Journal of Economic Behavior & Organization
Vol. 57 (2005) 448–473

JOURNAL OF
Economic Behavior
& Organization

www.elsevier.com/locate/econbase

Solving ecological management problems using dynamic programming

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Available online 10 August 2005

Abstract

We study an ecological management problem where the interaction of the maximizing-welfare dynamic decision and the dynamics of the ecosystem admits multiple equilibria. We follow the example of a shallow lake by Brock, etc. Low loading preserves resilience of the ecosystem while high loading may lead to the deterioration of the ecosystem. We consider instruments of a regulatory agency that may help to maintain and enhance resilience by enlarging the domain of attraction of the low-pollution equilibrium. The global dynamics of all our model variants, without and with tax rates, are analytically studied by the Hamilton–Jacobi–Bellman method and numerically solved through dynamic programming.

JEL classification: C61; C63; Q2; Q25; Q28

Keywords: Renewable resources; Ecological management; Optimal taxation; Bell equation; Dynamic programming

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doi:10.1016/j.jebo.2005.04.002

1. Introduction

Research in the last decade has shown that the relationship between the environment and economic activity is a rather complex one. Recent studies on ecological management problems reveal that the interaction of human activity and the ecological dynamics generates intricate dynamics that we need to understand in order to undertake welfare analysis and to make policy decisions.

To demonstrate the existence of such a complexity, researchers often have focused on a lake management problem. The lake model can be viewed as a symbolic model. Here, the problem of the behavior of a shallow lake that is subject to pollution by phosphorous is studied. The model employed here reflects the characteristics of many ecological systems. They imply the integration of two aspects: the dynamic decision problem maximizing welfare and the dynamics of the ecosystem. This often generates properties of complex dynamics such as multiple equilibria, history dependence, thresholds between multiple attractors and a discontinuous policy function.

Carpenter et al. (1999b) and Brock and Starrett (1999) propose a deterministic version of an optimal management problem for ecosystems where there is a phosphorous loading into the lake due to economic activities. This affects the stock of phosphorous in the lake. When the stock of phosphorous becomes too high, internal positive feedback mechanisms start to impair the ecosystem's ability to absorb and biodegrade the loading. Welfare is defined as sum of utilities from loading rate and disamenities from degraded lake quality proportional to the level of the stock variable. The management can measure the stock and can control the loading as a function of the stock. The management chooses these loadings to maximize welfare of the conflicting interests of polluters and lake users. The model has one state variable, and its dynamics is simplified as a one-dimensional ordinary differential equation.

The work by Carpenter et al. (1999a,b)is extended in Ludwig et al. (2002) to give a more precise account of the internal loading due to changing levels of dissolved phosphorous in the lake sediment in a stochastic environment. Using two state variables, the phosphorous in the water and the phosphorous in the lake sediment, the optimal loading is derived as a function of those two state variables. They argue that simple policies that neglect dynamics of the phosphorous in the sediments are inadequate unless the time horizon is short and the dynamics are slow. They also mention that a stochastic model is essential if there are substantial random fluctuations in loading. It is important particularly when the optimal solution to the system shows history dependence where the lake possibly flips between two attractors due to the disturbance. Thus, they argue that the management problem should be described as a stochastic two-dimensional state variable problem.

Another stream of literature to analyze this problem uses a game theoretic approach with N communities as in Mäler et al. (1999) and Dechert and Brock (2000). They focus on the Nash equilibria solutions to the dynamic lake game. Dechert and Brock (2000) use discrete dynamic programming to obtain a numerical solution and show that the social optimum loading is always less than the total loading in the dynamic game. As N becomes large, the divergence between the dynamic game solution and the social optimum becomes extreme and complex dynamics can appear in between.

Mäler et al. provide the optimal management solution in the same context but investigate whether it is possible to induce an optimal management in case of common use of the lake