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המרכז למחקר בכלכלה חקלאית

THE CENTER FOR AGRICULTURAL ECONOMIC RESEARCH

Working Paper No. 9603

Pollution Control in an
Uncertain Environment
by
Yacov Tsur and Amos Zemel

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Pollution Control in an Uncertain Environment

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Abstract:

The effects of the threat of occurrence of environmental catastrophes on optimal pollution control is considered. Recent analysis of irreversible events is extended to two types of reversible events: single-occurrence and multiple-occurrence (recurrent) events. While it is possible that the threat of irreversible events induces more pollution, we show that reversible events, under quite general conditions, induce more conservation (less pollution). The analysis is carried out via a simple method (the " $h\delta$ -method") to identify optimal steady states by comparing steady state policies with small variations from them. For recurrent events the optimal state process must approach a unique steady state from any initial level. In this case, the $h\delta$ -method characterizes the dynamic behavior of the optimal state process without actually solving for it.

Key words: Pollution management; Environmental uncertainty; Reversible events

JEL Classification: Q20, Q25, Q28

Pollution Control in an Uncertain Environment

1. Introduction

Some consequences of increased pollution of air, water and soil occur abruptly or over a short period of time. Such is the case, for instance, with the outbreak of pollution-induced diseases, or the collapse of an ecosystem as one of its links ceases to perform. When the conditions that lead to occurrence are well understood and involve no uncertainty, avoiding or preparing for such catastrophes is relatively easy. Doing this, however, is much harder when occurrence conditions involve uncertainty. In this note we study pollution control under uncertainty with regard to the occurrence of undesirable, pollution-induced events.

Earlier works on consumption/pollution tradeoff, e.g., Plourde (1972), Keeler *et al.* (1972), Smith (1972) and Forster (1975), are deterministic in nature. The importance of stochastic features was recognized and incorporated by Cropper (1976) and later studied by Heal (1984,1990), Reed (1989), Clarke and Reed (1994), Tsur and Zemel (1994,1995,1996), Plourde and Yeung (1989), and Conrad (1992). Except for the latter two references (in which uncertainty is with regard to the accumulation of pollution or to the flow of its damage), uncertainty in these works concerns the occurrence date of discrete events that adversely affect welfare.

The events considered are quite diversified, ranging from nuclear accidents [Cropper, (1976)], via natural collapse due to air or water pollution [Clarke and Reed, (1994), Tsur and Zemel (1995)], through consequences of global warming and species extinction [Tsur and Zemel, (1994,1996)]. Though different in many respects, classifying events based on two properties turns out to be particularly useful. The first is the

reversibility property: an event is *irreversible* if its occurrence stops the process for ever (either because life ceases to exist or because the resource under planning is rendered obsolete); otherwise, the event is *reversible* and its effects are specified in terms of some penalty. The second property concerns the conditions that trigger occurrence. Events whose occurrence is determined solely by the planner's actions are signified as *endogenous*. For this class of events, uncertainty refers to our ignorance concerning the occurrence conditions rather than to the intrinsic stochastic nature of the events. It follows that the occurrence hazard depends on the complete pollution history up to the current time as well as on the current trend. In contrast, we say that the event is *exogenous* if the event is triggered by environmental (exogenous) conditions. In this case, uncertainty stems from the genuinely random nature of the environmental processes that control occurrence. The occurrence hazard for exogenous events depend, therefore, only on the current pollution level, but not on the pollution history nor on the current trend.

Endogenous events were studied by Tsur and Zemel (1994,1995,1996) who looked at resource management under risk of events that occur as soon as the resource state crosses an unknown threshold level. While in the non-event situation the optimal state processes converge to a unique equilibrium state, the presence of event risk gives rise to equilibrium intervals. This peculiar structure was found to prevail both for reversible and irreversible events, and was traced to the fact that for endogenous events history matters: the threshold level must lie above all pollution levels that have been reached in the past.

In this work we focus on exogenous events--those triggered by stochastic environmental conditions--continuing the line of research set forth by Cropper (1976) and advanced recently by Clarke and Reed (1994). Clarke and Reed considered *irreversible* events. We develop a general framework, of which the irreversible events are a special case, and consider reversible events of two kinds: events that occur only once and events that may re-occur over and over again. Regardless of the reversibility property, it is established that the equilibrium structure differs significantly from that corresponding to endogenous events: the steady states are identified as the isolated roots of a simple function of the pollution level (the "evolution function"), and equilibrium intervals never occur.

The analysis is carried out via a comparison with a decision problem in which the event cannot occur. For this *non-event* problem, there exists a unique equilibrium state to which the optimal state processes (the pollutants concentration) converge from any initial state level. The presence of event threat shifts this equilibrium level. We say that the event risk induces conservation if the corresponding equilibrium state entails less pollution than the equilibrium state associated with the non-event problem.

While Clarke and Reed (1994) find that irreversible events often (though not always) lead to less conservation (more pollution), as compared with the non-event situation, we find the opposite for reversible events. The presence of such events always leads to more conservation. This observation is explained by the different state-dependence of the penalty associated with each type of event.

Our analysis is based on a method, denoted the $h\delta$ -method, that identifies the set of states that can serve as optimal equilibrium states. The $h\delta$ method has first been employed to exclude certain levels from the list of possible equilibria in the analysis of endogenous events [Tsur and Zemel, (1995)]. It is in the context of the present case of exogenous events that the method shows its full power, permitting one to characterize the equilibrium structure of the process without having to derive the dynamic solutions. The next section sets up the problem and applies the $h\delta$ -method to the general case. In section 3 we consider irreversible and two types of reversible events in more detail. Section 4 concludes.

2. The problem

The general setup follows closely that of Clarke and Reed (1994). The state variable P represents the total pollution level. Natural purification and decay processes reduce the amount of pollution at the rate $R(P)$. It is maintained that $R(P)$ is smoothly increasing (with a bounded first derivative) and concave. The natural, pre-industrial pollution level at which $R(P)$ vanishes is normalized at $P = 0$.

Anthropogenic activity increases the amount of pollution P at the emission rate g . The accumulated pollution, thus, evolves in time according to

$$dP_t/dt \equiv \dot{P}_t = g_t - R(P_t) \quad (2.1)$$

The pollution flow g is a by-product of production processes that generate goods. The tradeoff between the utility provided by these goods and the disutility caused by pollution is represented by the instantaneous net welfare function $B(g, P)$. This function accounts for the benefits resulting from the production activity corresponding to the emission rate g

as well as the direct environmental costs associated with the pollution level P . The latter might include increased health expenses, reduced agricultural crops, degraded economic value of recreational areas and enhanced corrosion of materials and buildings. We assume that B satisfies:

$$\begin{aligned} \partial B / \partial P \equiv B_2(g, P) \leq 0; \quad \partial^2 B / \partial g^2 \equiv B_{11}(g, P) < 0; \quad \partial^2 B / \partial g \partial P \equiv B_{12}(g, P) \leq 0; \\ \text{and } \partial^2 B / \partial P^2 \equiv B_{22}(g, P) \leq 0. \end{aligned}$$

We also postulate the existence of a limiting pollution level $\bar{P}$ above which the whole environmental system is bound to collapse. Thus,

$$B(g, P) \rightarrow -\infty \text{ as } P \rightarrow \bar{P}.$$

In addition to the direct costs, the planner must consider also the consequences of a possible occurrence, at any pollution level P , of an environmental event (possibly a catastrophe). The occurrence is determined by stochastic exogenous conditions and its probability is described in terms of a state-dependent hazard-rate function $\lambda(P)$. Thus, the probability that no event will occur before or at time T is given by

$$1 - F(T) = \exp\left\{-\int_0^T \lambda(P_t) dt\right\}. \quad (2.2)$$

We assume that $\lambda(P)$ is a smooth, non-decreasing function of P , with a bounded first derivative.

The events are classified according to their consequences: An event is *irreversible* if following its occurrence welfare is reduced irreversibly to zero (or to some other low constant level) and the planning problem is terminated (e.g., when the resource under consideration is rendered obsolete). This class of events was analyzed by Clarke and Reed (1994). An event is *reversible* if its occurrence inflicts an instantaneous penalty $\psi(P)$, following which the process proceeds. If there is no further

occurrence risk, i.e. the post-event hazard vanishes (for an example, see Section 3.3), we refer to the event as a *single-occurrence reversible* event. Finally, a reversible event is *recurrent* if it can re-occur in the future with a probability that is independent of past events.

For the two reversible events, the pollution level P plays a dual role: it affects the occurrence probability (through the hazard rate $\lambda(P)$), and it determines its consequences (through the penalty function $\psi(P)$). We investigate the effects of these events on pollution control policies.

A pollution policy (or plan) consists of the emission process g_t and the associated state process P_t , $t \geq 0$. A plan is feasible if, for all t , (2.1) is satisfied, g_t is piecewise continuous and nonnegative, and $P_t \leq \bar{P}$.

Let $\phi(P)$ be the post-event value function; that is, $\phi(P)$ is the value of the optimal plan if the event occurred at state P . In view of (2.2), the expected, pre-event value at any pre-event state P is expressed as

$$V(P) = \max_{\{g_t\}} \int_0^{\infty} \lambda(P_T) \exp\left\{-\int_0^T \lambda(P_t) dt\right\} \left\{ \int_0^T B(g_t, P_t) e^{-\rho t} dt + e^{-\rho T} \phi(P_T) \right\} dT \quad (2.3)$$

subject to (2.1), $g_t \geq 0$, $P_t \leq \bar{P}$ and $P_0 = P$, where ρ is the time rate of discount. Clarke and Reed (1994) have shown how the optimal plan associated with (2.3) with $\phi = 0$ (the irreversible case) can be characterized via optimal control techniques. Here we follow a different approach.

First we observe that problem (2.3) is autonomous in nature, hence the past history is irrelevant and the *optimal* state process associated with $V(P)$ (assuming it exists) must evolve monotonically in time [it is verified in Tsur and Zemel, (1994) that if the optimal plan is not unique, at least one optimal plan must be monotonic]. For recurrent events, monotonicity

applies to the entire process. For non-recurrent events, the post-event problem involves no uncertainty and the corresponding optimal process is trivially monotonic (the process combined of the pre-event and the post-event trajectories may, however, be non-monotonic).

Being monotonic and bounded, the optimal pre-event state process associated with $V(P)$ must approach a steady state. (Note that for the non-recurrent events, this planned steady state may never be reached if the event interrupts beforehand.) The location of the possible equilibria is therefore of prime importance and we identify such states via:

The $h\delta$ -Method

This method determines whether a state level P can be an optimal steady state by comparing the steady-state policy (which maintains the emission rate g equals to the removal rate $R(P)$ until a catastrophe occurs) to a small (infinitesimal) variation from it. If the variation improves the value, P is excluded from the list of possible steady states.

Let $W_e(P)$ represent the value generated by the steady state policy:

$$\begin{aligned} W_e(P) &= E_T \left\{ \int_0^T B(R(P), P) e^{-\rho t} dt + e^{-\rho T} \phi(P) \right\} \\ &= B(R(P), P)/\rho - [B(R(P), P)/\rho - \phi(P)] E_T \left\{ e^{-\rho T} \right\} \end{aligned}$$

or

$$W_e(P) = W_n(P) - [W_n(P) - \phi(P)] \lambda(P) / [\rho + \lambda(P)], \quad (2.4)$$

where E_T represents expectation with respect to the distribution (2.2) of T and $W_n(P) = B(R(P), P)/\rho$ is the non-event steady state benefit (when it is certain that a catastrophe will never occur).

For arbitrarily small constants $h > 0$ and δ , define the feasible variation on the steady state plan by

$$g_t^{h\delta} = \begin{cases} R(P) + \delta, & 0 \leq t < h \\ R(P_h), & t \geq h \end{cases} \quad (2.5)$$

With this plan, we find for all $t \leq h$, using the fact that $R'(P)$ is bounded,

$$P_t - P = \int_0^t [R(P) + \delta - R(P_s)] ds = \delta t + o(\delta t). \quad (2.6)$$

The expected benefit associated with $g_t^{h\delta}$ comprises two terms, depending on whether the event occurs before or after time h . If the event occurs at or before h , the expected benefit is

$$V_{T \leq h}^{h\delta} = \int_0^h \lambda(P_T) \exp\left\{-\int_0^T \lambda(P_t) dt\right\} \left[\int_0^T B(P_t, R(P) + \delta) e^{-\rho t} dt + e^{-\rho T} \varphi(P_T) \right] dT.$$

The benefit when $T > h$, weighted by the probability that $T > h$, is

$$V_{T > h}^{h\delta} = \exp\left\{-\int_0^h \lambda(P_t) dt\right\} \left[\int_0^h B(P_t, R(P) + \delta) e^{-\rho t} dt + W_e(P_h) e^{-\rho h} \right].$$

Using (2.6), we expand these expression around P , neglecting terms that are

$o(h\delta)$. For example, $\int_0^h \lambda(P_t) dt = \lambda(P)h + o(h\delta)$. Thus,

$$\begin{aligned} V_{T \leq h}^{h\delta} &= (1 - e^{-\lambda(P)h}) W_n(P) + (1 - e^{-(\lambda(P) + \rho)h}) \left(\varphi(P) - W_n(P) \right) \frac{\lambda(P)}{\lambda(P) + \rho} + o(h\delta) \\ &= W_e(P) - e^{-\lambda(P)h} W_n(P) - e^{-(\lambda(P) + \rho)h} \left(\varphi(P) - W_n(P) \right) \frac{\lambda(P)}{\lambda(P) + \rho} + o(h\delta), \end{aligned}$$

and

$$V_{T > h}^{h\delta} = e^{-\lambda(P)h} (1 - e^{-\rho h}) W_n(P) + W_e(P) e^{-(\lambda(P) + \rho)h} + [B_1(R(P), P) + W'_e(P)] h\delta + o(h\delta).$$

Combining terms, we use (2.4) and find that the total expected benefit

$$\begin{aligned} V^{h\delta}(P) &= V_{T \leq h}^{h\delta} + V_{T > h}^{h\delta} \text{ satisfies} \\ V^{h\delta}(P) - W_e(P) &= L_e(P) \delta h / \rho + o(h\delta) \end{aligned} \quad (2.7)$$

where $L_e(P) = \rho[B_1(R(P), P) + W'_e(P)]$ is denoted as the evolution function of the optimization problem. The crucial role played by the evolution

function in the determination of the equilibrium structure will be explained below.

It is expedient here to introduce the reduced hazard rate $\lambda_e(P) = \rho\lambda(P)/[\rho + \lambda(P)]$ and use (2.4) to eliminate W_e . Since $\rho W'_n(P) = B_1(R(P), P)R'(P) + B_2(R(P), P)$, we can express the evolution function $L_e(P)$ in the form

$$L_e(P) = L(P) - [(W_n(P) - \phi(P))\lambda_e(P)]' \quad (2.8)$$

where $L(P) = B_1(R(P), P)[\rho + R'(P)] + B_2(R(P), P)$ is recognized as the evolution function associated with the non-event optimization problem, for which it is known with certainty that a catastrophe will never occur [Tsur and Zemel, (1994)]. Observe that $L_e(P)$ reduces to $L(P)$ when $\lambda(P)$ vanishes for all P .

Equation (2.7) determines the equilibrium structure of the optimization problem (2.3). Every state level at which $L_e(P)$ does not vanish cannot qualify as an equilibrium state because one can choose the constants h and δ small enough (with δ and $L_e(P)$ having the same sign), to ensure that $V^{h\delta}(P) - W_e(P) > 0$, so that the steady state policy yielding $W_e(P)$ is sub-optimal. We have therefore established that only the roots of $L_e(P)$ can be equilibrium states. The only possible exception is the end-point level $P = 0$, since this unpolluted level can be an equilibrium state if $L_e(0) \leq 0$ because $\delta < 0$ is not feasible for this state. (The upper level $\bar{P}$ could also be an equilibrium state if $L_e(\bar{P}) \geq 0$, because $\delta > 0$ is not feasible for this overly polluted state. However, the assumed properties of $B(g, \bar{P})$ ensure that $L_e(\bar{P})$ must be negative.)

3. Catastrophic events

In this section we consider three types of events whose differences are manifested by their corresponding post-event value functions. Our major concern is the question of conservation: under which conditions does the presence of event uncertainty imply less pollution. As our point of reference is the non-event situation, we briefly summarize this case first.

3.1. Non-event

When no event can possibly interrupt the pollution control plan, the problem reduces to standard optimization, involving no uncertainty. This simple problem is treated as a reference case for most of the uncertainty models, using various techniques. Its analysis in terms of the evolution function L is first given by Tsur and Zemel (1994,1995). Here it also serves as a simple illustration of the usefulness of the $h\delta$ -method. For this problem, $L_e(P) = L(P)$. The assumed properties of B and R ensure that $L(P)/[\rho + R'(P)]$ is strictly decreasing, while $[\rho + R'(P)]$ is positive. We have already observed that $L(\bar{P})$ must be negative. Thus, there exists a unique state level $\hat{P}$ in $[0, \bar{P})$, satisfying

$$\begin{cases} \hat{P} = 0 & \text{if } L(0) < 0 \\ L(\hat{P}) = 0 & \text{otherwise} \end{cases}$$

Let P_t^n denote the optimal state process of the non-event problem. As P_t^n progresses monotonically in time and is bounded between 0 and $\bar{P}$, it must converge to a steady state. The $h\delta$ -method, then, implies that $\hat{P}$ is the unique equilibrium level to which P_t^n converges from any initial level.

3.2 Irreversible events

Irreversible events have been studied by Clarke and Reed (1994) as a model for catastrophes that reduce social welfare to zero. For these events $\phi(P) \equiv 0$ and (2.8) reduces to $L_e(P) = L(P) - [W_n(P)\lambda_e(P)]'$, or

$$L_e(P) = \{L(P) + \lambda(P)B_1(R(P), P) - \lambda'(P)B(R(P), P)/[\rho + \lambda(P)]\}\rho/[\rho + \lambda(P)]. \quad (3.1)$$

It is easily verified that the roots of $L_e(P)$ satisfy eq. (46) of Clarke and Reed (1994) which identifies the steady states. Below $\hat{P}$, when $L(P) > 0$, one finds that $B_1(R(P), P) > -B_2(R(P), P)/[\rho + R'(P)] \geq 0$.

Therefore, if the hazard rate is constant, $L_e(P) =$

$[L(P) + \lambda B_1(R(P), P)]\rho/[\rho + \lambda] > 0$ and L_e can have no roots at $P < \hat{P}$. This is consistent with Clarke and Reed's observation that a constant hazard rate implies *more* pollution at the steady state than the pollution at the equilibrium level of the non-event situation. However, if the hazard rate increases strongly with P , the term involving $\lambda'(P)$ may dominate the sign of L_e , yielding a root below $\hat{P}$. In this case, a more conservative plan will follow. A detailed interpretation of these results is provided by these authors.

3.3 Single-occurrence reversible events

A catastrophe of this type can occur only once, inflicting a penalty but not terminating the economic activity. For example, the extinction of a certain species results in a biodiversity loss (penalty) but otherwise does not cease the process that caused extinction [see Tsur and Zemel, 1994)]. For such events, the optimal post-event policy is to follow the non-event policy, hence the post-event value assumes the form $\phi(P) = V_n(P) - \psi(P)$, where $\psi(P)$ is the penalty associated with a catastrophe at the level P and $V_n(P)$ is the non-event value. We assume that $\psi(P)$ is

differentiable and non-decreasing. The evolution function L_e of (2.8) specializes to

$$L_e(P) = L(P) - [(W_n(P) - V_n(P))\lambda_e(P)]' - [\psi(P)\lambda_e(P)]'. \quad (3.2)$$

We show now that no equilibrium state can fall above $\hat{P}$, i.e., single-occurrence reversible events induce more conservation (less pollution).

Proposition 3.1: When the hazard rate $\lambda(P)$ and the penalty $\psi(P)$ associated with single-occurrence reversible events are non-decreasing, a state level $P > \hat{P}$ cannot be an optimal steady state.

Proof: For any state $P > \hat{P}$ we show that the non-event plan yields a higher value than the steady state policy. By the non-event plan we mean the plan that follows the optimal process P_t^n associated with the non-event problem both before and after occurrence, paying the penalty when required. The steady state policy means setting $g = R(P)$ until occurrence and following the non-event plan thereafter.

The benefit generated by the non-event plan is

$$U(P) = V_n(P) - E_T\{e^{-\rho T}\psi(P_T^n)\} = V_n(P) - \int_0^\infty \psi(P_T^n)\lambda(P_T^n)\exp\left\{-\int_0^T [\lambda(P_t^n) + \rho]dt\right\}dT,$$

where P_T^n is the level along the non-event trajectory at which the event occurs. From (2.4), the benefit generated by the steady state is

$$W_e(P) = \{B(P, R(P)) + [V_n(P) - \psi(P)]\lambda(P)\} / [\rho + \lambda(P)].$$

Since $U(P)$ is feasible, for a state P to be an optimal equilibrium state we evidently need $W_e(P) \geq U(P)$.

However, when passing through $P > \hat{P}$, the non-event process P_t^n decreases, hence $\lambda(P_t^n) \leq \lambda(P)$ for all T . Thus,

$$\rho\lambda(P_t^n) + \lambda(P)\lambda(P_t^n) \leq \rho\lambda(P) + \lambda(P)\lambda(P_t^n) = \lambda(P)[\rho + \lambda(P_t^n)] \quad \text{or,}$$

$$\lambda(P_t^n) \leq \lambda(P)[\rho + \lambda(P_t^n)] / [\rho + \lambda(P)].$$

Also, $\psi(P_T^n) \leq \psi(P)$ and

$$\begin{aligned}
 U(P) &\geq V_n(P) - \psi(P) \int_0^\infty \lambda(P_T^n) \exp\left\{-\int_0^T [\lambda(P_t^n) + \rho] dt\right\} dT \\
 &\geq V_n(P) - \frac{\psi(P)\lambda(P)}{\rho + \lambda(P)} \int_0^\infty [\rho + \lambda(P_T^n)] \exp\left\{-\int_0^T [\lambda(P_t^n) + \rho] dt\right\} dT \\
 &= V_n(P) + \frac{\psi(P)\lambda(P)}{\rho + \lambda(P)} \exp\left\{-\int_0^T [\lambda(P_t^n) + \rho] dt\right\} \Big|_{T=0}^{T=\infty} = V_n(P) - \frac{\psi(P)\lambda(P)}{\rho + \lambda(P)}.
 \end{aligned}$$

Thus, $W_e(P) \geq U(P)$ implies $[B(P, R(P)) + V_n(P)\lambda(P)]/[\rho + \lambda(P)] \geq V_n(P)$, or $B(P, R(P))/\rho \geq V_n(P)$, which is impossible unless $P = \hat{P}$. ■

To better understand the role played by the different terms of (3.2), we use the property that $L(P)$ and the difference $W'_n(P) - V'_n(P)$ always have the same signs [Tsur and Zemel, (1994)]. Denoting the optimal non-event emission policy by $g^n(P)$, standard dynamic programming considerations give $V'_n(P) = -B_1(g^n(P), P)$, while $\rho W'_n(P) = B_1(R(P), P)R'(P) + B_2(R(P), P)$. It follows that

$$\begin{aligned}
 \rho[W'_n(P) - V'_n(P)] &= B_2(R(P), P) + B_1(R(P), P)[R'(P) + \rho] + \rho B_{11}(\tilde{g}, P)[g^n(P) - R(P)] \\
 &= L(P) + \rho B_{11}(\tilde{g}, P)dP/dt,
 \end{aligned}$$

where $\tilde{g}$ is some value between $g^n(P)$ and $R(P)$, or

$$L(P) - \rho[W'_n(P) - V'_n(P)] = -\rho B_{11}(\tilde{g}, P)dP/dt,$$

which has the same sign as $L(P)$. Now, $\lambda_e(P) = \rho\lambda(P)/[\rho + \lambda(P)] \leq \rho$, hence $L(P) - \lambda_e(P)[W'_n(P) - V'_n(P)]$ also shares the same sign with $L(P)$. With an increasing hazard rate, $[V_n(P) - W_n(P)]\lambda'_e(P)$ is nonnegative, thus the sum of the first two terms on the right-hand side of (3.2) is positive below $\hat{P}$, while the last term is negative. At $\hat{P}$, the first two terms vanish and $L_e(\hat{P}) < 0$. The question whether a root of L_e which can serve as an equilibrium state is formed in $(0, \hat{P})$ depends on whether the sum of the

first two terms on the right-hand side of (3.2) exceeds in magnitude the negative $-\psi(P)\lambda_e(P)$ contribution. If the penalty is very large, or if it changes rapidly, such a root does not exist and the expected loss due to the event will drive the process towards the unpolluted, natural state.

3.4. Recurrent events

Consider a situation in which enhanced pollution, combined with certain atmospheric conditions, can trigger the outburst of a certain disease, which can be cured at a cost. Such an unfortunate scenario can repeat over and over again, when certain conditions reoccur. Unlike the previous case of a single event, occurrence here does not entail a resolution of uncertainty nor a passage to the non-event situation. Rather, apart from the inflicted penalty, nothing new is learnt and the ensuing pollution control problem is the same as before occurrence. For such events, therefore, $\phi(P) = V(P) - \psi(P)$ in (2.3). However, the derivation of the evolution function L_e based on this specification does not produce a useful form due to the presence of the value function $V(P)$, which is not a-priori known.

In deriving the relevant L_e function, the $h\delta$ -method considers steady state policies and small variations from them. For recurrent events the steady state policy should remain unaltered after occurrence, and the appropriate post-event value to be used in (2.4) is $\phi(P) = W_e(P) - \psi(P)$, where $W_e(P)$ is the value under the steady state policy, yielding

$$W_e(P) = W_n(P) - [W_n(P) - W_e(P) + \psi(P)]\lambda(P)/[\rho + \lambda(P)] \quad \text{or} \\ W_e(P) = W_n(P) - \lambda(P)\psi(P)/\rho. \quad (3.3)$$

To be consistent with this post-event value, we demand in the $h\delta$ -policy (2.5) that the steady state policy is implemented upon occurrence also if

$T < h$. Using (2.8) and (3.3) we obtain the evolution function for recurrent events

$$L_e(P) = L(P) - [\psi(P)\lambda(P)]'. \quad (3.4)$$

As both the penalty and the hazard functions are non-decreasing, the last term of (3.4) is nonnegative and $L_e(P)$ can have no roots above $\hat{P}$.

Therefore, recurrent events induce conservation, in similarity with single-occurrence reversible events. The existence of a root below $\hat{P}$ depends on the magnitude of $L(P)$ vis-a-vis the contribution of the $[\psi(P)\lambda(P)]'$ penalty term. Indeed, if the product $\psi(P)\lambda(P)$ is convex in P , this root is unique and the state process must approach it monotonically from any initial level.

Let $\hat{P}_e$ be the root of $L_e(P)$ if such a root exists in $[0, \hat{P}]$ and $\hat{P}_e = 0$ otherwise. The above considerations are summarized in terms of

Proposition 3.2. If $\psi(P)\lambda(P)$ is non-decreasing and convex in P , the state level $\hat{P}_e$ is the unique equilibrium state to which the optimal pollution process corresponding to recurrent events converges from any initial pollution level.

Observe that for recurrent events the true hazard rate $\lambda(P)$ appears in L_e , while for single events we find the reduced hazard rate $\lambda_e(P) = \rho\lambda(P)/[\rho + \lambda(P)]$. This reflects the different possibilities considering future occurrence. Indeed, when $\lambda(P) \ll \rho$, the damage due to a second event is diminished by the discount term. In this case $\lambda_e(P) \cong \lambda(P)$ and the two types of reversible events are nearly indistinguishable. In contrast, the difference between the two event types becomes noticeable at the other extreme, when $\lambda(P) \gg \rho$. In this case, one knows that the event

will come soon, almost regardless of the control policy. Following occurrence for single events, the planner needs not worry about future penalty and λ_e reduces to p in this limit. Under recurrent event uncertainty, however, occurrence probability remains unchanged and the high value of the hazard rate continues to dominate the time evolution of the state process along its way towards equilibrium.

4. Concluding comments

This work considers pollution control under uncertainty with regard to environmental catastrophes, continuing the line of research initiated by Cropper (1976). In particular, we extend Clarke and Reed's (1994) analysis of irreversible events to two types of reversible events: single-occurrence and multiple-occurrence (recurrent) events. While it is possible (as explained by Clarke and Reed) that the threat of irreversible events induces more pollution, we show here that reversible events, under quite a general condition, induce more conservation (less pollution). The "general condition" is that both the hazard rate of the occurrence date and the penalty the event inflicts are non-decreasing functions of the pollution level.

Why are the irreversible events so different? Formally, one could view them as reversible events, with a penalty that just equals the value forgone due to occurrence. The value function, however, generally *decreases* with pollution whereas for reversible events a *non-decreasing* penalty function has been postulated. For the latter type of events, pollution increases both the hazard rate and the penalty and both effects lead to more conservation, whereas for irreversible events pollution decreases the "penalty" and the conflicting trends may lead to less

conservation. In this respect, the exogenous events considered here vary greatly relative to the endogenous events of Tsur and Zemel (1994, 1995, 1996), for which event uncertainty always entails more conservation.

The analysis is carried out via a simple method (the $h\delta$ -method) to locate possible equilibria by comparing steady state policies with small variations from them. When only one optimal steady state exists, the $h\delta$ -method characterizes the dynamic behavior of the system, which must approach the steady state from any initial level. Such is the case for recurrent events when the instantaneous expected penalty $\lambda(P)\psi(P)$ is a non-decreasing and convex function of the pollution state. Deriving the optimal state process for the recurrent event problem will have to resort to dynamic programming methods because the value $V(P)$ in (2.3) is only implicitly defined when $\phi(P) = V(P) - \psi(P)$, and optimal control methods cannot be directly applied. It is remarkable that the $h\delta$ -method can locate the steady state and characterize the dynamics of the optimal state process without actually solving for it.

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