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Dynamic and stochastic analysis of environmental and natural resources

by

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Dynamic and stochastic analysis of environmental and natural resources

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Abstract

Uncertainty enters the dynamic tradeoffs of environmental and natural resource management in a variety of ways and forms. In this chapter we review the various sources of uncertainty, the methodologies developed to account for them and implications regarding management of environmental and natural resources.

Keywords: resource management; environmental policy; uncertainty; catastrophic events; irreversibility.

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1 Introduction

Environmental and resource economics is the branch of economics in which human activities interact with natural processes, giving rise to complex dynamical systems. Since the natural processes that constrain the options open to resource managers evolve in ways that are often poorly understood, the responsible management of natural resources must account for the dynamical and uncertainty aspects of the combined human-natural systems. These two aspects make the central theme of this chapter.

The importance of uncertainty considerations in the design of environmental policies has long been recognized and the literature dealing with this topic is vast (see the recent reviews of Heal and Kriström 2002, Pindyck 2007). In this chapter, we consider this issue emphasizing the rich variety of forms in which uncertainty enters all components of the management problems. Uncertainty stems from two main sources: (i) our own limitations in understanding key natural and economic parameters and (ii) genuine stochastic elements that govern the evolution of the systems under consideration. It can show up as unpredictable disturbances to the evolution of an ecosystem, either in the form of abrupt discrete occurrences ("catastrophic events") or as an ongoing stream of small stochastic shocks which drive diffusion processes that need to be controlled.

Obviously, the diversity of uncertainty sources and types calls for a variety of methods to model and handle them as well as for various (often conflicting) policy measures to respond to their influence on the systems to be managed. Here we review various methods and approaches that have been considered in the literature for dealing with uncertainty in the context of natural resource management. We begin with a schematic ("canonical") resource management model (Section 2) and proceed to show how the various types of uncertainty enter each of its elements (Section 3). In actual practice, resource managers may face more than a single type of uncertainty at the same time. We point out that the interaction between the various types can give rise to new complex effects.

In a more general setup the management problem cannot be restricted to the resource sector but must be considered in a wider context, with various economy-wide variables both affecting and being affected by the environmental and natural resource sectors. To account for such considerations we describe a framework that integrates natural resources and aggregate economic growth and use it to discuss additional effects of uncertainty (Section 4). In Section 5 we direct attention to the concept of irreversibility characterizing many resource management situations. Irreversible outcomes are particularly relevant when coupled with uncertainty, because they can otherwise be anticipated and avoided when so desired. Finally, we discuss briefly the case of Knightian uncertainty (Section 6) under which the underlying structure of uncertainty (e.g., the specification of the underlying distribution) is incompletely known.

2 The canonical resource management model

In a typical resource management situation, an initial resource stock Q_0 is to be exploited over some planning horizon $t \in [0, T]$, t being the running time index and T is the end of the planning period which may or may not be predetermined. At any instant of time the remaining stock $Q(t)$ is given and the exploitation rate $q(t)$ generates the instantaneous benefit $u(Q(t), q(t), t)$

and changes $Q(t)$ according to

$$\dot{Q}(t) \equiv dQ(t)/dt = G(Q(t), q(t), t). \tag{1}$$

A simple example of a stock dynamic process is obtained from the specification $G(\cdot) = R(Q) - q$, where $R(\cdot)$ represents natural recharge (growth, replenishment). For nonrenewable resources, e.g., minerals, R vanishes at all times and $G = -q$.

An exploitation policy $\{T, q(t), t \in [0, T]\}$ generates the payoff

$$\int_0^T u(Q(t), q(t), t)e^{-\rho t}dt + e^{-\rho T}v(Q(T)), \tag{2}$$

where ρ is the time rate of discount and $v(\cdot)$ is the post-planning value (the present value at time T of the benefit stream over the post-planning period $t > T$). The policy is feasible if it satisfies some given constraints on T and on $\{Q(t), q(t), t \in [0, T]\}$, e.g., T is given or restricted to a certain range, the stock $Q(t)$ is positive or bounded in some range and $q(t) \geq 0$ for all $t \in [0, T]$. We denote by Γ the set of all feasible policies.

The optimal policy is the feasible policy that maximizes (2) subject to (1) given $Q(0) = Q_0$. The value of (2) obtained under the optimal policy is denoted $V(Q_0; \Gamma)$ and is called the value function. For brevity, the argument Γ is often dropped, leaving the initial resource stock as the sole argument of the value function.

The formulation of the resource management problem in this way started with Hotelling (1931) who considered exhaustible (nonrenewable) resources and characterized optimal extraction policies in different market settings, using the Calculus of Variations to verify economic reasoning. The development of Optimal Control and Dynamic Programming methods opened the way for a wide range of extensions, including the incorporation of uncertainty of various kinds and forms.

In real world situations uncertainty is likely to be present in each of the components of the resource management problem: the planning horizon T, the instantaneous benefit $u(\cdot,\cdot,\cdot)$, the discount rate ρ, the post-planning value $v(\cdot,\cdot)$, the recharge process $R(\cdot,\cdot)$, the initial reserve Q_0 as well as the specification of the feasibility constraints. In this chapter we survey different approaches to deal with uncertainties often encountered in resource management problems.

2.1 Full information

Before delving into extensions involving uncertainty, it is expedient to summarize the salient properties of the optimal policy of the canonical management problem formulated above. Suppose that at some time t the resource owner is offered the opportunity to increase the remaining stock $Q(t)$ by a marginal unit. What is the maximal amount the owner will be willing to pay (at time t) to realize this opportunity? The answer, obviously, is the contribution of the added stock to the resource value at time t, i.e., $V'(Q(t)) \equiv \partial V(Q)/\partial Q|_{Q=Q(t)}$. Let $\lambda(t)$ represent this opportunity cost at time t when the remaining stock is $Q(t)$. The variable $\lambda(\cdot)$ comes under various names, including co-state, shadow price, scarcity or royalty rent and *in-situ* value. By definition, it embodies the economic implications of stock changes, such as increasing extraction costs as the resource dwindles and the price of scarcity when a nonrenewable resource is nearing depletion.

Exploitation at the rate $q(\cdot)$ bears two effects. First, it provides the instantaneous gratification $u(\cdot)$. Second, it changes the available stock via

Eq. (1), hence the potential to enjoy future gratifications. The (current-value) Hamiltonian,

$$H(Q, q, \lambda, t) \equiv u(Q, q, t) + \lambda G(Q, q, t),$$

balances these two effects such that the optimal exploitation rate maximizes it at each point of time. The economic interpretation of this "maximum principle" is readily seen under the specification $G(Q, q, t) = R(Q) - q$ and when the maximization admits an internal solution, in which case the optimal rate q satisfies $\partial u/\partial q = \lambda$: along the optimal path, the marginal benefit from exploitation should equal the shadow price of the resource, i.e., the marginal cost of exploitation.

Once the $\lambda(\cdot)$ process is given, the Hamiltonian maximization determines the optimal exploitation rate and, via Eq. (1), the ensuing stock process for the entire planning period $t \in [0, T]$. Solving the management problem, then, requires the determination of the shadow price process, for which Optimal Control and Dynamic Programming are two approaches.

In many cases the optimal stock process $Q(\cdot)$ approaches a steady state (perhaps only asymptotically when $T = \infty$), where exploitation and natural recharge just balance each other out. This is the case, for example, in infinite horizon, autonomous problems (where the time argument enters explicitly only via discounting) involving a single stock. In such problems, it has been shown that the optimal stock process is monotonic, hence (when bounded) must eventually converge to a steady state. Deriving the steady state is relatively easy even for problems that do not admit analytic solutions for the full dynamic evolution. Comparing the steady states under different conditions (model specifications, parameter values) provides a simple way to study the effects of changes in the underlying conditions on the optimal policy.

The canonical resource management problem has been studied extensively and the relevant literature is vast. For detailed treatments we refer to Clark (1976) and Dasgupta and Heal (1979) who discussed resource management in a variety of situations, emphasizing renewable and nonrenewable resources, respectively.

3 Resource management under uncertainty

As mentioned above, uncertainty abounds in resource management situations. It is important to distinguish at the outset between two types of uncertainty, depending on its origin. The first type is due to the participants (resource owners, users, regulators etc.) limited knowledge of certain parameters or functional relations characterizing the resource and the economic systems under consideration. The second type is due to genuine random elements often encountered when dealing with mother nature. We refer to the former type as *ignorance uncertainty* and to the latter as *exogenous uncertainty.* For example, the recharge or instantaneous benefit may undergo an abrupt shift when the stock process crosses some threshold, but the exact location of this threshold is a-priori unknown. There is nothing inherently random in the threshold parameter, except that it is unknown to the resource manager, hence the uncertainty is due to ignorance. If, however, the abrupt regime shift depends also on exogenous environmental factors such as weather variables affecting the outburst of a pollution-induced disease, then its occurrence is triggered by the confluence of environmental conditions which are genuinely stochastic and the uncertainty regarding the abrupt shift is exogenous. How to handle a particular source of uncertainty depends to a large extent on its type.

We proceed now to discuss the incorporation of uncertainty, considering in turn each component of the above canonical resource management model.

3.1 Uncertain T

Some resource management problems do not admit a natural completion time, in which case the planning horizon becomes infinite ($T = \infty$). In other cases extraction must cease at a finite date T, while the considerations related to later periods are summarized in the post-planning value $v(Q(T))$. For example, mine developers may be permitted to extract the mineral only until some given date T when their concession expires. Moreover, the depletion of nonrenewable resources (or of renewable resources like fisheries that can be exploited to extinction) marks the end of the planning horizon, which depends on the extraction policy. In these cases the planning horizon is either given exogenously or is a decision variable which can be determined for any extraction policy. In either case, its incorporation within the management problem involves no uncertainty and poses no particular difficulty.

In many situations, however, T is subject to uncertainty. A prominent example is that of an unknown initial stock – a situation studied initially by Kemp (1976). In such cases, T is a random variable whose realization marks the depletion of the resource, at which time management shifts to the post-planning period. A slight extension of the term "depletion" to include situations in which the resource can no longer be exploited or becomes obsolete allows to associate T with an uncertain date of nationalization (Long 1975) or with the uncertain arrival of a backstop substitute (Dasgupta and Heal 1974, Dasgupta and Stiglitz 1981). Cropper (1976) presented the problem in an environmental pollution context, identifying T with the random triggering of various environmental catastrophes.

While the uncertainty in the cake-eating problem of Kemp (1976) is solely due to ignorance, the uncertainty in political (nationalization) or economical (technological breakthrough) events often involve genuine stochastic elements and is therefore exogenous. The distinction between the two types of uncertainty plays out most pronouncedly via the specification of the hazard rate function, measuring the probability density of the event occurrence (the realization of T) in the next time instant. In all of these variants, the management problem seeks to maximize the *expected* value of the objective (2) with respect to the distribution of T and the latter closely depends on the type of uncertainty.

3.1.1 Ignorance uncertainty

A common ignorance-uncertainty situation involves a catastrophic event triggered by the stock falling below some unknown threshold. Examples, in addition to Kemp's cake-eating problem, include seawater intrusion into coastal aquifers (Tsur and Zemel 1995) and global warming induced catastrophes (Tsur and Zemel 1996, Nævdal 2006). The hazard rate in this case measures the probability of crossing the threshold during the next time instant. If the stock process does not decrease (e.g., extraction does not exceed the natural recharge) or if the stock process was in the past strictly lower than its current level, the hazard vanishes (it is certain that the threshold will not be crossed in the next time instant). In contrast, decreasing stock processes proceed under risk of occurrence. This feature complicates the formulation and solution of the management problem. The situation is greatly simplified if only monotonic stock processes are allowed. It turns out that in many cases of interest the *optimal* stock process is indeed monotonic.

The characterization of the optimal monotonic stock process proceeds along the following steps. Let $\hat{Q}^c$ be the optimal steady state of the risk-free (canonical) problem. Consider an initial stock $Q_0 < \hat{Q}^c$. Since it is not optimal to decrease the stock further even without the risk of triggering a damaging event, it is obviously not optimal to do so under the event risk. The optimal process under occurrence threat, then, coincides with the (increasing) risk-free process and approaches a steady state at $\hat{Q}^c$.

Suppose that $Q_0 > \hat{Q}^c$. Then, the optimal stock process cannot increase. For if it increases, the monotonicity property implies that it will never decrease, in which case the hazard vanishes at all times and the problem reduces to that of the risk-free problem. But without the occurrence risk, the optimal stock process converges to $\hat{Q}^c$ – a contradiction. So when $Q_0 > \hat{Q}^c$, the optimal stock process is non-increasing.

Let X denote the unknown threshold stock with the probability distribution $F(Q) \equiv Pr\{X \leq Q\}$ and the corresponding density $f(Q) = F'(Q)$. For a decreasing stock process, the distribution

$$F_T(t) \equiv Pr\{T \leq t\} = Pr\{X \geq Q(t)\} = 1 - F(Q(t))$$

and the density

$$f_T(t) = F_T'(t) = -f(Q(t))\dot{Q}(t)$$

of the random occurrence time T determine the expected payoff (the expectation of Eq. (2) with respect to T). This expected payoff defines the objective of a deterministic management problem, denoted the "auxiliary" problem, which also admits a monotonic optimal stock process that converges to a steady state $\hat{Q}^{aux} > \hat{Q}^{c}$. It turns out that the resource management problem under uncertain threshold splits into two distinct deterministic subproblems, depending on the initial stock: for $Q_0 < \hat{Q}^{c}$ the optimal stock process is the same as the increasing *risk-free* process and the occurrence risk can be ignored; for $Q_0 > \hat{Q}^{aux}$ the optimal process coincides with the decreasing *auxiliary* process and the occurrence risk is relevant. If $Q_0 \in [\hat{Q}^{c}, \hat{Q}^{aux}]$, the uncertainty process enters a steady state instantly (at the initial state Q_0) because any other policy is ruled out by the above considerations. The *steady-state interval* $[\hat{Q}^{c}, \hat{Q}^{aux}]$ is a peculiar feature, unique to optimal behavior under ignorance uncertainty.

Note the prudence implications of this characterization: decreasing stock processes turn on the occurrence risk, hence approach a higher (and safer) steady state than that obtained without occurrence risk. Another interesting observation relates to the role of learning in this model. Decreasing stock processes provide new information regarding the threshold location as these processes proceed. This information, however, is already accounted for by the auxiliary objective and the resource owners have no reason to update the original policy (designed at $t = 0$) as the information accumulates, unless the process is interrupted at some time by the catastrophic occurrence.

3.1.2 Exogenous uncertainty

Under exogenous uncertainty, the event is triggered by genuinely random conditions and the probability of occurrence within the next time instant is measured by the hazard rate (Long 1975, Cropper 1976, Heal 1984). The hazard rate in this case depends neither on the history of the process nor on its trend (increasing or decreasing) hence the splitting of the uncertainty problem into two distinct subproblems (that gave rise to the equilibrium interval under ignorance uncertainty) does not occur. The hazard rate can, however, depend on the current resource stock and exploitation rate, which allows the owners to affect, even if not avoid completely, the risk of future occurrence by adjusting the extraction policy. This type of events has been assumed in a variety of resource models, including Deshmukh and Pliska (1985) who studied exploitation and exploration of nonrenewable resources, Reed and Heras (1992) in the context of biological resources vulnerable to a catastrophic collapse, Clarke and Reed (1994) and Tsur and Zemel (1998) in the context pollution control, Cropper (1976) and Aronsson et al. (1998) who considered the risk of nuclear accidents and Gjerde et al. (1999), Haurie and Moresino (2006) and Bahn et al. (2008) in the context of climate policies under risk of environmental catastrophes.

Given the stock process $Q(\cdot)$, the stock-dependent hazard process $h(\cdot)$ is related to the probability distribution and density of the event occurrence time, $F(t) = Pr\{T \le t)$ and $f(t) = F'(t)$, according to

$$h(Q(t))\Delta \equiv Pr\{T \in (t, t+\Delta) \,|\, T > t\} = \frac{f(t)}{1 - F(t)}\Delta.$$

Thus, $h(Q(t)) = -d\ln(1 - F(t))/dt$ hence

$$F(t) = 1 - e^{-\int_0^t h(Q(s))ds} \text{ and } f(t) = h(Q(t))[1 - F(t)].$$

The expectation (with respect to T) of the objective (2) becomes

$$\int_0^\infty [u(Q(t), q(t), t) + h(Q(t))v(Q(t))]e^{-\int_0^t [\rho + h(Q(\tau))]d\tau}dt. \tag{3}$$

The optimal policy is the feasible policy that maximizes the objective (3) subject to Eq. (1) and $Q(0) = Q_0$. In this way, the uncertainty problem is recast as a standard deterministic infinite horizon problem. Its optimal policy is relevant only as long as the event has not occurred. Once the event occurs, the optimal policy switches to that of the post-event problem (represented by the post-event value v).

The event occurrence risk affects the resource management problem via the hazard rate, which enters the objective (3) both in the discount rate and in the instantaneous benefit $(u + hv)$. The discount rate increases from ρ to $\rho + h$ with two conflicting effects. First, the increased impatience (due to the higher discount rate) promotes aggressive exploitation (less conservation). Second, the discount rate $\rho + h(Q)$ turns endogenous through its dependence on the stock. The possibility to control the discount rate via the extraction policy typically encourages conservation, and the tradeoffs associated with the discounting effect are represented by the hazard rate of change $h'(Q)/h(Q)$.

The other effect of the occurrence threat on the management problem comes through the $h(Q)v(Q)$ term, which is added to the instantaneous benefit in the objective (3). When this term depends on the stock, the resource owners can control the expected damage of the event by adjusting the extraction policy. The overall uncertainty effect results from balancing these conflicting trends. In a particularly simple example, the post-event value $v(\cdot)$ vanishes identically at all Q levels. This is the case, for example, when the event occurrence renders the resource obsolete with no further consequences or when it is possible to renormalize the instantaneous benefit in such a way that the post-event value vanishes (see, e.g., Tsur and Zemel 2009, Karp and Tsur 2011). In this case, only the discounting effects remain. When the hazard is independent of the stock, only the impatience effect is active and the ensuing optimal policy entails more aggressive exploitation than its risk-free counterpart: if the world may come to an end tomorrow and there is noting we can do about it, we may as well exploit the resource today while we can. However, if the hazard is sensitive to the resource stock, such that more exploitation increases the occurrence probability, then the endogeneity of the discount rate encourages conservation. Which of these effects dominates depends on $h'(Q)/h(Q)$ (see discussion in de Zeeuw and Zemel 2012).

A slightly more general formulation describes the post-event value $v(\cdot)$ in terms of a penalty inflicted upon occurrence. Tsur and Zemel (1998) distinguish between single occurrence and "recurrent" events. The latter entails multiple penalties inflicted each (random) time the event occurs. For penalty functions that decrease with the stock, both types of events imply more conservative exploitation vis-à-vis the risk-free policy. A prominent example of recurrent events is the case of forest fires which affect forest rotation management (see Reed 1984).

Events that impact ecosystems often entail abrupt changes in the system dynamics. The post-event value in such cases is the outcome of the (risk-free) post-occurrence optimization problem proceeding under the new regime. When the change in dynamics implies a loss (e.g. via reduced natural replenishment of the resource) the extraction policy under uncertainty is more conservative than its risk-free counterpart (see Polasky et al. 2011, and references they cite).

Catastrophic events of global nature, such as those induced by global warming, are often exogenous to local decision units (countries, regions). In such cases, the occurrence hazard is taken parametrically by the decision maker. The damage inflicted by the event, however, may change across locations, with particular grave outcomes to some specific nations. A possible response by local governments to this state of affairs is to consider adaptation activities in order to reduce or eliminate the damage that will be inflicted by the event, should the mitigation efforts (via reduced exploitation) fail to avoid its occurrence. The adaptation activities entail some given costs while the benefit (of reduced damage) will be enjoyed only following the (uncertain) occurrence date. The optimal adaptation policy should balance these costs and benefits (see de Zeeuw and Zemel 2012, Tsur and Withagen 2011, and references therein). When the occurrence probability can be affected by mitigation policies, the two policy measures interact strongly and must be considered simultaneously to obtain optimal outcomes. Indeed, the mere presence of the adaptation option can modify the extraction policy even prior to the actual implementation of this option.

Our discussion has focused on unfavorable events such as environmental catastrophes. Favorable events, e.g., technological breakthroughs, can be modeled in a similar way. Early studies of the uncertain arrival of a backstop substitute for nonrenewable resources with R&D efforts include Dasgupta et al. (1977), Kamien and Schwartz (1978) and Davison (1978). Bahn et al. (2008) considered such events in a renewable resource context of a climate policy that includes R&D efforts to develop clean energy technologies.

3.2 Stochastic stock dynamics

The dynamics of resource stocks is often driven by stochastic elements. Examples include biomass growth subject to random shocks, the replenishment of groundwater aquifers under uncertain precipitations, atmospheric pollution decay varying with changing weather conditions and oil and mineral reserves subject to uncertain discoveries. The random shocks can come in the form of an ongoing stream of small fluctuations or as abrupt and substantial discrete occurrences. The latter show up, for example, when the resource evolution process undergoes a regime shift which entails the uncertain T scenario discussed above. Here we consider the continuous flow of small fluctuations giving rise to a diffusion (or random walk) process. As before, uncertainty regarding the stock evolution may be due to genuine random environmental shocks (Reed 1979, Pindyck 1984), or due to incomplete information. For example, the resource owners may be unable to measure the current stock precisely or to follow exactly the optimal extraction rule, leading to errors in predicting the next period's stock (Clark and Kirkwood 1986, Roughgarden and Smith 1996).

Reed (1974, 1979) considered a biomass stock (e.g. fish population) Q_t following the discrete-time natural growth rule

$$Q_{t+1} = Z_t R(Q_t),$$

where $R(\cdot)$ is the *expected* stock recruitment and Z_t are independently and identically distributed unit-mean random variables representing stochastic shocks affecting the population growth in each reproduction season. The resource stock is revealed following the realization of Z_t, yet the future evolution of the stock process cannot be predicted. In general, the concept of a steady state must be replaced by that of steady state distribution. However, if the realizations of the random shocks are observed before harvest decisions are made, the optimal policy maintains a constant escapement (post-harvest biomass), i.e., the optimal steady state distribution of escapement degenerates to a constant (Reed 1979). When additional sources of uncertainty (e.g. errors in the measurement of current stocks) are added, the constant escapement rule no longer holds (see Section 3.6). A similar stochastic growth rule has been used by Weitzman (2002) to compare fishery regulation via landing fees with (the more common) harvest quota. He found that the former measure is more effective in this case.

Pindyck (1984) formulated the resource management problem under stochastic stock evolution in continuous time, employing Itô's stochastic calculus. The stock evolution follows a diffusion process which evolves according to the stochastic differential equation

$$dQ = [R(Q) - q]dt + \sigma(Q)dZ, \tag{4}$$

where Z is a standard Wiener process and $\sigma^2(\cdot)$ is the corresponding variance. Specifying $\sigma(Q) = \sigma Q$, with σ a given constant, gives rise to a geometric Brownian motion and greatly facilitates the analysis. Taking again the expected cumulative net benefit as the objective for optimization, one can employ stochastic Dynamic Programming to derive the optimal extraction rule $q(Q)$ and the associated steady state distribution. The prudence implications for this type of uncertainty are again ambiguous, and depend on the properties of the recharge and benefit functions (see Pindyck 1984, for examples in which the optimal exploitation rule $q(Q)$ increases, remains unchanged or decreases as the variance parameter σ is increased).

Other examples of resource management under stochastic stock dynamics include Plourde and Yeung (1989), Knapp and Olson (1995) and Wirl (2006). The former considers pollution control when the accumulation process is stochastic due to the random absorption capacity of the ecosystem and finds that a user charge on inputs is preferable to the common "pollution standards" approach. This result is similar to that obtained by Weitzman (2002) in the discrete time setting. The second paper studies groundwater management with stochastic recharge due to uncertain precipitation, while the third studies climate policies under a stochastic global temperature process.

3.3 Discounting

Effects of discount rate variability are most pronounced when consequences of resource exploitation extend far into the distant future, such as in climate change or in nuclear waste disposal problems. In such cases, even slight changes in the discount rate entail exceedingly large differences in the weight assigned to the well being of generations in the distant future and on optimal policies.

The discount rate changes with time preferences and technological shocks. Uncertain discounting due to future technological shocks has been analyzed in a number of works (see Gollier and Weitzman 2010, and references therin). Based on the discount rate distribution, an expression for the effective discount rate is derived and shown to decline gradually over time, approaching the lower end of the distribution in the long run. This feature can have large effects on optimal policies since it weighs the far future much more heavily than under the standard constant-rate discounting.

In light of the large variability observed in intra-generational time preferences, it is expected that the same holds for time preferences across generations. Thus, the time preferences of future generations are highly uncertain. These preferences depend on economic performance, technological progress and availability of resources in the far future and the treatment of the associated uncertainty requires integrating the canonical resource model of Section 2 within an economy-wide model. These issues are considered in Section 4.

3.4 Instantaneous benefit

The flow of instantaneous benefit is also likely to be influenced by uncertain shocks, some of which are in the form of a stochastic diffusion process while the others are substantial and abrupt. An example of the latter is a sudden drop of the demand for the resource as a result of a technological breakthrough (e.g. the effect of the development of fiber-optics communication on the demand for copper transmission lines). Such discrete shocks can be discussed in the context of uncertain time horizon T. A benefit diffusion process can be driven by a stochastic stock evolution (via the dependence of $u(\cdot)$ on the stock Q) as discussed in Section 3.2, or by benefit-specific fluctuations. An example of the latter is the stochastic demand for a nonrenewable resource introduced by Pindyck (1980).

Tsur and Graham-Tomasi (1991) studied renewable groundwater management when the demand for the resource fluctuates with rainfall. They distinguished between two information scenarios, depending on whether groundwater extraction decisions are made before or after the rainfall realization is observed. They also considered the reference case in which rainfall is stable at the mean. By comparing these three scenarios, they have been able to define the value of groundwater (the "buffer value") due to its role in mitigating the fluctuations in water supply.

Conrad (1992) considered the control of stock pollutants when the pollution damage follows geometric Brownian motion while Xepapadeas (1998) incorporated stochastic benefit shocks within a climate change model. The pollution stock process (atmospheric greenhouse gas concentration) is assumed to follow deterministic dynamics, but the damage it inflicts is modeled again as a diffusion process. The model considers a group of countries with deterministic private emissions and a stochastic public damage which depends on the global stock of pollution. The problem of coordinating emission abatement is analyzed via the optimal stopping methodology under cooperative and noncooperative modes of behavior on part of the participant countries.

3.5 Post-planning value

The post-planning value determines the loss associated with occurrence hence the degree of effort that is optimally invested in avoiding the event or reducing its occurrence hazard. Uncertainty regarding this value is similar to that associated with the pre-planning regime, such as uncertain post-planning stock dynamics or instantaneous benefit. For example, Goeschl and Perino (2009) study R&D efforts to develop a backstop substitute for a polluting resource. The exact nature of the substitute is subject to uncertainty, as it is not known in advance whether the backstop technology will also turn out eventually to be harmful to the environment (a “boomerang”) in which case yet another technology will need to be developed later on, or it will solve the pollution problem for good. They show how the probability of either outcome affects the timing of adoption of the new technology.

Problems of long time horizons, such as global climate change, exacerbate the uncertainty regarding the post-planning value. Even if we knew precisely the temperature change a century ahead, it would be extremely hard to estimate the damage such a change would inflict on a future society which will surely differ greatly in its economic, technological and demographic characteristics from what can be observed or predicted at the present time. Integrated Assessment Models, discussed in Section 4 below, deal with this kind of uncertainty in an ad hoc fashion.

3.6 Compound uncertainties

The various uncertainty types presented above drive different responses in terms of the changes induced relative to the canonical certainty policy, with the *sign* of the change depending on the particular type under consideration. It is often of interest to study how the *magnitude* of these changes depends on uncertainty, when the latter is measured, for instance, by the variance of a related key parameter (e.g. the parameter σ^2 of Eq. 4). Typically, each source of uncertainty drives the policy along a well-defined trend, and the effect responds monotonically to changing uncertainty. However, many resource management problems are subject to the combination of more than one type of uncertainty. When two (or more) types of uncertainty are combined, the policy response becomes more involved than in the case of a single type because the interaction between the types can give rise to new phenomena. Aiming to account for such situations, Clark and Kirkwood (1986) combined Reed's (1979) discrete stochastic fish stock dynamics with measurement errors on the stock size at the beginning of each harvesting period, while Sethi et al. (2005) added a third component, namely the inaccurate implementation of the harvest policy in each period. They showed that Reed's (1979) constant escapement rule is no longer optimal when harvest decisions are made before realizations of the random shocks are observed, in which case the optimal policy may not admit analytic solution and the planner must resort to numerical methods.

The effect of the interactions among different types of uncertainty is evident in the work of Saphores (2003) who considered stochastic stock dynamics under the threat of extinction if the biomass hits a barrier, and found a non-monotonic response to increasing the stochastic variance: The increase in variance implies more precaution when the variance is small, but calls for more aggressive harvesting when the variance is large enough. More recently, Brozović and Schlenker (2011) obtained a similar outcome when the stochastic stock dynamics is combined with the risk of an abrupt shift in ecosystem dynamics. These models allow the planner to take actions at discrete points of time, and the non-monotonic behavior is attributed to changes implied by increasing the variance on the tradeoff between reducing the shift probability vs. the cost of precautionary behavior.

Leizarowitz and Tsur (2012) studied optimal management of a stochastically replenished (or growing) resource under threat of a catastrophic event such as eutrophication (of shallow lakes), species extinction or ecosystem collapse. They considered discrete time and discrete state and action spaces. The catastrophic threat renders the single-period discount factor policy-dependent and as a result the compound discount factor becomes history-dependent. The authors investigated whether an optimal Markovian-Deterministic stationary policy exists for this problem. They answered this question in the affirmative and verified that the optimal state process converges to a steady state distribution. They identified cases under which the steady state distribution implies that the event will eventually occur with probability one and contrasted them with cases under which the catastrophic event will never occur.

Employing a continuous time formulation, Yin and Newman (1996) combined a stochastic output price process (as in Conrad 1992) with the catastrophic forest fires of Reed (1984) and found that the risk of fire entails different responses depending on whether the fire is a single event that prevents further exploitation or investments and fires can reoccur. In a similar framework, Balikcioglu, Fackler and Pindyck (2011, and references therein) combined the stochastic pollution stock dynamics (analogous to Eq. 4) with stochastic uncertainty regarding the damage inflicted by this stock (as in Xepapadeas 1998). The optimal response is analyzed again via stopping theory, and the complexity introduced by the dual source of uncertainty necessitates the development of a sophisticated numerical method of solution.

Zemel (2012) provides an analytic, continuous-time confirmation of the non-monotonic response by incorporating the uncertain regime shifts of de Zeeuw and Zemel (2012) into the stochastic stock model (4). It is verified that the simultaneous action of both types of uncertainty is indeed required to obtain this behavior. When one or the other sources of uncertainty is switched off, the other acts to promote conservation (as expected). However, when the two sources interact, increasing the stochastic variance enhances the hazard effect when the variance is small, but works in the opposite direction when the variance is large. In a world of multiple sources of uncertainty, it is therefore likely that non-monotonic response is more common than the simple, single-uncertainty-type models would suggest.

Obviously, combining several uncertainty sources greatly complicates the management problem and one usually has to resort to numerical methods to derive the optimal policy. This is the approach adopted by the Integrated Assessment Models discussed in Section 4 below.

4 Integrating natural resources and aggregate growth models

Some uncertain elements affect resource exploitation indirectly via their influence on economy-wide variables. Examples include the intra- and intergenerational variability of time preferences and technological shocks. Accounting for these uncertain elements requires incorporating the canonical resource model of Section 2 within an economy-wide (growth) framework. We briefly outline an integrated model of this kind and use it to discuss additional effects of uncertainty.

4.1 An integrated model

An important (though not the only) role of natural resources is to serve as sources of production inputs. Accordingly, suppose the extracted resource q is used as an input of production alongside capital K and human capital augmented labor AL (A is an index of human capital and L represents the labor force) to produce the output Y according to the technology $Y = F(K, q, AL)$. The wealth of an economy is measured by its stocks of natural capital Q, producible capital K and human capital A. The former changes according to Eq. (1) and K changes according to

$$\dot{K} = F(K, q, L) - C - z(Q, q) - \delta K,$$

where C is aggregate consumption, δ is a depreciation parameter and $z(\cdot)$ is the extraction cost. (In the canonical model of Section 2, $z(Q, q)$ is embedded in the instantaneous benefit $u(Q, q, t)$, which is here replaced by the consumption utility.) The evolution of human capital may be driven by exogenous labor-augmenting technical change processes or by endogenous policies.

Per-capita consumption, $c = C/L$, generates the per-capita instantaneous utility $u(c)$ and welfare is measured by the present value of the utility stream

$$\int_0^T Lu(c)e^{-\rho t}dt + e^{-\rho T}v(Q(T)), \tag{5}$$

where ρ is the utility discount rate which discounts future consumption solely due to the passage of time and should be distinguished from the interest rate r (the price of capital). The resource allocation problem requires to find the feasible consumption-exploitation-investment policy that maximizes the welfare (5) subject to the dynamic evolution of the capital stocks, given the endowment Q_0, K_0 and A_0. More general variants of this model allow for multiple resources and for an explicit dependence of the utility also on some of the stocks (e.g. a clean environment or the preservation of species; see Heal and Kriström 2002, and references therein).

In equilibrium the optimal policy follows (under some conditions) Ramsey's formula $r = \rho + \eta g$, where η is the elasticity of marginal utility and g is the rate of growth of per-capita consumption. This condition varies with intergenerational variations in preferences (ρ and η) and in the growth rate (g). The "correct" rate to be used is controversial (see Stern 2008, and references therein), and the controversy is exacerbated by the uncertain future evolution of these variables.

4.2 Uncertainty in the integrated model

The integrated model allows us to address a wider range of uncertainties as well as to study feedback effects between natural resources and the wider economy. For example, Tsur and Zemel (2009) looked at the effect of economic growth on climate policy regarding greenhouse gas (GHG) emission under threat of a catastrophic climate change whose occurrence probability depends on atmospheric GHG concentration. They found that economic growth motivates more vigorous mitigation of GHG emission such that in the long run anthropogenic GHG emission (beyond the natural rate) should be banned altogether. The reason is rather straightforward: as the economy grows richer it stands to lose more in case the catastrophe strikes while at the same time it can more easily afford to relinquish the resources needed to use and develop clean substitutes. What is less obvious is that, due to the global public bad nature of the threat induced by atmospheric GHG concentration, the market outcome gives rise to the opposite allocation, namely, maximal (in economic terms) use of polluting fossil fuels. Such an interaction between an economy-wide phenomenon, in the form of economic growth induced by technical change, and resource exploitation affecting the probability of triggering a damaging event, can be addressed only within an integrated framework.

As integrated models (particularly those aiming at describing faithfully the real world) tend to be analytically intractable, they call for the use of numerical analysis. Examples are the so called Integrated Assessment Models that link together climate and aggregate growth models (see Nordhaus 2008, and references therein). Uncertainty in these models is often treated by considering a distribution for each of the unknown parameters and deriving the results for a large number of "scenarios", each corresponding to a particular parameter specification. The results are then reported in terms of the most likely values as well as of some measure of their spread.

The integrated framework also allows the incorporation of natural capital into aggregate welfare measures, such as the Net National Product (NNP), that traditionally rely exclusively on producible capital (see Aronsson and Löfgren 2010, and other references compiled in this handbook). The (negative) contribution of the hazard of catastrophic occurrences to the NNP was studied by Tsur and Zemel (2006).

5 Irreversibility and uncertainty

A ubiquitous feature of environmental management problems is the irreversibility characterizing many natural processes. This feature can come in the form of the abrupt catastrophic occurrences discussed above (examples of which are the reversal of the flow of the Gulf Stream due to global temperature rise, species extinction due to over-harvesting or habitat destruction, the collapse of groundwater aquifers due to seawater intrusion or the eutrophication of lakes as a result of the use of fertilizers along their shores). Otherwise, some of our actions (polluting emissions, forest clearing or the extraction of exhaustible resources) cannot be undone (or can be corrected very slowly) when an unfavorable outcome is realized.

The presence of irreversibility really matters only under uncertainty, because otherwise undesirable outcomes can be anticipated in advance and avoided. Heal and Kriström (2002), Pindyck (2007) and the references they cite discuss in detail the effect of irreversibility on management policies under uncertainty. Presenting the problem in terms of the theory of real options, they identify two diametrical effects. If the damage associated with occurrence will turn out in the future to be very large, then exercising the option of aggressive extraction today entails a significant social loss. This effect pushes the cost-benefit balance towards more conservation. However, abatement activities often involve sunk costs (e.g. the purchase of abatement equipment that can be used only for that purpose) which give rise to the opposite effect. If it eventually turns out that the occurrence hazard or the associated damage have been overestimated, the abatement investment cannot be undone and failing to exercise the option to wait and learn more about the hovering threat might turn out costly.

The irreversibility-induced tradeoffs are particularly pronounced in optimal stopping problems (e.g. Balikcioglu, Fackler and Pindyck 2011, and the references they cite) where the problem is to determine the optimal time to enact an irreversible change in policy (e.g. reduce emissions) at a sunk cost when the pollution and damage processes follow stochastic dynamics. This regime shift problem is reminiscent of the uncertain regime shift time T discussed in Section 3.1. Here, however, the time of shift is the decision variable rather than an exogenous parameter subject to uncertainty. Optimal stopping has also been used to study the optimal time to invest in R&D efforts aimed at developing a substitute for a nonrenewable resource (Hung and Quyen 1993) or for a polluting technology (Goeschl and Perino 2009).

Wirl (2006) considered the consequences of two types of irreversibility on optimal CO_2 emission policies when the temperature follows a diffusion process. First, emissions are irreversible in the sense that active collection of the polluting gases out of the atmosphere is not allowed. Moreover, stopping is irreversible so that once the decision to stop emissions is taken, it cannot be reversed. He found that these effects work against conservation and that irreversible stopping is never optimal.

6 Knightian uncertainty

The literature cited so far treats uncertainty by converting random variables into expectations based on well specified distribution functions. Often, however, the distribution functions themselves are only partially known – a situation referred to as Knightian (or structural) uncertainty. For example, as perceived at present, future growth rates may be random with unknown mean and/or standard deviation. When realizations of an informative random variable are progressively observed, the underlying distribution can be deduced via Bayesian updating with progressive levels of accuracy.

However, if the downside of possible outcomes (e.g., the consequences of a climate change induced catastrophe) is not bounded, the expected present value may be unbounded as well for any incomplete information (finite number of observations) underlying the Bayesian updated (posterior) probabilities. This situation was illustrated by Weitzman (2009) in a two-period model in which growth is random (due to a random climate parameter) with a distribution that is known only up to a scale parameter. The analysis points to the potential limitations of combining expected utility theory and Bayesian updating in analyzing decisions under uncertainty in general and for resource management in particular. Alternative approaches, involving the precautionary principle and ambiguity-averse learners, have recently been considered for resource management problems (see Vardas and Xepapadeas 2010, and references therein).

7 Conclusions

The proper response to uncertainty has become a prevailing consideration in the resource management literature and the survey in this chapter attempts to expose the diversity of approaches developed for this purpose. A necessary step in dealing with uncertainty is the recognition that uncertainty is present in nearly every aspect of a resource management problem and that different types of uncertainty call for policy responses that may differ substantially, and in some cases even diametrically. For example, some types of uncertainty encourage more conservation and cautious exploitation, while other types induce the opposite response – of a more vigorous exploitation (relative to the comparable situation managed under certainty).

Although our aim was to cover the wide range of stochastic aspects relevant for environmental and natural resources management, it is recognized that a comprehensive treatment is not feasible within the limits of a single chapter and some important aspects had to be left out. For example, environmental resources are often shared by several agents and their management is subject to strategic interactions among competing stake holders. These interactions are usually studied via the theory of dynamic games and involve again uncertainty of various types, including that due to asymmetric information among the different players (see Dockner et al. 2000, and the literature cited therein). The treatment of this important and complex topic is beyond the scope of this chapter.

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