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Analysis

Optimal management of an ecosystem with an unknown threshold

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ABSTRACT

We consider an ecosystem with two distinct equations of motion that are separated by a threshold value of the state variable. We find that increasing uncertainty (both uncertainty embedded in the natural system and uncertainty of the decisionmaker about the location of the threshold) can lead to nonmonotonic changes in precaution: a reduction in uncertainty can first increase and then decrease optimal precautionary activity. This nonmonotonicity can help to explain why regulators often give conflicting arguments about optimal abatement policies in the face of uncertainty. For example, some regulators argue for an immediate reduction in pollutant loading until uncertainty about the underlying process is reduced while others call for no costly reductions in pollutant loading until the same uncertainty is reduced. These statements can be consistent even if both sides agree on both economic objectives and the system dynamics, but have different priors on the uncertainty involved.

Natural systems can have abrupt changes in system dynamics even though system variables such as climate, nutrient flux, or human harvesting rates are changing gradually (Mayer and Rietkirk, 2004; Scheffer et al., 2001). For example, shifts in system dynamics have been observed in ecosystems such as freshwater lakes (Scheffer et al., 1993), coral reefs (Hughes, 1994), riparian meadows (Chambers and Linnerooth, 2001), tropical forests (Sternberg, 2001), and savanna (Rietkirk and van de Koppel, 1997). At a much larger scale, discontinuous shifts are also thought to be important processes in climate change and global biogeochemical cycles, for example potentially leading to an abrupt reversal of the Gulf Stream that carries warm water from the Gulf of Mexico to Europe and causing sudden cooling of Europe (Broecker, 1997; Stocker and Schmittner, 1997). There has been an active discussion about the consequences of such thresholds for optimal economic behavior and about how much precaution is warranted when the threshold is unknown and uncertain.

We analyze the problem of a dynamic stochastic system with a possibly unknown, reversible threshold and derive an analytical solution of the value function. While earlier studies had to rely on numerical simulations, we use stochastic dynamic programming to obtain an analytical solution as well as comparative statics results on precautionary behavior.[1]

Our main result is a nonmonotonic relationship between precautionary behavior and uncertainty. An increase in the variance of the stochastic component of the *natural system* (natural variability) that determines whether the threshold is crossed may first increase the level of precautionary behavior, but for a large enough variance will eventually always decrease precautionary behavior. Moreover, this result is not limited to certain parameter sets: we show that for all possible parameter values there exists a critical threshold where such nonmonotonicity is observed. There is also a nonmonotonic relationship between the uncertainty of the *utility maximizer* about the unknown threshold (threshold uncertainty) and precautionary behavior. This nonmonotonicity can help to explain why regulators often give conflicting arguments about optimal pollution abatement policies in the face of uncertainty. For example, some regulators argue for an immediate reduction in the pollutant until uncertainty about the underlying natural processes is reduced while others call for no costly reductions until the same uncertainty is reduced. Both views can be consistent with the same underlying economic objectives and system dynamics, and their

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[1] Earlier studies that relied on numerical simulations found a nonmonotonic relationship between precautionary behavior and uncertainty, but attributed it to a numerical approximation error (see the discussion in Section 5). Our analytical results show that the observed nonmonotonicity is *not* necessarily an approximation error but rather an inherent result of the model setup.

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differences can be attributed to different beliefs about the uncertainty with which important thresholds are known. Intuitively, if a decisionmaker knows with certainty that he/she is right below the threshold and understands system dynamics well, there is no expected benefit from engaging in precautionary behavior. Once uncertainty increases (either about the natural system or the utility maximizer's belief about the threshold), so does the probability that the threshold will be crossed and hence precautionary reductions in loading have a payoff from lowering that probability. If the uncertainty continues to grow, the decisionmaker will eventually feel that he/she has no knowledge at all and precautionary reductions will be too costly compared to the negligible expected reduction in the probability that the threshold is crossed.

Finally, recent research in ecology has emphasized the need to increase ecosystem resilience but has argued that utility maximization would make ecosystems vulnerable to undesirable repeated threshold crossing (Peterson et al., 2003).[2] Our analytical approach leads to our second finding that utility maximization yields a decision rule with precautionary behavior if the system is close to the threshold, thereby increasing system resilience. Differences to earlier studies are discussed in Section 5 below.

The remainder of our paper is organized as follows. We first contrast our paper with the literature on thresholds in Section 1. We present our model specification in Section 2 and analyze the case when the threshold location is *known* in Section 3. Section 4 extends the analysis to the case where threshold location is uncertain and the main policy implications are discussed in Section 5. Finally, Section 6 concludes.

1. Literature Review

Our paper is directly related to previous literature that emphasizes boundaries (points or regions) where system dynamics change abruptly. Previous studies predominantly do not focus on uncertainty but rather examine trajectories to optimal steady state in environmental systems where the dynamics are known (Brock and Starrett, 2003; Grüne et al., 2005; Mäler et al., 2003). The prime empirical application of these studies is to lake ecosystems, where excess nutrient inputs can cause switching from oligotrophic (ecologically desirable) to eutrophic (ecologically undesirable) states. The abrupt change in system dynamics has been modeled in two ways. First, some studies use continuous nonconvex equations of motion that show a rapid change in system behavior over a small interval (Brock and Starrett, 2003; Grüne et al., 2005; Irwin et al., 2007; Mäler et al., 2003). To date, these types of system have only been solved numerically. Second, some studies use multiple discontinuous equations of motion with switches occurring when a threshold is crossed (Carpenter et al., 1999; Ludwig et al., 2003; Peterson et al., 2003). We follow the latter approach in this study. In general, studies that assume multiple discontinuous equations of motion separated by thresholds use numerical approximation methods and suggest that optimal policy choices are insensitive to threshold proximity. An exception is Naevdal (2001), who uses a deterministic optimal control model with a jump equation at the threshold to obtain a mix of analytical and numerical solutions and to show that for at least some parameter values, the optimal control ‘chatters’ around the threshold.

[2] There are several definitions of resilience in the ecology literature. The Resilience Alliance research consortium defines it as “the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes.”

A more common way of modeling catastrophes in the economic literature is to consider catastrophic events as penalty functions with an associated hazard rate. In some studies economic behavior influences the probability of event occurrence, while in others the probability is taken as exogenous. An irreversible catastrophe can be viewed as instantaneously and permanently reducing social welfare (Clarke and Reed, 1994), whereas a reversible catastrophe is modeled as imposing an instantaneous penalty equal to the sum of damages from the catastrophe and healing costs for the resource (Tsur and Zemel, 1998, 2004). A common way of solving such models is to rewrite them as a problem where the survival probability is a state variable, thus yielding a deterministic control problem. Examples of *irreversible* thresholds with penalty functions that have been studied by economists include species extinction, collapse of the thermohaline circulation (Keller et al., 2004), disintegration of the West Antarctic ice sheet cite (Naevdal, 2006), climate change (Tsur and Zemel, 1996), and aquifer salinization (Tsur and Zemel, 1995, 2004). Many of these studies find that increasing uncertainty decreases the amount of managers' precaution. Clarke and Reed (1994) show that an exogenous increase in the risk of catastrophe can increase or decrease the degree of precaution undertaken by resource managers behaving optimally. Tsur and Zemel (1998) and Tsur and Zemel (2004) argue that such nonmonotonicity is a characteristic of *irreversible* catastrophes, resulting from the tradeoff between an increasing hazard rate (as pollution levels increase) and a decreasing penalty function (because the value function is decreasing in pollution level). Conversely, Tsur and Zemel (2004) argue that for *reversible* events with an instantaneous penalty function, increasing pollution increases both the hazard rate and the penalty, so that exogenous increases in the risk of a catastrophe always increase the degree of precaution. When there is only uncertainty about the location of the threshold, increasing uncertainty always makes the manager more careful: it is never desirable to cross the threshold, and once it has been located, it is never crossed again.[3]

This is different from our finding of a nonmonotonic relationship between uncertainty and precautionary activity in a reversible setup. What causes the difference in findings? In our model there are two sources of uncertainty: (i) uncertainty embedded in the system dynamics over which the manager has no control; and (ii) uncertainty of the manager about where the threshold is located. Previous models with an instantaneous penalty function only incorporated the latter source of uncertainty. In such models, once the threshold is crossed and the location is revealed, it will never be crossed again.

2. Model

We begin by presenting a model for the management of an ecosystem with a reversible threshold that describes the dynamics of an ecosystem pollutant or characteristic, X_t, through time. We

[3] A broad definition of a catastrophic event can include the extinction of a renewable resource such as a fishery. Analysis of the conditions under which extinction may be optimal goes back to the deterministic model of Clark (1973). If the resource growth rate is below the discount rate, immediate extinction of the resource is economically rational. More recent work relaxes some of Clark's assumptions and emphasizes nonconcave biological growth functions and initial stock size as well as welfare functions that depend not only on the harvest rate but also the stock of the resource — fish harvested and fish stock in the ocean (Cropper, 1988; Olson and Roy, 2000; Mitra and Roy, 2006). Olson and Roy (2000) find that the choice between conservation and extinction may be complex: for example, an increased but uncertain productivity can reduce the range of initial stocks for which conservation is efficient, and therefore increase the likelihood of extinction. There is also an analogous literature on optimal nonrenewable resource extraction, where extraction occurs while the ultimate size of the resource is unknown (in this case, the ‘threshold’ event is exhaustion of the resource). Cropper (1976) shows that the optimal path of planned extraction is no longer necessarily monotonic when reserves are uncertain.