ECOLOGICAL ECONOMICS 63 (2007) 219–229

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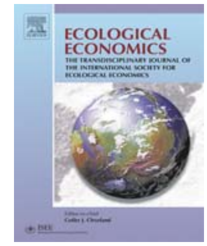

ANALYSIS

Nonlinear behavior of the socio-economic dynamics for lake eutrophication control

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ARTICLE INFO

Article history:
Received 28 May 2006
Received in revised form
2 November 2006
Accepted 3 November 2006
Available online 15 December 2006

Keywords:
Socio-economic choice
Ecosystem dynamics
Social pressure
Lake management
Bistability

ABSTRACT

To succeed in combating lake eutrophication, cooperation of local inhabitants, small factories, and farmers in reducing phosphorus discharge is very important. But the willingness of each player to cooperate would depend on the cooperation of other players and on the level of environmental concern of the society in general. Here we study the integrated dynamics of people's choice of behavior and the magnitude of eutrophication. Assumptions are: there are a number of players who choose between alternative options: a cooperative and environment-oriented option is more costly than the other. The decision of each player is affected by "social pressure" as well as by economical cost of the options. The lake pollution increases with the total phosphorus released, and a high pollution level in the lake would enhance the social pressure. The model includes a positive and a negative feedback loops which create diverse dynamical behavior. The model often shows bistability — having an equilibrium with a high level of cooperation among people and clean water, and the other equilibrium with low cooperation and polluted water, which are simultaneously stable. The model also shows fluctuation between a high and a low levels of cooperation in alternating years, cycle with a longer periodicity, or chaotic fluctuation. Conservatism of people stabilizes the system and sometimes helps maintaining cooperation. The system may show unexpected parameter dependence — the improved phosphorus removing efficiency might make water more polluted if it causes the decline in the environmental concern and cooperation among people.

1. Introduction

Most ecosystems receive a heavy influence of human activity over hundreds, sometimes thousands of years. To achieve a sustainable use of an ecosystem, we need to consider the integrated dynamics of ecological processes and socio-economic choice by human beings. For example, the water quality of shallow and large lakes is affected most importantly by nutrient input from various sources (Carpenter et al., 1998; Havens et al., 2001). For the success of combating lake eutrophication, an essential element is cooperation of many people, such as local inhabitants who implement efficient but costly sewage disposal, small factories whose operation is accompanied by reduced phosphorus discharge, and farmers who choose agriculture method with reduced phosphorus release from the farmland (Tabuchi, 2005). In these examples, cooperative players adopt environmentally benign but economically costly option over the alternative, and how much people are willing to contribute would be affected by the state of lake ecosystem.

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0921-8009/$ - see front matter
doi:10.1016/j.ecolecon.2006.11.003

Incorporating human economical choice in population and ecosystem dynamics has been discussed in fishery management (Clark, 1976) and in water pollution control (Carpenter et al., 1999a). More recently the need of understanding coupled ecological and economic dynamics for successful ecosystem management has been emphasized (Constanza et al., 1993; Medley et al., 1995; Peterson, 2000). To reveal the fundamental properties of integrated ecological and socio-economic dynamics, studying simple cases in detail would be useful. For example the deforestation process was studied in a Markov chain of land-use state transition, which combines ecological succession and the land owner's decision making (Satake and Iwasa, 2006; Satake et al., 2007). Another example is a simulator for lake water quality management (Carpenter et al., 1999b), which concludes the possibility of large fluctuation caused by the noise amplified by the decision making process.

In these socio-ecological problems we often face a dilemma. The effect of a single player constitutes only a minute portion of the total because there are a large number of players who can affect the lake water quality. Suppose there are N players who release phosphorus for their economic activity. Also suppose each one appreciates the benefit B of having the lake with improved water quality, but he has to pay the cost C to contribute. Even if the benefit is greater than the cost ($B>C$), the "rational" option prescribed by the standard economics theory is to play the economical option (not to pay the cost) and to hope that all the other N - 1 players might take the environmentally benign option. However if every one adopts this free-riding option, the water is kept polluted. This social dilemma is formalized as a public-goods game (Palfrey and Rosenthal, 1991; Parks and Hulbert, 1995; Keser and van Winden, 2000; Fischbacher et al., 2001). In fact many of the environmental problems, including ecosystem management and biodiversity conservation, are problem of cooperation under social dilemma situation (Ostrom, 1990). Adopting an environmentally benign option in spite of the cost is an example of collective and voluntary cooperation (Gachter and Fehr, 1999).

In the last two decades, environmental psychology and experimental economics have discovered that people are able to cooperate under social dilemma situations because their behavioral choices are made considering not only monetary gain, but also noneconomical factors that correspond to social acceptance, reputation, feeling of responsibility and of the contribution to the social good (Fransson and Garling, 1999; Kaiser and Shimoda, 1999; Hagen and Hammerstein, 2006). The strength of this tendency depends on the particularities of the social dilemma as well as the behavior of other players, and hence is strongly frequency dependent (Biel and Garling, 1995; Henrich and Boyd, 1998; Gachter and Fehr, 1999; Pillutla and Chen, 1999; Kaiser and Shimoda, 1999; Keser and van Winden, 2000; Fischbacher et al., 2001; Kurzban and Houser, 2005).

In this paper we study the situation in which there are many players who choose between two options. Alternative options differ in the environmental impact, specifically phosphorus discharge to the lake. An option that is more environmentally benign is economically more costly to the player than the alternative. However people might adopt the environmentally favorable option, if there is enough environmental concern on the water pollution, and if many other players also cooperate. Here we postulate that each player makes decision considering both the direct economic cost he pays and "social pressure". Social pressure is stronger if more players cooperate, and if the environmental concern in the society is greater. The environmental concern is enhanced if water quality becomes low and the problem is exposed to mass media (e.g. newspaper or the local television). These assumptions are consistent with the studies in environmental social psychology and experimental economics (e.g. Biel and Garling, 1995; Henrich and Boyd, 1998; Gachter and Fehr, 1999; Pillutla and Chen, 1999; Kaiser and Shimoda, 1999; Fischbacher et al., 2001; Kurzban and Houser, 2005), as discussed later in detail.

Due to the frequency-dependent nature of the social pressure, the socio-economic system shows behaviors typical of nonlinear dynamics. To show this clearly, we here choose deliberately simple assumptions concerning limnological dynamics. We then analyze the dynamics of the fraction of people who cooperate and water pollution level. The model includes a positive and a negative feedback loops, which cause diverse nonlinear behavior: such as multiple stable equilibria, periodic or chaotic fluctuation, and unexpected parameter dependence.

2. Model

We consider a number of people whose decision collectively affects the nutrient load to the lake. Each player chooses between two options: a cooperative option contributes to the improvement of lake water quality but is accompanied by a cost.

2.1. *Social pressure*

One option, labeled A, is more economical than the other, named B, but the latter is more benign to the environment. Specifically option A and option B are accompanied by economic cost c_A and c_B, respectively, and $c_A<c_B$ holds. In contrast the amount of phosphorus discharge is p_A and p_B, respectively, and $p_A>p_B$ holds. If players consider only the direct economic cost, most of them will end up with taking option A and the lake suffers pollution by receiving a high phosphorus input.

We conjecture that there is another element affecting the decision making in addition to the direct monetary cost. We call it "social pressure", which expresses the psychological cost of not contributing to the good of the society. This moral sentiment would drive the player toward cooperation. It may reflect the player's expectation of future inconvenience or discomfort he expects in the society when he takes the noncooperative option. But we here do not ask the origin of the social pressure. Instead we examine what happens to the ecosystem management if players' behavior is affected by the social pressure with given properties.

The social pressure is stronger if there are more people who cooperate, and if the water pollution problem receives a