Ecol Res (2007) 22: 431–438
DOI 10.1007/s11284-007-0361-4

SPECIAL FEATURE

Sustainability and biodiversity of forest ecosystems: an interdisciplinary approach

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Bio-economic resource management under threats of environmental catastrophes

Received: 6 January 2006 / Accepted: 10 August 2006 / Published online: 28 March 2007

Abstract We combine ecological and economic dynamics to study the management of a natural resource that supports both ecosystem and human needs. Shrinking the resource base introduces a threat of occurrence of catastrophic ecological events, such as sudden ecosystem collapse. The occurrence conditions involve uncertainty of various types, and the distinction among these types is important for optimal resource management. 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. Genuinely stochastic events shift the optimal equilibrium states, but maintain the structure of isolated equilibria.

Keywords Ecosystem dynamics · Resource management · Event uncertainty · Biodiversity · Extinction

Introduction

Recent chronicles are marked by a series of freak environmental events of catastrophic dimensions. Tsunami waves, hurricanes, floods, earthquakes, and extended droughts have stricken various parts of the globe with devastating intensity, inflicting tremendous loss of human lives and impairing the livelihood of millions of people. Threats of deadly epidemic eruptions are also the source of universal concern. The reports on these events have naturally focused on their humanitarian aspects, but it is clear that some of the events also bear significant long-term ecological consequences, including habitat destruction and biodiversity loss.

In some cases the events are the outcome of natural processes that are not affected by human activities, and their policy implications concern mainly the steps required to mitigate the damage. Often, however, anthropogenic pressures on natural resources enhance the threat of occurrence of detrimental events. A case in mind is climate change exacerbated by greenhouse gases released by intensive use of fossil fuels. It is believed that this process can act as a major cause of extinction of numerous animal and plant species (Peterson et al. 2002; Thomas et al. 2004 and references therein). Other important examples are discussed below.

It is clear that a responsible management of our natural resources must account for these risks, which should be properly weighted against the benefits derived from resource exploitation. This work adopts an economic perspective in which human welfare is the dominant consideration. Ecosystem services, then, are valued according to their contribution to human well-being (Heal 2000; Limburg et al. 2002; Brock and Xepapadeas 2003). Often, the affected species do not contribute directly to economic production, 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) or crop resistance (Chichilnisky and Heal 1998). Economic valuations of biodiversity also emphasize its insurance role, building on the ecological premise that genetically rich ecosystems are more resilient and less prone to productivity loss or collapse as the environmental conditions change (Brock and Xepapadeas 2003).

We study the management of a natural resource that serves a dual purpose. First, it provides inputs for

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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 extinction and biodiversity loss. Examples for such conflicts abound, including: (1) water diversions for irrigation, industrial or domestic use reduce in-stream flows that support the existence of various fish populations; (2) reclamation of swamps and wetlands that serve as habitat for local plant, bird and animal populations and as "rest areas" for migrating birds (Czech and Parsons 2002); (3) large-scale deforestation (Achard et al. 2002) reduces the living territory of a large number of species, exposing them to risk of extinction (Brooks et al. 1997, 1999); (4) intensive pest control by farmers may entail a take-over by an immune pest species that is harder to control (Hueth and Regev 1974); (5) overgrazing interferes in grass-tree competition in the savannas, pushing towards states of lower productivity (Walker et al. 1981). Overgrazing is also claimed to induce soil erosion and fertility loss over vast semi-arid areas, accelerating desertification processes (Tsoar 1990; Villamil et al. 2001); (6) airborne industrial pollution falls as acid rain on lakes and rivers and interferes with freshwater ecosystems (Jeffries et al. 2003); (7) phosphorus loading into lakes due to agricultural use of fertilizers along the shores can induce an irreversible transition from the oligotrophic (clear) state into a eutrophic (turbid) state (Harper 1992; Carpenter et al. 1999), which severely degrades the value of the lake for fishing and recreation. A similar process is believed to endanger the future of the Baltic Sea (Jansson and Velner 1995).

Biodiversity loss is a good example of the issue under consideration. This process is often induced by a sudden collapse of the ecosystem that shifts the underlying ecology from the current species-rich regime to a new, species-poor regime. This is so because ecosystems are inherently complex, and their nonlinear dynamics can give rise to instabilities, sensitivity to various thresholds and hysteresis phenomena (Holling 1973; Ludwig et al. 1978, 1997; see also Mäler 2000; Limburg et al. 2002; Brock and Starrett 2003; Dasgupta and Mäler 2003 for an economic perspective). We refer to the occurrence of a sudden system collapse as an ecological event.

When the degradation 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 possible to avoid the damage by ensuring that the event will never occur. Often, however, the time of occurrence cannot be predicted in advance because the conditions that trigger ecological events involve uncertainty of various types. The present study characterizes optimal resource exploitation policies under the threat of such events.

Impacts of event uncertainty on resource exploitation policies have been studied in a variety of situations and contexts, including emission-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, 2004), and political crises (Long 1975; Tsur and Zemel 1998a). The hovering 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, 2007) 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 source of uncertainty: stochastic environmental conditions or partial ignorance (on the part of the planner) of key system parameters. We show that this 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 states. This feature, it turns out, no longer holds under ignorance-related 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. In contrast, stochastic events maintain the structure of isolated equilibria and the effect of uncertainty is manifest via the shift it induces on the equilibrium states.

In this paper, we avoid detailed exposition and mathematical derivations of optimal resource management under uncertainty [these are presented in Tsur and Zemel (2004, 2007) and the references they cite]. Our aim here is to explain the economic reasoning and show how ecological dynamics (manifest via abrupt event occurrence at some unknown future time) combine with economic considerations to characterize optimal exploitation policies under threats of environmental events.

The management problem

Resource economics analysis typically revolves around tradeoffs and balances. To determine optimal exploitation policies one needs to weigh the benefits derived from the use of the resource against the associated costs. The tradeoffs take various forms depending on the specific context. In the simpler cases, one compares the diminishing marginal benefits from resource use to the increasing cost or damage implied by this use. The solution to this static optimization problem determines optimal extraction, beyond which further exploitation is not worthwhile, giving rise to 'economic depletion'. In other scenarios, the tradeoff is between current benefits and future scarcity. Problems of this type are analyzed using dynamic optimization techniques and attention is focused on the physical depletion of the resource: under what conditions is depletion desirable, and when should depletion take place? The considerations of the present work are intertemporal, but the tradeoff is between current benefits and the increasing hazard of a hovering environmental catastrophe.

We consider the management of some environmental resource that is essential to maintain a functioning ecosystem and at the same time is exploited for human production activities. The stock S of the resource can represent the uncultivated area of land of potential agricultural use, the water level at some lake or river or the degree of cleanliness (measured, e.g., by atmospheric concentrations or as the pH level of a lake affected by acid rain or polluting effluents). Without human interference, the stock dynamics are 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 $G'(\bar{S}) \leqslant 0$. With x_t representing the rate of resource exploitation, the resource stock evolves with time according to

$$\mathrm{d}S_t/\mathrm{d}t = G(S_t) - x_t. \tag{2.1}$$

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). Second, it bears the exploitation cost $C(S)x$, where the unit cost $C(S)$ can depend on the resource stock. Third, reducing the stock level [by setting $x > G(S)$] entails decreasing the value of the services derived from the ecosystem that depends on the same resource for its livelihood. This loss of value is expressed in terms of the damage rate $D(S)$. 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 stochastic 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. Both types of uncertainty imply that the occurrence time cannot be predicted in advance. Nevertheless, it turns out that the optimal policies are sensitive to the distinction between these types.

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 $Y(x_t) - C(S_t)x_t - D(S_t)$ defined above is the pre-event net benefit flow at time $t < T$. Let $\varphi(S_T)$ denote the post-event value at the occurrence time T, consisting of the present value generated by the optimal post-event policy from time T onward (discounted to time T) as well as the immediate consequences of the event (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

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

where E_T denotes the expectation operator with respect to the probability distribution of T and r is the time rate of discount (for extended discussions on the choice of the discount rate, see the collection of works edited by Portney and Weyant 1999). The distribution of T and the ensuing conditional expectation depend on the type of uncertainty and on the exploitation policy. Given the initial stock S_0, we seek the feasible policy that maximizes (2.2) subject to (2.1). In the next section, we consider the reference case in which T can be predicted prior to occurrence and characterize the optimal policy for this case. Endogenous and exogenous uncertainty are discussed in Sects. 4 and 5, respectively.

Predictable occurrence time

Suppose that driving the stock to some *known* critical level S_c triggers ecosystem collapse, which entails an immediate damage (penalty) $\psi > 0$ and prohibits any further decrease of the resource stock. Given that the critical state S_c has been reached, the optimal post-event policy is to maintain the stock at that level and 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 present value generated by the steady-state policy that sets the exploitation rate at the natural regeneration rate $G(S)$. The post-event value $\varphi(S_c)$, thus, accounts both for the fact that the stock cannot be further decreased (to avoid further damage) and for the penalty implied by occurrence. The event is triggered at the critical level S_c, hence the 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

$$V^{c}(S_0) = \mathrm{Max}_{\{T,x_t\}}\left\{\int_0^T [Y(x_t) - C(S_t)x_t - D(S_t)]e^{-rt}dt + e^{-rT}\varphi(S_T)\right\} \quad (3.2)$$

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. 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, the stock is kept above the critical level for all t and $T = \infty$. The certainty problem, thus, is reformulated as

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

subject to (2.1), $x_t \geq 0$; $S_t > S_c$ and S_0 given. The effect of the known critical stock enters only via the lower bound imposed on the stock process. 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 Zemel 1994, 1995, 2004). Here, we 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 the optimal stock process exhibiting a local maximum, 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, which is determined by the model specifications. 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 $L(\cdot)$, 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 problem at hand, we find that 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 maximum level $\bar{S}$. The condition for convergence to the other corner solution (the critical level S_c) is discussed below.

Under the appropriate curvature assumptions, $L(S)$ has a unique root $\hat{S}^c$ in $[S_c, \bar{S}]$. In this case, $\hat{S}^c$ is the unique steady state to which the optimal state process S_t^c converges monotonically from any initial stock.

When the function $L(S)$ obtains a root above the critical state S_c, the constraint $S_t > S_c$ is never binding because there is no advantage in shrinking the stock below the steady state. Thus, the risk of occurrence has no effect on the optimal policy. However, with $S_c > \hat{S}^c$ a process approaching the root of $L(S)$ must cross the critical state and trigger the event, which cannot be optimal. 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.

While the discussion above implies that the stock process must approach a steady state, the time to enter this 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 and the approach of S_t^c towards the steady state is asymptotic, i.e., the optimal stock process will not enter 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).

The event in this formulation 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. In fact, 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 analyzing the effect of uncertain catastrophic events on resource management policies.

Endogenous events

A catastrophic event is called endogenous if its occurrence is determined solely by the resource exploitation policy, although the exact threshold level S_c at which the event is triggered is not a-priori known and the event occurrence time, for a given exploitation policy, cannot be predicted in advance. This type of uncertainty, however, allows avoiding the occurrence risk altogether by keeping the resource stock at or above its initial state

S_0. The post-event value is specified again as $\varphi(S) = W(S) - \psi$.

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 the threshold S_c induces a distribution on the occurrence time T in a nontrivial way, which depends on the exploitation history. 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 the lowest state so far, $\tilde{S}_t = \text{Min}_{0 \leqslant \tau \leqslant t}\{S_\tau\}$ (otherwise the event would have occurred at some time prior to t). Thus, the distributions of S_c and T involve the entire history up to time t, which complicates the evaluation of the conditional expectation in (2.2). It appears, therefore, that (2.2) is not a proper formulation of a dynamic optimization problem. However, 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) and $\tilde{S}_t = S_t$ if the process is non-increasing (and all the relevant information is given by the current stock S_t).

As in the case of a known threshold, the *optimal* stock process evolves monotonically in time also under uncertainty. 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. For a complete proof, see Tsur and Zemel (1994).

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) 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). For non-increasing stock process the distribution of T is obtained from the distribution of S_c as follows:

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

Using this T-distribution, the conditional expectation (2.2) can be evaluated for non-increasing state processes, yielding the following management problem

$$V^{\text{aux}}(S_0) = \max_{\{x_t\}} \left\{ \int_0^\infty \{Y(x_t) - C(S_t)x_t - D(S_t) + q(S_t)[x_t - G(S_t)]\varphi(S_t)\} \frac{F(S_t)}{F(S_0)} e^{-rt} dt \right\} \tag{4.3}$$

subject to (2.1), $x_t \geq 0, S_t \geqslant \hat{S}^c$ and S_0 given. This problem is referred to as the *auxiliary* problem, and the associated optimal processes are denoted by the superscript *aux*.

Formulated as an autonomous problem, the auxiliary problem also gives rise to an optimal stock process that converges monotonically to a steady state. We find that the associated steady state $\hat{S}^{\text{aux}}$ represents a higher resource stock than the steady state $\hat{S}^c$ corresponding to the certainty problem, and the difference depends on the quantity $q(S)r\psi$ that measures the expected loss due to an infinitesimal decrease in stock. (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 current level S.)

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. In order to determine the optimal process S_t^{en} implied by endogenous events, we compare the trajectories of the auxiliary problem with those obtained with the certainty problem corresponding to $S_c = 0$. The following characterization holds:

(a) S_t^{en} increases at stock levels below $\hat{S}^c$ (coinciding with the certainty process S_t^c).
(b) S_t^{en} decreases at stock levels above $\hat{S}^{\text{aux}}$ (coinciding with the auxiliary process S_t^{aux}).
(c) All stock levels in $[\hat{S}^c, \hat{S}^{\text{aux}}]$ 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 intertemporal exploitation problem to two distinct optimization problems depending on the initial trend of the optimal stock process. At $\hat{S}^{\text{aux}}$, 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 exogenous events that do not give rise to equilibrium intervals.

Endogenous uncertainty implies 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 critical state S_c.

A feature similar to both the certain event and the endogenous 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 find out if 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 and the damage will be inflicted.

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 no exploitation policy is completely safe since 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, when exogenous circumstances turn out to be less favorable. Therefore, the mechanism that gives rise to equilibrium intervals 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

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

hence

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

where

$$\Omega(t) = \int_0^t h(S_\tau)\mathrm{d}\tau \quad (5.3)$$

can be considered as a cumulative 'hazard stock'. With a state-dependent hazard rate, the quantity $h(S_t)\mathrm{d}t$ measures the conditional probability that the event will occur during the infinitesimal interval $(t, t + \mathrm{d}t)$ 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 ecosystem conditions and increases the hazard for environmental collapse.

Given the distribution of T, the management problem (2.2) is formulated as

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

subject to (2.1), $x_t \geq 0$; $S_t \geq 0$ and S_0 given. Unlike the auxiliary problem (4.3) used above to characterize decreasing policies under endogenous events, problem (5.4) provides the correct formulation for exogenous events regardless of whether the stock process decreases or increases. We use the superscript '*ex*' to denote variables associated with the exogenous uncertainty problem (5.4).

The explicit time dependence of the distribution $F(t)$ of (5.2) renders formulation (5.4) of the optimization problem non-autonomous. [Note the presence of the hazard stock $\Omega(t)$ in the effective discount factor]. Nevertheless, the argument for the monotonic behavior of the optimal stock process S_t^{ex} holds, and the associated steady states can be derived (see Tsur and Zemel 1998b).

When the event corresponds to species extinction, it can occur only once and the loss is irreversible. If a further reduction in the hazard-mitigating stock is forbidden, the steady state $\hat{S}^{ex}$ 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 shift in steady states, 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 stock-independent ($h'(S) = 0$), 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 hazard, regardless of how severe the damage may be. For a decreasing hazard function ($h'(S) < 0$), 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 steady states, 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 a penalty, but does not affect the hazard of future events. For this case, we find that the shift in equilibrium states depends on $d[\psi h(S)]/dS$, which measures the sensitivity of the expected damage to small changes in stock.

When the event penalty ψ also depends on the stock S, policy implications become more involved. Curiously, the case of increasing $\psi(S)$ and constant hazard implies more vigorous exploitation, compared to the risk-free environment (Clarke and Reed 1994). An example for this situation is the case of a "doomsday" event (following which the ecosystem is ruined forever, so that no post-event benefit can be derived) induced by an earthquake or a volcanic eruption (hence the corresponding hazard is independent of S). In this case, the damage equals the overall value of the ecosystem, which increases with the resource stock. As the rate of extraction does not affect the occurrence probability, the hovering threat encourages enhanced extraction in order to enjoy as much benefit as is possible prior to occurrence.

Concluding comments

Exploitation of natural resources is typically considered in the context of their direct contribution to human activities, while their roles in supporting ecological needs are often overlooked in the economic analysis. In this work, we examine ways to incorporate ecological considerations within resource exploitation models. We focus on threats of abrupt ecological events whose occurrence inflicts a penalty due to an adverse change in the ecosystem regime. Unlike gradual changes (time-varying costs and damage, stochastic regeneration processes, etc.), which allow adaptation and updating the exploitation policy in response to the changing conditions, abrupt event uncertainty is resolved only upon occurrence, when policy changes cannot prevent the damage. Thus, the expected loss must be fully accounted for prior to occurrence, with significant modifications to the optimal resource management 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 random environmental conditions. We find that the optimal exploitation policies are sensitive to the type of the threatening events. Under endogenous events, the optimal stock process approaches the nearest edge of an equilibrium interval or remains fixed if the initial stock lies inside the equilibrium interval. The eventual equilibrium stock depends on the initial conditions. 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 they imply. In most cases, the hovering threat encourages conservation.

A feature common to all the 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. 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. While learning and expectations have been incorporated within economic models of gradual environmental damage (see Karp and Zhang 2006), the investigation of these more complicated models in the context of abrupt events is yet to be undertaken.

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