t)]e^{-rt}dt \mid T>0\right\}$$
$$=E_T\left\{\int_0^\infty [Y(x_t)-C(S_t)x_t-D(S_t)]e^{-rt}I(T>t)dt \mid T>0\right\}$$
$$=\int_0^\infty [Y(x_t)-C(S_t)x_t-D(S_t)]e^{-rt}(1-F(t))dt$$

and $E_T\left\{e^{-rT}\varphi(S_T) \mid T>0\right\}=\int_0^\infty e^{-rt}\varphi(S_t)f(t)dt=\int_0^\infty e^{-rt}\varphi(S_t)h(S_t)(1-F(t))dt$.

Using (5.2), the biodiversity management problem is formulated as

$$V^{ex}(S_0)=\max_{\{x_t\}}\int_0^\infty [Y(x_t)-C(S_t)x_t-D(S_t)+h(S_t)\varphi(S_t)]e^{-rt-\Omega(t)}dt \tag{5.4}$$

subject to (2.1), $x_t \geq 0$; $S_t \geq 0$ and S_0 given. Unlike the auxiliary problem (4.4) used above to characterize decreasing policies under endogenous events, problem (5.4) provides the correct formulation under exogenous events regardless of whether the stock process decreases or increases. We use the superscript '*ex*' to denote optimal variables associated with the exogenous uncertainty problem (5.4).

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 value $W(S)$ defined in (3.1) to describe the value obtained from the steady state policy without occurrence risk. Under the steady state policy, (5.2) reduces to the exponential distribution $F(t) = 1 - exp[-h(S)t]$, yielding the expected steady state value

$$W^{ex}(S) = W(S) - [W(S)-\varphi(S)]h(S)/[r+h(S)], \tag{5.5}$$

where the second term represents the expected loss over an infinite time horizon. The explicit time dependence of the distribution $F(t)$ of (5.2) renders formulation (5.4) of the optimization problem non-autonomous. 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

$$L^{ex}(S) = L(S) + d\{[\varphi(S) - W(S)]rh(S)/[r+h(S)]\}/dS. \tag{5.6}$$

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 $\varphi(S) = W(S) - \psi$, and the second term of (5.6) 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 at or below $\hat{S}^c$. Thus, the root $\hat{S}^{ex}$ of $L^{ex}(S)$ must lie above the certainty equilibrium $\hat{S}^c$, implying more prudence and conservation compared to the policy free of uncertainty.

Biodiversity conservation considerations enter via the second term of (5.6) 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 a more prudent exploitation policy. Indeed, if the hazard is state-independent ($h'(S)=0$), the second term of (5.6) vanishes, implying that the evolution functions associated with the problems with certain events and exogenous uncertain events are the same and the resulting steady states coincide. In this case, exploitation has no effect on the expected loss hence the tradeoffs that determine the optimal equilibrium need not account for the biodiversity hazard, regardless of how severe it may be. For a

decreasing hazard function, however, the degree of prudence (as measured by the difference $\hat{S}^{ex} - \hat{S}^{c}$) increases with the penalty ψ.

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

Another interesting situation involving exogenous events arises when the damaged ecology can be restored at the cost ψ. For example, the extinct population may not be endemic to the inflicted region and can be renewed by importing individuals from unaffected habitats. When restoration is possible, event occurrence inflicts the penalty but does not affect the hazard of future events. Under the steady state policy, then, one remains at the steady state also after occurrence and receives the post-event value $W^{ex}(S) - \psi$. With the fixed hazard rate $h(S)$, the exponential distribution 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 that $W^{ex}(S) = W(S) - \psi h(S)/r$, reducing (5.6) to

$$L^{ex}(S) = L(S) - d[\psi h(S)]/dS. \tag{5.7}$$

When the event penalty ψ depends on the stock, policy implications become more involved. Of particular interest is the case of *increasing* $\psi(S)$ and constant hazard, for which (5.7) implies more *vigorous* exploitation. An increasing penalty is typical for situations in which the damage is related to the uninterrupted value, which usually increases with the resource stock. This result is similar to the outcome of the 'irreversible' catastrophic events of Clarke and Reed (1994), which also give rise to exploitation policies that are less prudent than their certainty counterparts.

6. 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 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 gradual sources of uncertainty (time-varying costs and demand, stochastic regeneration processes, etc.), which allow updating the exploitation policy in response to changing conditions, event uncertainty is resolved only upon 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. In most cases, the presence of event threat encourages conservation, but the opposite behavior can also be obtained.

A common feature to the types of events considered here is that information accumulated in the course of the process regarding occurrence conditions does not affect the original policy until the time of occurrence (see discussion of decreasing processes under endogenous events). In some situations, however, it is possible to learn during the process and continuously update estimates of the occurrence probability. This possibility introduces another consideration to the tradeoffs that determine optimal exploitation policies. In this case one has to account also for the information content regarding occurrence probability associated with each feasible policy. The investigation of these more complicated models is outside the scope of this chapter.

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