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Managing a renewable resource facing the risk of a regime shift in the ecological system[☆]

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ABSTRACT

Resource management has to take account of the possibility of regime shifts in the ecological system that provides the resource. Regime shifts are uncertain and lead to structural changes in the system dynamics, lowering the carrying capacity of the resource. Optimal management is driven by two considerations. First, it becomes precautionary if a higher stock of the renewable resource decreases the hazard of a regime shift. Second, it either becomes precautionary or more aggressive depending on the adjustments that are needed after the regime shift. This in turn depends on the elasticity of intertemporal substitution. In conclusion, facing the risk of a regime shift in the ecological system, optimal management is ambiguous but precautionary if the marginal hazard rate of the regime shift is sufficiently high.

1. Introduction

Many renewable resources are embedded in a larger ecosystem. In managing these ecosystem services, it is important to take into account that the ecosystem may be vulnerable to so-called regime shifts, and that the risk of regime shifts occurring may depend on how the resources are managed. An example is a fishery that is part of a coral reef ecosystem: overfishing may affect the ecosystem and this in turn may affect the carrying capacity of the fishery. In ecology the term regime shift was introduced for large, abrupt and persistent changes in the structure and the functioning of an ecosystem (Biggs et al., 2012). For example, lakes may shift from a clear to a turbid state (Scheffer, 1997; Carpenter, 2003), thereby affecting water quality, fish populations and recreation. Coral reefs may shift from a coral dominated state to an algae dominated state (Hughes et al., 2003), thereby affecting fish populations and aesthetics. At a larger scale, the climate system may shift to a different state (Stern, 2007; Lenton et al., 2008), thereby affecting precipitation patterns and agricultural productivity. The abrupt change usually comes as a surprise because the underlying system dynamics is complex and not well understood. The system has different domains of attraction (regimes) with different steady states, but it can usually not be predicted when the system

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will tip from one regime to the other. Optimal management of renewable resources has to take account of the possibility of structural changes in the ecosystem.

Standard optimal management of a renewable resource, such as a fishery, takes parameters such as the growth rate and the carrying capacity as given (e.g., Clark, 1990). However, the possibility of a structural change in the ecosystem implies that a rapid shift may occur towards a different value for these parameters. The idea is, for example, that if a coral reef breaks down, this has an effect on the habitat and the breeding facilities of a fish species which shifts down the carrying capacity of that fishery. The uncertain event of this tipping to another regime can be modelled with a hazard rate or, equivalently, with the probability of surviving in the current regime (e.g., Kamien and Schwartz, 1971; Cropper, 1976; Reed, 1988; Tsur and Zemel, 1996). Polasky et al. (2011) identify four possible outcomes in case of a standard fishery. If the hazard rate is an exogenous constant and if the ecosystem and therefore the fishery totally collapses, the hazard rate augments the discount rate, thereby increasing the exploitation of the fishery. However, if the ecosystem does not collapse but shifts to a regime with a lower but positive carrying capacity for the fishery, it is optimal to wait until the event occurs and to adjust instantaneously to the lower steady-state fish stock in the new regime. If the hazard rate is endogenous and depends on the stock of fish, because of the interdependencies in the ecosystem, a precautionary incentive is introduced. The idea is that the hazard rate is lower for a higher stock of fish, because the ecosystem is less vulnerable, and this will decrease the exploitation of the fishery. It follows that in the case of a total collapse, optimal management is ambiguous, but in the case of a regime shift, optimal management is always precautionary. Their main conclusion is that an endogenous stock-dependent hazard rate implies precautionary behaviour. Precautionary behaviour is defined here as less exploitation of the fishery and aiming for a higher targeted steady-state fish stock before the regime shift occurs.

This result is based on a standard linear fishery with a fixed price for every unit of harvest and no harvesting costs, so that the marginal value of the stock is always equal to the price. It follows that there is no incentive to prepare for the possible regime shift because when it occurs, the fishery will adjust instantaneously to the lower steady-state fish stock. However, this paper will show that when the utility of harvest has diminishing returns, it will be optimal to prepare for the regime shift with less or with more exploitation before the event, depending on the elasticity of intertemporal substitution. This is essentially a consumption smoothing argument. Adding this to the precautionary incentive from an endogenous stock-dependent hazard rate, it follows that either precaution is enhanced or a countereffect occurs. In the last situation a trade-off arises between preparing for the event with higher exploitation, on the one hand, and decreasing the risk of the event with lower exploitation, on the other hand. It will be shown that if the marginal hazard rate of the regime shift is sufficiently high, optimal management is always precautionary. The ambiguity here was also found numerically, in a similar discrete-time model, by Ren and Polasky (2014). This paper extends their work and characterizes precisely what happens in the standard fishery model with a concave utility function of harvest.

The literature on optimal management facing the risk of regime shifts is rapidly growing, especially with regards to potential climate change (e.g., Gjerde et al., 1999; Keller et al., 2004) but also on more general issues (e.g., Brozovic and Schlenker, 2011). The papers that come closest to our paper are Tsur and Zemel (1998), Lemoine and Traeger (2014). Tsur and Zemel (1998) introduce a loss function (which is a function of the stock of pollution in their case) as a consequence of the regime shift. They show that optimal management becomes precautionary, assuming that this loss function is non-decreasing. We will show that this assumption does not generally hold in a standard renewable-resource model with a concave utility function. Therefore optimal management is not always precautionary. In their analysis of the effect of climate tipping points on the optimal carbon tax, Lemoine and Traeger (2014) develop the theory and distinguish what they call the differential welfare impact and the marginal hazard rate effect (see also Lemoine and Traeger, 2016). The additional incentive for the fishery model that is discussed in this paper is essentially the same thing as the differential welfare impact. Furthermore, Lemoine and Traeger (2014) have a numerical analysis with an integrated assessment model for climate change. This paper is mainly theoretical and attends to renewable resources as part of an ecological system. To fix ideas, we focus our discussion on harvesting a fishery facing a potential rapid downward shift in the carrying capacity, but the analysis is generally applicable to renewable resources that are subject to potential regime shifts in the ecosystem.

Section 2 presents the fishery model and introduces the hazard rate and the shift in the carrying capacity. Section 3 considers optimal management of this fishery with potential regime shifts and a concave utility function. In Section 4 conditions for precautionary behaviour are derived. Some concluding remarks can be found in Section 5.

2. Fishery with potential regime shifts

The objective of a standard fishery is to maximize the present value of the revenue from harvesting h, that is

$$\max_{h(.)} \int_0^{\infty} e^{-rt} U(h(t)) dt, \tag{1}$$

where U is the revenue from harvesting h and r is the discount rate, subject to the dynamics of the fish stock S, given by

$$\dot{S}(t) = G(S(t)) - h(t), \qquad G(S) \equiv gS\left(1 - \frac{S}{K}\right), \qquad S(0) = S_0, \tag{2}$$

where g is the growth rate and K is the carrying capacity of the logistic growth function G, and S_0 is the initial fish stock.