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ANALYSIS

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

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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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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

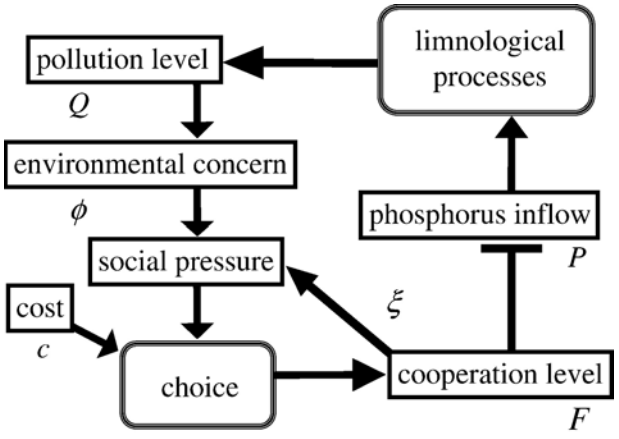


Fig. 1 – Scheme of the model. Allows indicate interaction. A negative feedback loop includes the reduction of phosphorus inflow by a higher cooperation and a positive feedback loop includes the frequency dependence of social pressure. Symbols are explained in text.

greater attention of the society in general. To clarify the idea, we assume that the social pressure term is the product of two factors: *cooperator frequency factor* and *environmental concern factor*:

$$[\text{social pressure}] = \alpha(1 + \xi F_t)\phi(Q). \tag{1}$$

α is a constant for the basic strength of social pressure. The second factor of Eq. (1) is the cooperator frequency factor. F_t is the fraction of cooperative players who adopt option B in year t. As more people cooperate (greater F_t), the social pressure becomes stronger. ξ is a positive constant for the strength of frequency dependence. The last factor of Eq. (1), $\varphi(Q)$, indicates the society's concern on the water pollution, which increases with the water pollution level, denoted by Q. The social pressure working on each player is zero if there is no environmental issue and the society does not pay much attention to the lake water quality. In contrast, if the water is polluted (large Q), environmental concern of the society becomes high. For simplicity, we assume that the environmental concern over the water pollution is proportional to the pollution level: $\phi(Q)=\phi_0 Q$.

Lake water pollution level depends on the amount of phosphorus input P (Fig. 1). These dynamics should include all the limnological processes in the lake, such as the increase in phytoplankton abundance, which enhances the abundance of zooplankton and other consumers, resulting in a higher level of biomass production and sedimentation. These subsequently change the oxygen level in the lake bottom, enhance the recycling of nutrients accumulated in the soil, and reduce the water transparency, which then suppresses macrophytes (Scheffer and Carpenter, 2003; Carpenter 2005). Modelling of all these processes would require complicated dynamics including many variables. In the present paper, we focus on the effect of human decision making on the dynamics of pollution control, and we here adopt the simplest possible assumption: The water pollution level is proportional to the phosphorus input: $Q=q_0P$. Hence the environmental concern factor is: $\phi(Q)=\phi_0 q_0 P$.

Phosphorus release per player is $P=p_A(1-F_t)+p_BF_t$ which decreases with the fraction of cooperators F_t because $p_A>p_B$. A higher P would increase the pollution level of lake water. The total costs for players adopting A and B are

$$\text{CostA} = c_A + \alpha\phi_0 q_0(1 + \xi F_t)[p_A(1-F_t) + p_BF_t], \tag{2a}$$

and

$$\text{CostB} = c_B, \tag{2b}$$

respectively. Since players tend to choose the option with the lower total cost, social pressure term works to promote cooperation.

2.2. *Dynamics of people's behavior*

Players change their options stochastically. This transition occurs faster if it results in the decrease in the total cost, and it occurs slower if it results in the increase in the total cost.

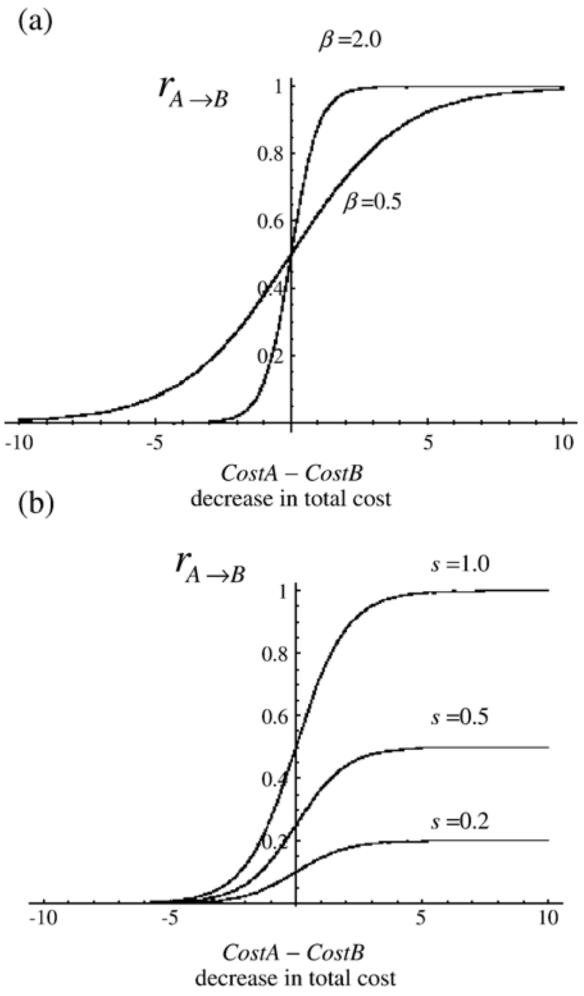
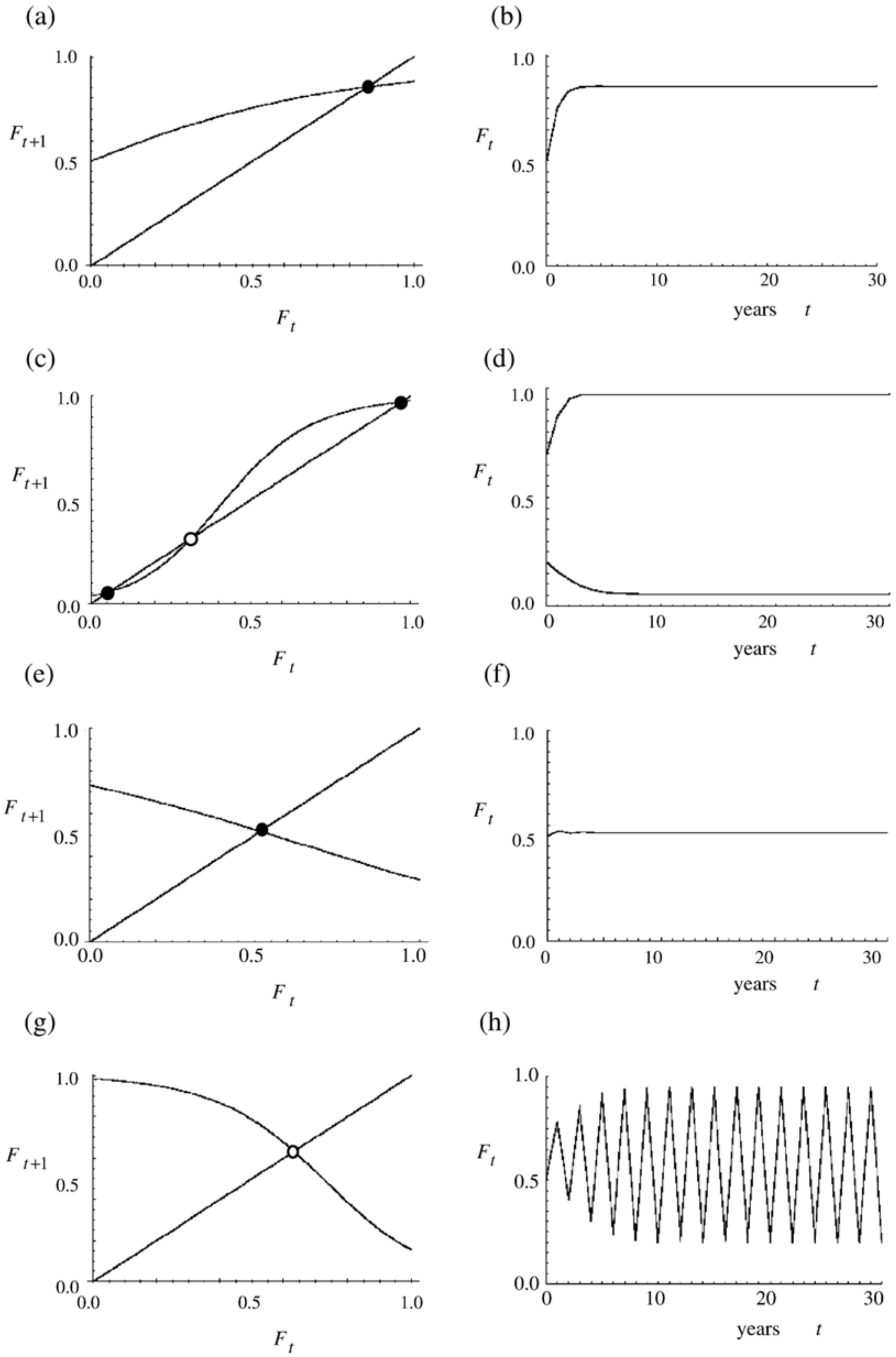


Fig. 2 – The transition rate between options. A transition that decreases the total cost occurs faster than the one that increases the total cost, but the latter also occurs at a positive rate. Parameters are: (a) $s=1$, $\beta=0.5$, 2, (b) $s=0.2$, 0.5, 1, $\beta=1$.

Specifically, the rate of transition from option *A* to option *B*, and that from option *B* to option *A* are:

$$r_{\mathrm{A}\rightarrow\mathrm{B}} = \frac{s}{1+e^{\beta(\mathrm{CostB}-\mathrm{CostA})}}, \text{ and } r_{\mathrm{B}\rightarrow\mathrm{A}} = \frac{s}{1+e^{\beta(\mathrm{CostA}-\mathrm{CostB})}}. \qquad (3)$$

If the costs are replaced by the utility with a negative sign, Eq. (3) is the same formalism as in Satake and Iwasa (2006). Fig. 2 illustrates the transition rate as a function of the difference in the total cost. Parameter β indicates the sensitivity of the rate on the cost difference. A large β indicates the deterministic model in which the player always switches the option to the one with the smaller total cost. If β is small, players tend to switch strategies randomly, irrespective of the change in the total cost. s is the maximum probability of



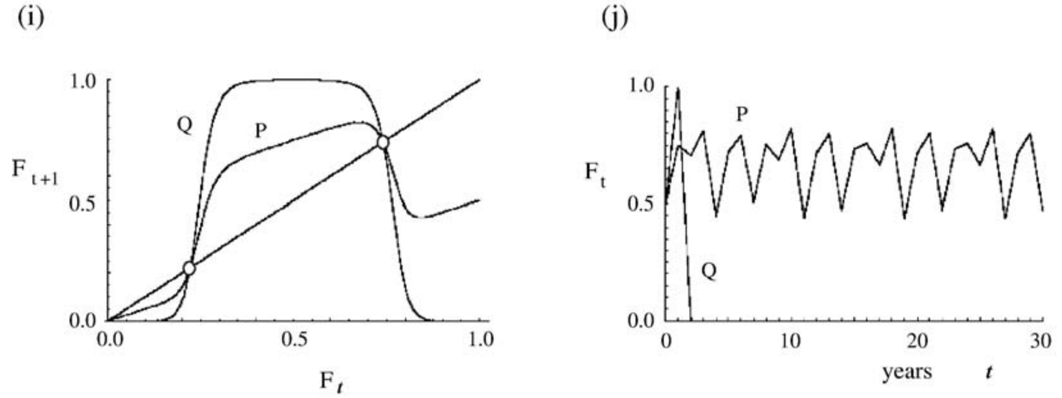


Fig. 3 – Return maps and corresponding dynamics. (a) and (b): The return map is increasing, because the positive feedback loop in Fig. 1 is strong. There is a single equilibrium that is globally stable. (c) and (d): There are three equilibria and two of them are stable. (e) and (f): the return map is decreasing because the negative feedback loop in Fig. 1 is strong. There is a single stable equilibrium. (g) and (h): The single equilibrium is unstable and the dynamics show oscillation of period two. (i) and (j): The return map have a maximum at an intermediate value. Curves labeled P are for cyclic fluctuation of period eight. Curves labeled Q show a temporary fluctuation followed by the convergence to the equilibrium of low cooperation. If stated otherwise, parameters are: $\xi=0.1$, $\beta=1$, $p_A=3$, $p_B=1$, $c_A=1$, $c_B=6$, $\alpha=3$, $q_0=1$, $\phi_0=1$, and $s=1$. This standard set of parameters are used for (g) and (h). Parameters specific to each case are: (a) and (b): $p_B=2.5$, $c_A=3$, $\alpha=1$; (c) and (d): $\xi=3$, $p_B=2.5$, $c_B=7.3$, $\alpha=1$; (e) and (f): $c_B=3$, $\alpha=1$; (i) and (j): $\xi=10$, $p_A=10$, $c_B=28$, $\alpha=1$, $s=0.5$, 1. Initial value F_0 (b), (d), (f), (j): $F_0=0.5$. (h):$F_0=0.2$ and $F_0=0.7$.

change per year. When s is large, people are reactive to the change in the total cost. In contrast, a small s indicates conservative attitude — people are reluctant to change their option immediately even if the alternative is very good. $1/s$ is the expected number of years until a transition occurs to a very profitable alternative.

This is a stochastic model. However for simplicity of the analysis, we examine the behavior of the corresponding deterministic model in which the total population size is large. The fraction of players adopting option B (environmentally oriented) in the following year is given by:

$$F_{t+1} = F_t + \frac{s}{1+e^{\beta(\mathrm{CostB}-\mathrm{CostA})}}(1-F_t) - \frac{s}{1+e^{\beta(\mathrm{CostA}-\mathrm{CostB})}}F_t. \tag{4}$$

The second term in the right hand side is the fraction of players who change from option A to option B, and the third term is the fraction of players who change from option B to option A. Eq. (4) can be rewritten as

$$F_{t+1} = (1-s)F_t + s\psi(F_t), \tag{5a}$$

where $\psi(F)$ is given by

$$\psi(F) = 1/(1+\exp[\beta(c_B - c_A - \alpha\phi_0 q_0(1+\xi F)(p_A(1-F)+p_B F))]). \tag{5b}$$

Note that $0<\psi(F)<1$ holds for any $0\le F\le 1$. Hence the fraction of cooperators F_t is confined between 0 and 1, and F_t is calculated using the dynamics Eqs. (5a) and (5b) for all t.

3. Reactive players ($s=1$)

We first consider the case of $s=1$, which implies that players are reactive, or nonconservative. If the alternative option is much better than the current one, all the players could switch its option in one year. Later we consider the cases with conservative players ($s<1$). The dynamics are $F_{t+1}=\psi(F_t)$. The return map is rewritten as

$$\psi(F) = 1/\left(1+\exp\left[\lambda(F_t-\mu)^2 + (\text{terms independent of } F_t)\right]\right), \tag{6}$$

where $\lambda=\beta\alpha\phi_0 q_0(p_A-p_B)\xi$ and $\mu=1/2(P_A/(P_A-P_B)-1/\xi)$. The terms in the exponent are quadratic function of F with the maximum at $F=\mu$. Hence $\psi(F)$ increases with F for $F<\mu$, and decreases for $F>\mu$.

The behavior of a map such as $F_{t+1}=\psi(F_t)$ is well studied. The cross point of the graph of $y=\psi(x)$ and line $y=x$, corresponds the equilibrium. The dynamics of F_t can be traced on this graph. Fig. 3a, c, e, g illustrate return maps, and Fig. 3b, d, f, h are for the dynamics.

Here we do not explain the model's behavior exhaustively. Instead we illustrate typical behaviors of the model by several examples. According to the shape of return map $\psi(F)$, we distinguish the following three cases: (Case 1) $\mu\ge 1$, and return map $\psi(F)$ is an increasing function in $0\le F\le 1$. (Case 2) $\mu\le 0$, and return map $\psi(F)$ is a decreasing function. (Case 3) $0<\mu<1$, and return map $\psi(F)$ has its maximum at an intermediate value. Using the expression of μ, the condition for these three cases can be expressed in terms of ξ and $(p_A-p_B)/p_A$. $(p_A-p_B)/p_A$ is the fraction of reduced phosphorus discharge by changing from A to B. It indicates the effectiveness of the environmentally benign option (B). ξ is the frequency dependence of social pressure. The relative magnitude of these two determines the classification of these three cases.

3.1. *Increasing $\psi(F)$*

If $(p_A-p_B)/p_A\le\xi/(2\xi+1)$, function $\psi(F_t)$ monotonically increases in $0\le F_t\le 1$ (Case 2). This occurs when frequency dependence of social pressure ξ is large compared with the effectiveness of the option in reducing phosphorus input. The dynamics have either a single equilibrium or three equilibria within $0<F<1$. Fig. 3a and b illustrate an example in which the dynamics would converge to a single equilibrium. The equilibrium is globally stable and F_t would converge to it starting from any initial value. Fig. 3c and d illustrate the case with three equilibria, showing bistability. The equilibrium with the smallest F and the one with the largest F are both locally stable, but the one between them is unstable.

The system converges either to the equilibrium with small F and large Q (polluted water) or to the one with large F and small Q (clean water). The domains of attraction of these stable equilibria are separated by the unstable intermediate equilibrium. If the initial fraction of people adopting the environmentally oriented option is large, the equilibrium with a high level of cooperation is achieved. But if the initial level of cooperation is low, the society's environmental concern remains stabilized at the low F equilibrium (see also Gachter and Fehr, 1999).

Since $\psi(F)$ is monotonically increasing, all the equilibrium are approached monotonically, either from above or from below. There is no overshooting.

3.2. *Decreasing $\psi(F)$*

If $\xi \le (p_A - p_B)/p_A$, function $\psi(F)$ decreases monotonically in $0 \le F \le 1$ (Case 1). This occurs when the reduction of phosphorus discharge by option B is large. The system has always a single equilibrium, which may or may not be stable. Fig. 3e and f illustrate a case in which the equilibrium is stable. In alternating years, F_t is above and below the equilibrium and eventually converges to it. Fig. 3g and h illustrate the case in which the equilibrium is unstable.

If the fraction of cooperators (adopting method B) is high in a year (large F_t), the lake water quality is improved (small Q), causing the reduction of the society's concern over the lake pollution. In the following year, the number of cooperators decreases (small F_{t+1}). Then the phosphorus discharge P is enhanced, and the water becomes polluted (large Q). Again the people's concern becomes high and in the following year we have more cooperators (large F_{t+2}). Hence this system tends to show a high F and a low F in alternating years.

The stability of the equilibrium can be known from whether the magnitude of derivative $|d\psi/dF|$ is greater than 1.

3.3. *$\psi(F)$ with an intermediate maximum*

Finally in between Case 1 and Case 2, there is Case 3 in which $\xi/(2\xi+1)<(p_A-p_B)/p_A<\xi$. Here the return map $\psi(F)$ has a peak in the middle of the interval $0<F<1$. As in Case 1, the system might have three equilibria. The equilibrium with the highest F, which was always stable in Case 1, can be unstable and the system might have an oscillation around it, just like in Case 2.

For the curves labeled P in Fig. 3i and j, the dynamics oscillates with chaotic fluctuation. Around the equilibrium with the highest cooperation F, the oscillation is caused by a similar mechanism as for a decreasing return map in the last section. There is another equilibrium with low cooperation (small F) which is stable. If we start from a small F, the cooperation level stays low. Hence the model's behavior is a combination of bistability (Case 1) and oscillation (Case 2).

If the amplitude of the fluctuation around the equilibrium with the highest F becomes very large, the trajectory can be trapped in the domain of attraction of the equilibrium with low F, and then the system stays there. Curve labeled Q in Fig. 3i and j illustrates an example in which F_t increases temporarily but then declines very quickly and finally stays low.

4. Conservative players (small *s*)

Even if the alternative option is very much profitable, it normally takes some number of years before most players

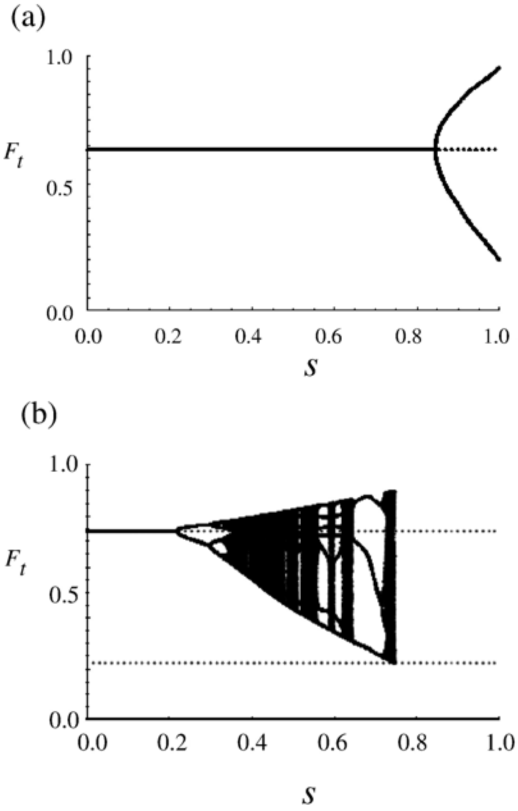


Fig. 4 – Bifurcation diagrams showing the effect of conservatism. Horizontal axis is the maximum fraction of change s. (a) The return map is decreasing, and the cooperation level fluctuates with period two when $s=1$. Parameters (except s) are the same as in Fig. 3g and h. Solid curves are for stable equilibria, and dotted curves are for unstable equilibria. The model shows fluctuation with period two for large s, but stable equilibrium for small s. (b) The return map has an intermediate peak when $s=1$. The parameters (except for s) are the same as in Fig. 3i and j. For large s, trajectories hit the unstable equilibria (indicated by a dotted line) and finally converges to the equilibrium with small F. For intermediate s, chaotic fluctuation around the equilibrium with high F is maintained, and for small s the equilibrium with high F is locally stable. Dotted horizontal lines separates the range of F that eventually converges to the high and the low equilibria. Parameters are: (a) $\xi=0.1$, $\beta=1$, $p_A=3$, $p_B=1$, $c_A=1$, $c_B=6$, $\alpha=3$, $q_0=1$, $\phi_0=1$. (b) $\xi=10$, $p_A=10$, $c_B=28$, $\alpha=1$. Others are the same as in (a).

change their option. This conservatism can be expressed as a small s ($s<1$). The number and the location of equilibria of Eqs. (5a) and (5b) are independent of s. The equilibrium that is unstable for a large s becomes stable for a small s.

4.1. Increasing $\psi(F)$

If $(p_A-p_B)/p_A \le \xi/(2\xi+1)$, function $\psi(F_t)$ is monotonically increasing for all $s<1$. If the system has a single equilibrium when $s=1$, then for $s<1$ the same equilibrium exists and is globally stable. If the system has three equilibria with two equilibria simultaneously stable and an intermediate unstable equilibrium for $s=1$, then this conclusion remains valid for all $s<1$. The boundary between two domains of attraction are given by the intermediate unstable equilibrium for all s. Smaller s makes the movement slower, but the location and the stability of equilibria are unchanged.

4.2. Decreasing $\psi(F)$

If $\xi \le (p_A-p_B)/p_A$, the dynamics has a single equilibrium in $0<F<1$. If it is stable with $s=1$, then the equilibrium remains stable for any smaller $s<1$. Even if the equilibrium is unstable for the dynamics with $s=1$, it can be stable for the dynamics with $s<1$. In fact, the equilibrium always becomes stable for a sufficiently small s. Fig. 4a illustrates bifurcation diagram. For large s, the equilibrium is unstable and the dynamics show a cycle of two-year period with a large magnitude. As s becomes smaller, the amplitude of oscillation becomes smaller, and finally the equilibrium becomes stable. This implies that if people are more conservative, the fraction of change per year becomes smaller and originally unstable equilibria become stable. A high level of environmental concern of the society tends to be maintained more often if people are conservative, not quick to change their attitude.

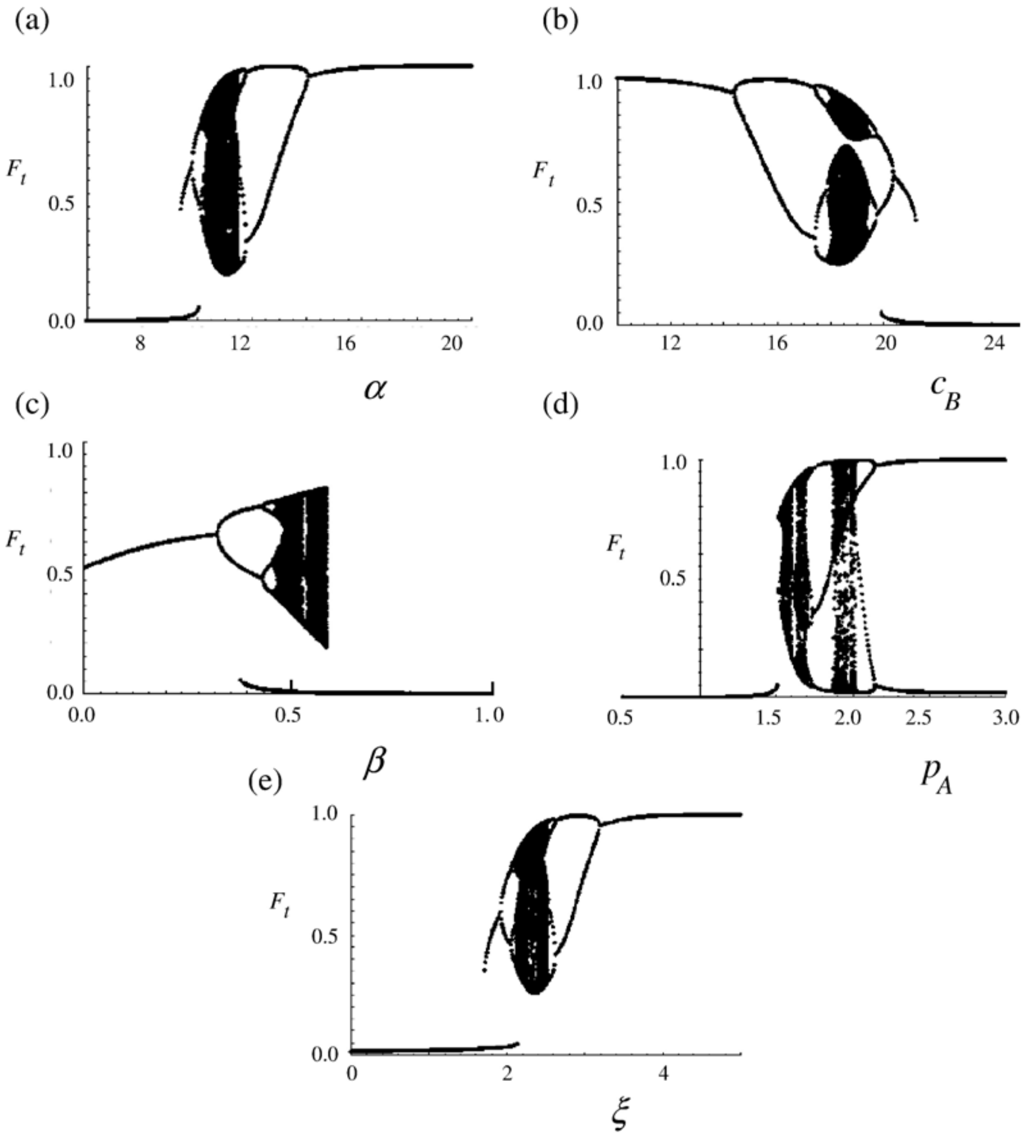


Fig. 5 – Bifurcation diagrams. Horizontal axis is: (a) α; (b) c_B; (c) β; (d) p_A; (e) ξ. In each graph, one parameter in the horizontal axis is changed with all the others fixed. Parameters are: $\xi=2$, $s=1$, $\beta=1$, $p_A=1.5$, $p_B=0.5$, $c_A=1$, $c_B=20$, $\alpha=10$, $q_0=1$, $\phi_0=1$, unless specified otherwise.

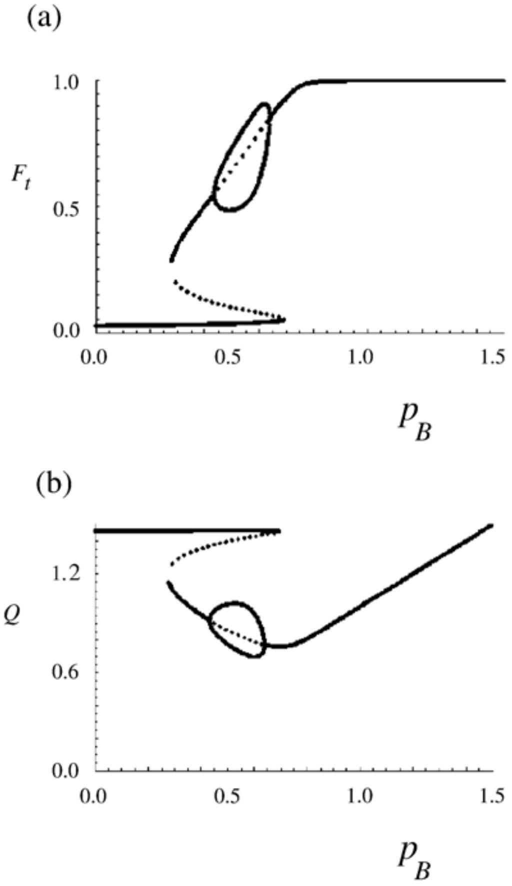


Fig. 6 – Bifurcation diagram. Horizontal axis is the phosphorus release made by a cooperative player p_B. (a) Fraction of cooperators. (b) Water pollution level. Technological advancement results in smaller p_B, which produces lower cooperation F and more polluted water (large Q). Parameters are: $\xi=2$, $\beta=1$, $p_A=1.5$, $p_B=1$, $c_A=1$, $c_B=20$, $\alpha=10$, $q_0=1$, $\phi_0=1$, $s=1$.

4.3. *ψ(F) with an intermediate maximum*

Fig. 4b illustrates a bifurcation diagram for the case in which the model with $s=1$ has a stable equilibrium with a very low level of cooperation, which is globally stable. Horizontal axis is for s and the vertical axis if for F_t. For large s ($s>0$), the equilibrium with a high cooperation level is unstable, causing a fluctuation of period 2. For a very large s, trajectory is trapped in the domain of attraction for the low cooperation equilibrium. For a smaller s, the amplitude of the fluctuation around the high cooperation equilibrium becomes smaller. For even smaller s (less than about 0.2), the equilibrium with a high cooperation becomes stable. Again showing conservatism (small s) contributes to the maintenance of cooperation.

5. Parameter dependence

We here consider the dependence of the equilibrium level of cooperation F on different parameters. We do not show the behavior of the model exhaustively. But we show the cases especially interesting, and sometimes unexpected outcome, which are caused by the nonlinearity of the system.

5.1. *Bifurcation diagram*

Fig. 5 illustrates parameter dependence of the model. In all these figures, vertical axis indicates the equilibrium level of F. Horizontal axis is α in Fig. 5a, c_B in Fig. 5b, β in Fig. 5c, p_A in Fig. 5d, ξ in Fig. 5e.

The diagrams show diverse patterns of bifurcation. For example when F_t converges to a cycle of period three for a particular value, the figure has three curves indicating the three values of F with the same value of the parameter in horizontal axis. The diagram shows changes in periodicity. There are also a range of s for which an interval of F is filled by points, which corresponds to chaotic fluctuations.

5.2. *Unexpected parameter dependence*

Fig. 6 illustrates an especially interesting case showing unexpected parameter dependence. Horizontal axis is p_B, the phosphorus release by option B. As the efficiency of the environmentally benign option is improved by the advancement of technology to remove nutrients, less phosphorus becomes to be released, and hence p_B decreases. In such a case, we expect that the lake pollution should become lower. However according to Fig. 6a, as p_B decreases, the fraction of people who cooperate (adopting option B) declines and finally drops to a very small value (small F). As a result, phosphorus discharge level increases and finally becomes the highest value for small p_B (Fig. 6b).

6. Discussion

6.1. *Positive and negative feedback loops*

Observed diverse behavior of the dynamics can be understood clearly if we note that the model includes two different ways of feedback regulation, as illustrated in Fig. 1. These originate from two properties of the social pressure. There is a positive feedback via the frequency dependence of the fraction of cooperative players (Fig. 1). If there are more cooperators, each player tends to feel a stronger social pressure which forces him to cooperate. As a result, a higher cooperation level would be maintained. In contrast, if the initial level of cooperation is low, the social pressure is weak and cooperation will stay low. Hence bistability is an outcome of the positive feedback regulation. This is typically shown by the case when return map $\psi(F)$ is an increasing function (Fig. 3abcd).

There is also a negative feedback loop caused by the society's environmental concern over the lake pollution. If the cooperation among players is low, people release more phosphorus and lake water becomes more polluted. Lake water pollution would strengthen the environmental concern and enhance the level of cooperation in the subsequent year. This negative feedback drives the cooperation level toward an intermediate equilibrium. If the negative feedback regulation is very strong, the cooperation level may overshoot the equilibrium and may even cause oscillations of pollution and cooperation levels. This is the case when return map $\psi(F)$ is a decreasing function (Fig. 3efgh).

The relative magnitude of these two feedback loops are given by the ratio between the effectiveness of the cooperative option in reducing phosphorus, $(p_A - p_B)/p_A$, and the frequency dependence of the social pressure, ξ. As a result of combination of these two processes, the model shows diverse behavior, including bistability, oscillations with a long period, and chaotic fluctuations (Figs. 4 and 5).

Unexpected parameter dependence shown by Fig. 6 most clearly illustrates the need of considering people's decision making process in eutrophication control. When a more advanced technology of phosphorus removal becomes available, which provides cleaner water to release at the same cost as before (smaller p_B), we might expect that the water quality should be improved. However Fig. 6b demonstrates that the water quality can become worse than before as a result of the improvement of the technology. This is because the realized water quality is also controlled by the fraction of cooperators among players, which might decline as p_B becomes smaller (Fig. 6a). In the end, system is trapped in a low-cooperation equilibrium at which the lake water stays very much polluted.

6.2. *Integrated social and ecological dynamics*

Traditional economics theory focuses on the equilibrium of a game. However the people's behavioral change takes some time, and may require a length of time comparable to ecological changes. Then, we need to consider the simultaneous dynamics of ecological and socio-economical changes, instead of the equilibrium assumption of economic part. Evolutionary game dynamics describing the temporal change of the people's behavior have also been studied (Hofbauer and Sigmund, 2003). Eq. (3) gives the rate of change for a player between behaviors. The change to a more desirable option occurs faster than that to a less desirable option. When β is very large, it gives "best response" dynamics by which the players change to the option with the higher profit (the lower total cost) with probability one. A positive but finite β implies that people may change to a less profitable option by chance, representing the idea of bounded rationality (McKelvey and Palfrey, 1995).

Satake and Iwasa (2006) developed a Markov chain model for the land-use dynamics in a forested landscape. A forest is composed of many land parcels, and the land-use state at each land parcel changes stochastically. The state-transition is caused both by the forest succession and by the decision of landowners, the latter following equations similar to Eq. (3). The landowner considers the current as well as the future utilities out of the land parcel. Satake and Iwasa show that when land owners make myopic choice focusing on the short-term benefit, the individual decision tends to push the entire landscape towards an agricultural state in spite that forested state provides the highest utility. A long-term management perspective and enhanced rate of forest recovery can make the land-use composition closer to the social optimum. Satake et al. (2007) extend this formalism to the situation in which deforestation of a land parcel may modify the surrounding forest sites, and observe wave-like patterns of deforestation.

For a lake ecosystem, Carpenter et al. (1999b) analyzed several versions of simulators for the lake water management. For example in the market manager model, each player chooses his option considering the cost and benefit to himself, and the benefit is the function of water quality representing how he appreciates the improvement of water quality. Large fluctuations of water quality can be caused by the stochastic input of phosphorus to the lake and the high cost of information needed for proper decision making.

Both models are very simple, and they do not attempt to fit parameters to a particular situation. Detailed study of simple systems is useful in promoting our understanding on the fundamental properties of integrated ecological and economic dynamics.

6.3. *Social pressure*

Many environmental problems include social dilemmas (Ostrom, 1990). The social pressure in the present paper represents the propensity of each player to choose pro-social, or pro-environmental behavior in spite of the accompanying cost.

Pillutla and Chen (1999) showed that people tend to cooperate more if the same game is framed as a non-economical situation (i.e. contribution to a social event) than an economical situation (i.e. investment to a fund), showing that people have goals besides maximizing monetary payoffs. Social acceptance or reputation is likely to play an important role (Gachter and Fehr, 1999). According to the analysis by environmental psychologists, environmentally oriented behaviors are encouraged by knowledge, positive control beliefs, personal responsibility, and perceived threats to personal health (Fransson and Garling, 1999; Kaiser and Shimoda, 1999). People are more likely to take pro-social options and constrain egoistic behavior in environmental problems if the pollution or depletion of resources is certain, and less so if it is uncertain (Biel and Garling, 1995). It is quite likely that people are more willing to make a costly contribution if the cooperative action is more effective in mitigating or solving the pressing social problem.

Second, the experimental study of public goods games, a large fraction of people are conditional cooperators who tend to cooperate more if others in the same groups cooperate (Fischbacher et al., 2001; Kurzban and Houser, 2005). Positive correlation between a player's contribution and other people's contribution is an example of conformist transmission of behavior (Boyd and Richarson, 1985; Henrich and Boyd, 1998).

Based on these, we postulated two properties of the social pressure: First the social pressure is stronger if there are more cooperators in the population. Second the social pressure reflects the public concern over the environmental issue, which in the current case the lake water pollution. These two aspects of social pressure create a positive and a negative feedback loops, respectively, of the regulation of the cooperation level (Fig. 1), and result in behavior typical of nonlinear dynamics.

How these tendencies arise is an important issue of human evolution (Hagen and Hammerstein, 2006). Recent researches on the evolutionary mechanisms for cooperation focus punishment (Sigmond et al., 2001; Nakamaru and Iwasa, 2005, 2006) and indirect reciprocity using social reputation (Nowak and Sigmund, 1998, 2005; Ohtsuki and Iwasa, 2004, 2006). The social pressure in the present paper might represent the effect of the expectation of being punished or the effect through the reputation modification.

6.4. *Future development*

In this paper, we aimed to show the potential effect of people's decision making on ecosystem dynamics clearly. To achieve this goal, we adopted deliberately simplified assumptions. There are many ways to improve the model and to make it more realistic.

First, in the current paper, we adopted a very simple relationship between the inflow of phosphorus and the level of pollution $Q=q_0P$. This may be acceptable if only the phosphorus in lake water is considered because the turnover time of lake water in Lake Kasumigaura is 7 months (Tabuchi, 2005), but we need a slower turnover if the phosphorus in soil sediment is considered (Carpenter, 2005). In addition, nonlinear dependence of the pollution level in a lake and the nutrient input may result in "catastrophic regime shift" when environmental changes smoothly (Scheffer and Carpenter, 2003; Genkai-Kato and Carpenter, 2005; Carpenter, 2005). If we introduced the nonlinear relationship between the phosphorus inflow and the pollution level, this could be coupled with the nonlinearity caused by the human choice dynamics. This is an important subject of future theoretical study.

Second, if only a small number of players are involved, stochasticity caused by the smallness of the number becomes important. Then a stochastic model rather than a deterministic model needs to be studied. Another source of stochasticity is caused by the environmental fluctuation. For example the nutrient input to a lake includes fluctuation which may be amplified in the process of management decision (Carpenter et al., 1999b).

Third, if the number of players in the lake water management N is small, players know each other well and are able to watch what others do. Hence the social pressure is stronger than the case with a large N. In contrast if each player feels that he is just one of thousands, the cooperation would become less motivated. Tight linkage among players is one of the most important factor for successful ecosystem management (Levin, 1999). The optimal design of social institution that can foster cooperation is an important theoretical question.

In spite of the simplicity of the model, the current study clearly shows the need of close examination of the integrated ecological and socioeconomic dynamics to achieve successful ecosystem management.

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