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Dynamic resource management under the risk of regime shifts

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ABSTRACT

This paper provides a framework through which a dynamic resource management problem with potential regime shifts can be analyzed both in a strategic environment and from a social planner's perspective. Based on a fairly general model, a condition for a precautionary policy is discussed. By applying the framework to a common-property resource problem with a linear production technology, we illustrate how the qualitative as well as quantitative nature of equilibrium is altered due to the possibility of regime shifts. In particular, when the risk is endogenously affected by the players' behavior, potential regime shifts can facilitate the precautionary management of resources as long as the resource stock is in good shape. As the stock of resource becomes scarce, however, the precautionary effect vanishes and more aggressive resource exploitation emerges. The impacts of irreversibility on the equilibrium behavior are highlighted. It is also shown that there can exist a resource-depletion trap in which a regime shift, once it happens, triggers a continuous decline of resource stock no matter which regime materializes in the subsequent periods.

Introduction

This paper studies a dynamic problem in which a system characterizing the economy shifts from one regime to another at unpredictable points in time. A typical situation described by such a problem is the joint exploitation of common-property resources such as lakes, forests, marine fish populations, and at a larger scale, the global climate system. These resources have complex dynamic systems that are known to undergo sudden and drastic changes in terms of their underlying regimes (Scheffer et al., 2001; Scheffer and Carpenter, 2003; Folke et al., 2004). Shallow lakes, for instance, tend to at some point suddenly lose transparency and vegetation due to the heavy use of fertilizers on the surrounding land and increased inflow of waste water from human settlements and industries (Scheffer et al., 1993). A potential collapse of the West Antarctic Ice sheet or a change in the global ocean circulation is expected to happen quite abruptly and is anticipated to be caused by anthropogenic climate change (Oppenheimer, 1998; Broecker, 1997). Aside from common-property resource problems, dynamic systems with potential regime shifts can also be found in financial markets (Cass and Shell, 1983; Guo et al., 2005).

The existing literature that studies potential regime shifts in dynamic systems has mainly focused on optimal management of the systems. Cropper (1976) considers a regime shift in the form of a catastrophic plunge of utility level triggered by pollution. Reed (1988) determines the socially optimal harvesting policy for a fishery subject to random

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catastrophic collapse. In a more general setting, Clarke and Reed (1994) consider the impact of a stock-dependent risk of catastrophic environmental collapse on the optimal management of resources, which was later extended by Tsur and Zemel (1996). In these studies, regime shifts are commonly formulated as a catastrophic damage or the collapse of resource stock. In a more recent paper, Polasky et al. (2011) consider changed system dynamics as a general type of regime shift and show that the optimal management of resources with potential regime shifts can be a precautionary measure. A similar kind of precautionary optimal policy was also found by de Zeeuw and Zemel (2012) in the context of pollution control. In this strand of literature, however, strategic aspects inherent in the management of common-property resources are not fully taken into account. Moreover, the analysis is commonly focused upon steady states, especially when the risk of a regime shift is endogenously affected.

There exists vast literature on non-cooperative dynamic games. A seminal paper by Levhari and Mirman (1980), for instance, examines the dynamic and steady-state properties of a fish population that results from strategic interaction among players. Several issues of importance such as the existence, multiplicity, and inefficiency of equilibria have already been discussed by Benhabib and Radner (1992), Dockner and Sorger (1996), and Sorger (1998), among others. Only a few papers, however, incorporate the risk or uncertainty surrounding the joint exploitation of productive resources. Recently, Antoniadou et al. (2013) introduced a simple random shock into the growth function of a common-property resource and identified a class of dynamic games that support a linear symmetric Markov-perfect Nash equilibrium in their setting. Their analysis shows that the existence of uncertainty can amplify or mitigate the commons problem, depending on preference and technology in the economy. Yet consideration of uncertain regime shifts is largely absent in the analysis of dynamic games.

The present paper provides a general framework with which a dynamic resource management problem with potential regime shifts can be analyzed in a strategic environment as well as from a social planner's perspective. The General framework section explains the structure of the model and introduces its basic assumptions. Based on a fairly general model, necessary and sufficient conditions for the solution of each player's problem are derived. Accordingly, a symmetric Markov-perfect Nash equilibrium is defined for the model in a general form. We also discuss a general condition for a precautionary policy under the risk of regime shifts.

A common-property resource problem section demonstrates how the framework presented in this paper can be used to investigate problems of interest. To this end, we focus on a dynamic common-property resource problem with a linear production technology. This class of games allows a continuous growth of economy, which in turn makes it possible to illustrate the off-steady-state dynamics under the risk of regime shifts. In order to clarify the implications of potential regime shifts, three different cases are considered: one with no regime shift, one with exogenous risk of regime shift, and one with endogenous risk of regime shift. It is shown that when the risk is affected by the level of resource stock, the potential of the regime shifts can facilitate precautionary management of common-property resources even in a strategic environment. This precautionary behavior is reinforced when the regime shift is irreversible and in particular if the consequence is catastrophic. When the remaining resource stock is small, however, the precautionary effect disappears and the equilibrium extraction by players can be even more aggressive than in the absence of a regime shift. Equilibrium dynamics are also examined. In particular, it is shown that unlike the models with no regime shift, there can exist a resource-depletion trap in which a regime shift, once it happens, triggers an irreversible accumulation dynamics in the direction of a resource collapse. The final section concludes the paper.

General framework

Regime

Consider an economy with $N \in \mathbb{N}$ identical players sharing a productive resource. Although our framework allows for the case with a single decision maker, we refer to each individual as a 'player' to fix the context. Let θ be a vector of parameters that characterize the current system of economy. We call θ a *regime*. We assume that the utility of each player in general depends both on the flow and stock of a resource. Therefore the utility function of player $n \in \{1, 2, \ldots, N\}$ is given by

$$U(x_n(t), z(t); \theta), \tag{1}$$

where $z(t) \in \mathbb{R}_+$ is the stock of resource and $x_n(t) \in \mathbb{R}_+$ is the extraction by player n at period t. Since the players are identical, we suppress the subscript n whenever confusion is unlikely. We denote a time path of stock and extraction by $\{z(t)\}$ and $\{x(t)\}$, respectively. Technology available in the economy is represented by a growth function G and the accumulation process is expressed as

$$\dot{z}(t) = G\left(z(t), \sum_{n=1}^{N} x_n(t); \theta\right), \tag{2}$$

which governs the relationship between the stock and flow of a resource under a given regime. This also provides a channel through which players can strategically interact.

The economy experiences regime shifts, which we model as discontinuous changes in θ at unpredictable points in time. Let Θ be the set of all possible values of θ. A regime shift, say from $\theta_1 \in \Theta$ to $\theta_2 \in \Theta$, might cause a sudden change in the players' taste, a sharp decline in the productivity of a resource, or both. Such a shift is triggered by stochastic events. The risk