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ANALYSIS

Conflict between groups of players in coupled socio-economic and ecological dynamics

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ABSTRACT

Conflict among multiple groups is a major source of difficulty in environmental conservation. People are often divided into various groups that have different social factors, sometimes leading to differences in the degree to which they cooperate in environmental conservation. This obstructs the social consensus needed to solve the environmental problems. Here we study the coupled dynamics of human socio-economic choice and lake water pollution, and examine the magnitude of the difference in cooperation levels between two groups. In the model, many players choose between a costly but cooperative option and a selfish option. The former results in a reduced phosphorus discharge into the lake. Each player's choice is affected by an economic cost and social pressure. Social pressure is a psychological factor that promotes cooperation: it becomes stronger when more players in the society are cooperative (conformist tendency) and when the problem at hand is a greater concern to society. In the model, two groups sometimes show large differences in their cooperation levels even when both have exactly the same social factors. However, cooperation levels are more likely to differ between groups that have different social factors. Enhancement of the cross-group conformist tendency is the most effective way to minimize differences in cooperation levels and to mitigate conflict between groups.

1. Introduction

Many environmental efforts, including ecosystem management and biodiversity conservation, involve the problems of cooperation under situations that pose social dilemmas (Ostrom, 1990). For example, individuals in a society may choose between two options: a costly but pro-environmental (cooperative) option and a selfish option. As the number of individuals who choose the cooperative option increases, all individuals benefit to the same degree from a healthier environment, whether or not they cooperated. Since each individual can gain more by taking the selfish option than by cooperative one, society would end up with a situation where no one cooperates. This situation is called the tragedy of the commons (Hardin, 1968).

Unlike the model of the tragedy of the commons, the cooperative tendency in human is affected not only by economic factors but also by various psychological factors. Recently, such psychological factors have been incorporated into models of the cooperative tendency in economics (Brekke et al., 2003; Nyborg and Rege, 2003). We also incorporated psychological factors into our model as a social

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pressure (Iwasa et al., 2007; Suzuki and Iwasa, in press). In our model, the cooperative tendency was determined by the balance between economic cost and the social pressure. Experimental economics has revealed that people tend to contribute to the public good when many others do so, and to punish those who do not contribute enough (Pillutla and Chen, 1999; Fehr and Gächter, 2000; Fischbacher et al., 2001). People also tend to willingly accept the cost of environmental conservation if they are informed about the related environmental crisis (Milinski et al., 2006). Based on these empirical results, we assumed that social pressure is stronger when more individuals in a society are cooperative (conformist tendency), and when water pollution problem is a greater concern in the society. Simulation results showed that a high conformist tendency is effective in creating a stable equilibrium with low pollution level and high cooperation level. When single group has a concern in the environmental conservation, social dilemma may be resolved by a high conformist tendency.

Conflict among multiple groups is also a major source of difficulty in environmental conservation as well as social dilemma. Conflict in resource management is often assumed to reflect differences in economic interests among groups, but the origins of conflict go beyond material incompatibilities (Adams et al., 2003). Conflict is frequently caused by differences in perspectives or philosophies concerning resource management and environmental conservation, which may lead to differences in cooperation levels among groups. The greater the differences in cooperation levels, the more serious the conflict may become. To achieve successful environmental conservation, we must understand the factors that create the differences in cooperation levels between groups and to reduce those differences.

In this paper, we study a dynamic model of cooperation levels in two groups in a lake pollution problem. We extend the single-group model of Suzuki and Iwasa (in press) to two groups. We first show that the cooperation levels may differ even when both groups have exactly the same social factors. However, differences in social factors cause further differences in cooperation levels and create greater conflict between groups. We discuss how to reduce differences in cooperation levels between groups.

2. Model

We consider a number of players whose choices affect the water pollution level in the lake. Players choose between a costly but cooperative option with a low phosphorus discharge and an economical option with a high phosphorus discharge. $x(t)$ represents the proportion of players who take the cooperative option, which is thus the cooperation level in year t. $y(t)$ represents the pollution level in the lake in year t. We coupled the dynamics of $x(t)$ and $y(t)$.

2.1. Individual decision-making

First, we explain the model of individual decision-making presented in Iwasa et al. (2007) and Suzuki and Iwasa (in press). In experimental economics, people tend to contribute to the public good when many others contribute to it (Pillutla and Chen, 1999; Fischbacher et al., 2001). These findings imply that morality, fairness preference, and conformity are among the psychological factors involved in cooperation, and have been adopted in theoretical models (e.g., Boyd and Richerson, 1996; Henrich and Boyd, 1998). People also tend to willingly pay for environmental conservation if they are informed about the related environmental crisis (Milinski et al., 2006). Based on these results in experimental economics, we assumed that the utilities for a player choosing the cooperative option and a player choosing the non-cooperative option are:

$$U_C = \lambda(y(t)) - c, \tag{1a}$$

$$U_N = \lambda(y(t)) - \gamma(1 + \xi x(t))(1 + \kappa y(t)), \tag{1b}$$

respectively. $\lambda(y(t))$ is the utility obtained from the quality of the lake water, and is provided to both the cooperator and the non-cooperator equally. Eq. (1a) indicates that the utility for a cooperative player is reduced by c, the economic cost of cooperation. Eq. (1b) indicates that a non-cooperative player pays no economic cost, but does suffer a psychological cost (social pressure). γ is the basic level of social pressure, but the social pressure grows when more players cooperate, as indicated by factor $1+\xi x(t)$. Social pressure also grows when water is more polluted, as indicated by factor $1+\kappa y(t)$.

Players choose the option probabilistically by comparing the utilities of these two cases. We adopted a model for probabilistic choice (McFadden, 1981).

$$\psi = \Pr[\text{to take cooperative option}] = \frac{e^{\beta U_C}}{e^{\beta U_C} + e^{\beta U_N}} = \frac{1}{1 + e^{\beta(U_N - U_C)}}. \tag{2}$$

Each player takes the cooperative option with the probability ψ (Mckelvey and Palfrey, 1995).

2.2. Dynamics of cooperation level

From the viewpoint of evolutionary game theory, we consider the dynamics of the proportion of cooperative players. As a result of choices made by many players, the proportion of cooperative players in the next year is represented by

$$x(t+1) = (1-s)x(t) + s\psi(x(t), y(t)), \tag{3}$$

where s is the fraction of players who will decide whether or not to cooperate in that year. Eq. (3) is the "logit dynamics" representing the stochastic best response dynamics in evolutionary game theory (Hofbauer and Sigmund, 2003). Logit dynamics have also been adopted for the decision-making of farmers in Carpenter et al. (1999b) and, more recently, for the decision-making of landowners in Satake et al. (2007). However, those models did not consider psychological factors like the social pressure.

We extend the basic, single-group model of Suzuki and Iwasa (in press) to two groups. Let x_1 and x_2 be the cooperation levels of groups 1 and 2, respectively (Fig. 1). We first consider

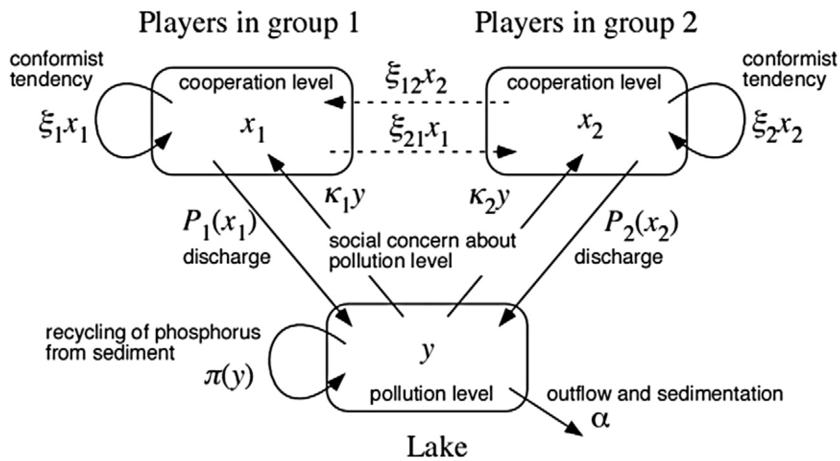

Fig. 1 – Model of two groups.

the situation where the conformist tendency within each group (ξ_1, ξ_2) is strong, but the cross-group conformist tendency can be neglected ($\xi_{12}=\xi_{21}=0$ in Fig. 1).

The cooperation levels x_1 and x_2 in the next year are given by

$$x_1(t+1) = (1-s)x_1(t) + \frac{s}{1+exp(\beta\{c_1-\gamma(1+\xi_1 x_1(t))(1+\kappa_1 y(t))\})}, \quad (4a)$$

$$x_2(t+1) = (1-s)x_2(t) + \frac{s}{1+exp(\beta\{c_2-\gamma(1+\xi_2 x_2(t))(1+\kappa_2 y(t))\})}. \quad (4b)$$

The phosphorus concentration in inflow to the lake is given by

$$\sum n_i P_i(x_i(t)) = n_1\{p_{H1}(1-x_1(t)) + p_{L1}x_1(t)\} + n_2\{p_{H2}(1-x_2(t)) + p_{L2}x_2(t)\}. \quad (5)$$

In Eq. (5), n_i represents the proportion of phosphorus inflow from group i, indicating the ratio of the group size. We assume two groups of the same size, or $n_1=n_2=0.5$. From Eq. (5), inflow $\Sigma n_i P(x_i(t))$ is represented by

$$\sum n_i P_i(x_i(t)) = 0.5(p_{H1}+p_{H2}) - 0.5\{(p_{H1}-p_{L1})x_1(t) + (p_{H2}-p_{L2})x_2(t)\}. \quad (6)$$

The difference in phosphorus discharges between options, or $p_{Hi}-p_{Li}$, indicates the effectiveness of cooperation in improving lake water quality. When the effectiveness of cooperation is much higher in group i than in group j, total phosphorus discharge does not change much with the cooperation level in group j. Then, the dynamics of the cooperation level in group i and the pollution level will show multiple equilibria and oscillations, which are qualitatively similar to the dynamics in the model of a single group with $p_H=0.5(p_{H1}+p_{H2})$ and $p_H-p_L=0.5(p_{Hi}-p_{Li})$ studied by Suzuki and Iwasa (in press). In the following analysis, we focus on cases where the effectiveness of cooperation is the same in both groups.

2.3. *Dynamics of pollution level in lake*

Suzuki and Iwasa (in press) assumed that the pollution level in the lake follows a non-linear dynamics. Many studies have reported that the pollution levels in some lakes showed hysteresis caused by nutrient recycling from the lake sediment (Carpenter et al., 1999a,b; Gunderson and Holling, 2001; Scheffer and Carpenter, 2003; Scheffer, 2004).

In the present paper, we also use the dynamics of the pollution level including the non-linear function as Suzuki and Iwasa (in press) adopted. We assume the following dynamics of the pollution level in the lake:

$$y(t+1) = (1-\alpha)y(t) + \pi(y(t)) + \sum n_i P_i(x_i(t)), \quad (6)$$

where α represents the outflow and sedimentation rate of lake water. The phosphorus in the water is lost by outflow and sedimentation, but is supplied by recycling from the sediment $\pi(y(t))$ and by inflow $\Sigma n_i Pi(x_i(t))$. Following Carpenter et al. (1999a), we assume that the amount of recycled phosphorus per year is

$$\pi(y(t)) = \frac{ry(t)^q}{m^q + y(t)^q}. \quad (7)$$

This describes a non-linear switching for a large q: phosphorus recycling is slow for a low pollution level (if $y(t)<m$) but fast for a high pollution level (if $y(t)>m$). m is the threshold between low and high levels. We set $q=2$ as in previous studies (e.g., Brock and de Zeeuw, 2002; Dechert and O'Donnell, 2006; Suzuki and Iwasa, in press).

3. Result 1

3.1. *Two groups with the same parameters (symmetrical case)*

We first analyzed a symmetrical case, where the individuals in both groups had exactly the same parameters ($c_1=c_2$, $\xi_1=\xi_2$, $\kappa_1=\kappa_2$, $p_{H1}=p_{H2}$, and $p_{L1}=p_{L2}$). In such a case, we may expect the cooperation levels to be the same in both groups. However, cooperation levels can become very different according to the dependence on initial conditions. In the case illustrated in Fig. 2, the dynamics showed oscillation with both groups having the same cooperation level, if initial cooperation levels in both groups were the same ($x_1(0)=x_2(0)$), or if the initial pollution level $y(0)$ was low (Fig. 2(a)). However, if $x_1(0)$ differed significantly from $x_2(0)$, and if $y(0)$ was near 1.0 (Fig. 2(b)), the groups maintained a very large difference in their cooperation levels. Thus, strong conflict between two groups can emerge even if both have exactly the same social and ecological backgrounds.

The initial condition dependence in Fig. 2 was investigated in terms of the domains of attraction. A domain of attraction is a region of the initial condition from which the system converges to the same stable equilibrium or the same limit cycle. We numerically calculated the domains of attraction to conflict equilibria. In the case of Fig. 2, there are conflict equilibrium with low x_1 and high x_2, and that with high x_1 and low x_2. We denoted the domains of attraction to these conflict

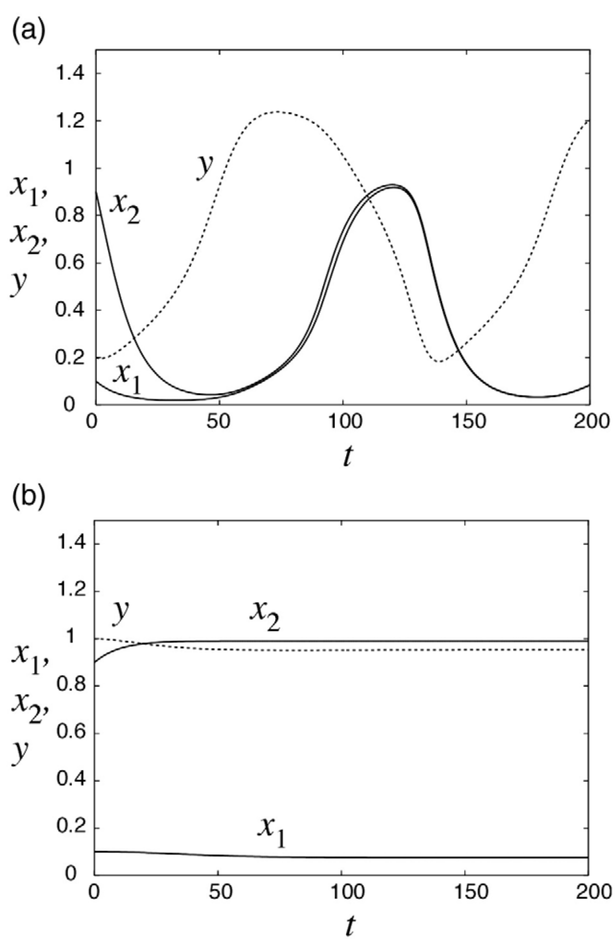

Fig. 2 – Initial condition dependence in a symmetrical case. (a) Oscillation with low initial pollution level. $x_1(0)=0.1$, $x_2(0)=0.9$, $y(0)=0.2$. (b) Conflict equilibrium with relatively high initial pollution level and different initial cooperation levels. $x_1(0)=0.1$, $x_2(0)=0.9$, $y(0)=1.0$. Parameter settings are $s=0.1$, $\beta=1$, $\gamma=2$, $c_1=c_2=7$, $\xi_1=\xi_2=2$, $\kappa_1=\kappa_2=1$, $p_{H1}=p_{H2}=0.08$, $p_{L1}=p_{L2}=0.02$, $\alpha=0.4$, $m=1$, and $r=0.7$.

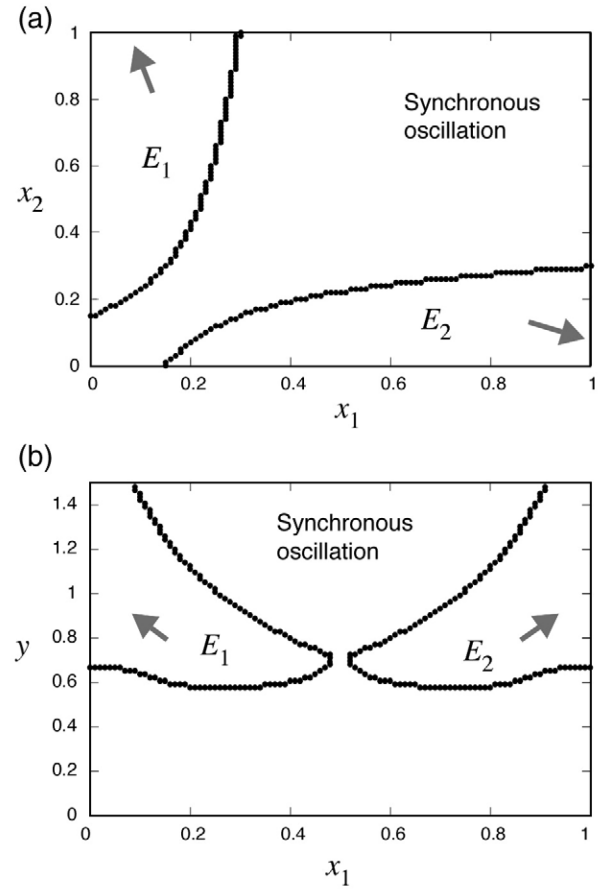

Fig. 3 – The domains of attraction to conflict equilibria in a symmetrical case. We select 101 × 101 initial conditions on the grid within an initial condition space, and show whether the system converges to either of the two conflict equilibria or to symmetrical oscillation from the initial condition. The circles represent the boundaries of three domains. (a) E_1 and E_2 in initial condition space where $x_1(0)$ and $x_2(0)$ are changed from 0.0 to 1.0 with an interval of 0.01, and $y(0)$ is fixed at 1. (b) E_1 and E_2 in initial condition space where $x_1(0)$ is changed from 0.0 to 1.0 with an interval of 0.01, and $x_2(0)$ is changed, satisfying $x_1(0)+x_2(0)=1$. $y(0)$ is changed from 0.0 to 1.5 with an interval of 0.015. The parameter settings are the same as those in Fig. 2.

equilibria by E_1 and E_2, respectively. In the region located between E_1 and E_2, the cooperation levels become equal and show synchronous oscillation (Fig. 2(a)). In Fig. 3(a), we illustrate the results with the initial condition space satisfying $0 \le x_1(0) \le 1$, $0 \le x_2(0) \le 1$, and $y(0)=1$. In Fig. 3(b), we illustrate E_1 and E_2 in the initial condition space satisfying $0 \le x_1(0) \le 1$, $0 \le y(0) \le 1.5$ and $x_1(0)+x_2(0)=1$. E_1 and E_2 occupy about 38% of the initial conditions in Fig. 3(a) and about 32% of those in Fig. 3(b).

The boundaries of the domains of attraction change with the change in social factors. The effects of changing social factors on E_1 and E_2 were quite complicated (see Appendix A). The dependence of a domain of attraction on these parameters is not monotonic.

3.2. *Two groups with different parameters (asymmetrical case)*

Next we analyzed an asymmetrical case where two groups had different parameters. We here focused on several simple cases where only one or two parameters were different between the groups, and examined the difference in cooperation levels between the groups. In Fig. 4, conflict between the groups is caused by different economic costs (Fig. 4(a)), different conformist tendencies (Fig. 4(b)), and different social concerns (Fig. 4(c)). In Fig. 4, the stable cooperation level in group 1 is higher than that in group 2. In the case of Fig. 4(b), there are three points of conflict equilibria: that of high x_1, low x_2, and low y, that of high x_1, low x_2, and high y, and that of low x_1, high x_2, and high y. However, the cooperation levels rarely reached the conflict equilibrium of low x_1 and high x_2 because the domain of attraction to it was very small.

We also assumed a case where both the conformist tendency and the social concern differ between the groups (Fig. 5). The individuals in group 1 had a stronger conformist tendency but weaker social concern than those in group 2 ($\xi_1 > \xi_2$, $\kappa_1 < \kappa_2$). In this case, the initial condition determined whether the cooperation levels would reach the conflict equilibrium of low x_1 and high x_2, or that of high x_1 and low x_2. If the cooperation level in group 1 was low initially (Fig. 5(a) and (c)), it stayed low because of weak conformist tendency. The low cooperation level in group 1 led to a high pollution level, which enhanced the cooperation level in group 2 because they had higher level of social concern. On the other hand, the cooperation level in group 1 remained high if that group's initial cooperation level was high (Fig. 5(b) and (d)). The high cooperation level in group 1 led to a low pollution level, which decreased the social concern about pollution level and reduced cooperation level in group 2. Thus, differences in social factors between groups readily cause greater differences in cooperation levels than were found when both groups had the same social factors.

4. Result 2: cross-group conformist tendencies between two groups

So far, we have assumed that the cross-group conformist tendency was negligible ($\xi_{12} = \xi_{21} = 0$). If the cross-group conformist tendencies are important, the dynamics of the cooperation levels can be represented by

$$x_1(t+1) = (1-s)x_1(t) + \frac{s}{1 + exp(\beta\{c_1 - \gamma(1 + \xi_1 x_1(t) + \xi_{12} x_2(t))(1 + \kappa_1 y(t))\})}, \quad (9a)$$

$$x_2(t+1) = (1-s)x_2(t) + \frac{s}{1 + exp(\beta\{c_2 - \gamma(1 + \xi_2 x_2(t) + \xi_{21} x_1(t))(1 + \kappa_2 y(t))\})}. \quad (9b)$$

where ξ_{ij} represents the cross-group conformist tendency to group *j* in group *i*. If ξ_{ij} is large, the cooperation level in group *i* is greatly influenced by the cooperation level in group *j*. We compared the results of this model with those of the corresponding cases without the cross-group conformist tendency.

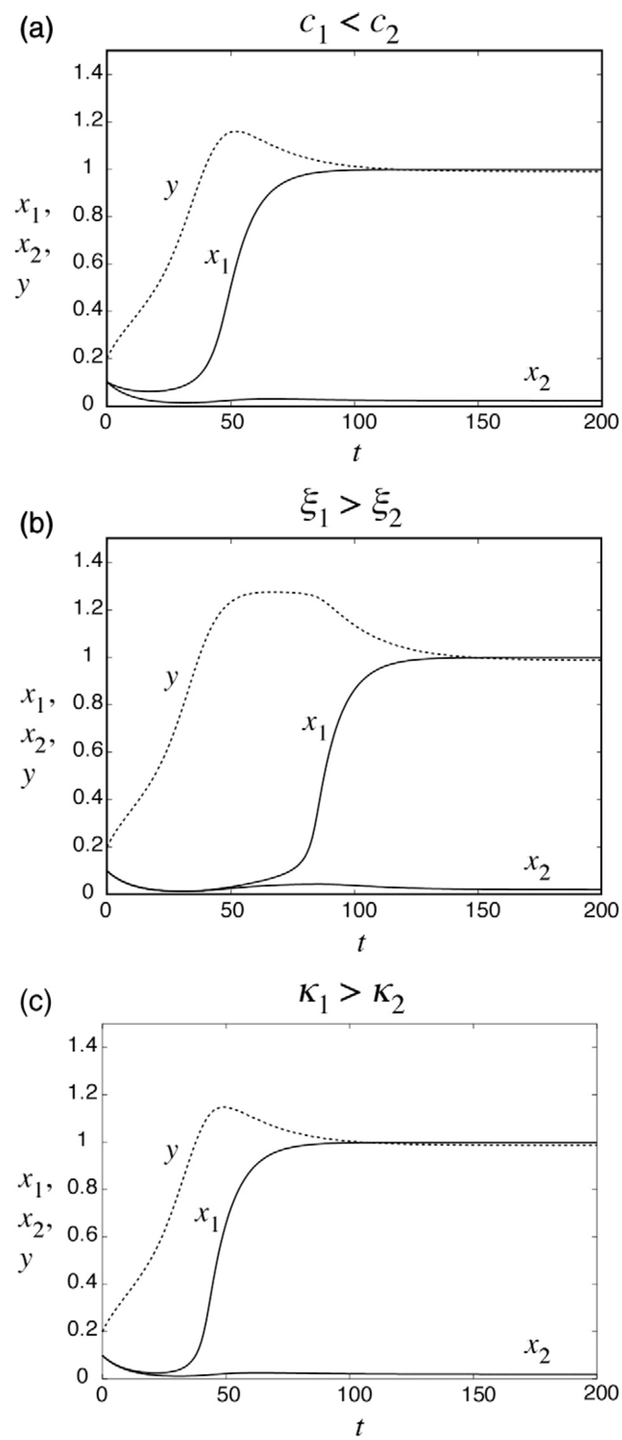

Fig. 4 – Examples of conflict between the groups by different values of parameters. (a) Different economic costs. $c_1 = 6$, $c_2 = 8$. (b) Different conformist tendencies. $\xi_1 = 4$, $\xi_2 = 2$. (c) Different social concerns. $\kappa_1 = 2$, $\kappa_2 = 1$. Default parameter settings except for focal parameters are $c_1 = c_2 = 8$, $\xi_1 = \xi_2 = 2$, and $\kappa_1 = \kappa_2 = 1$. The other parameter settings are the same as those in Fig. 2.

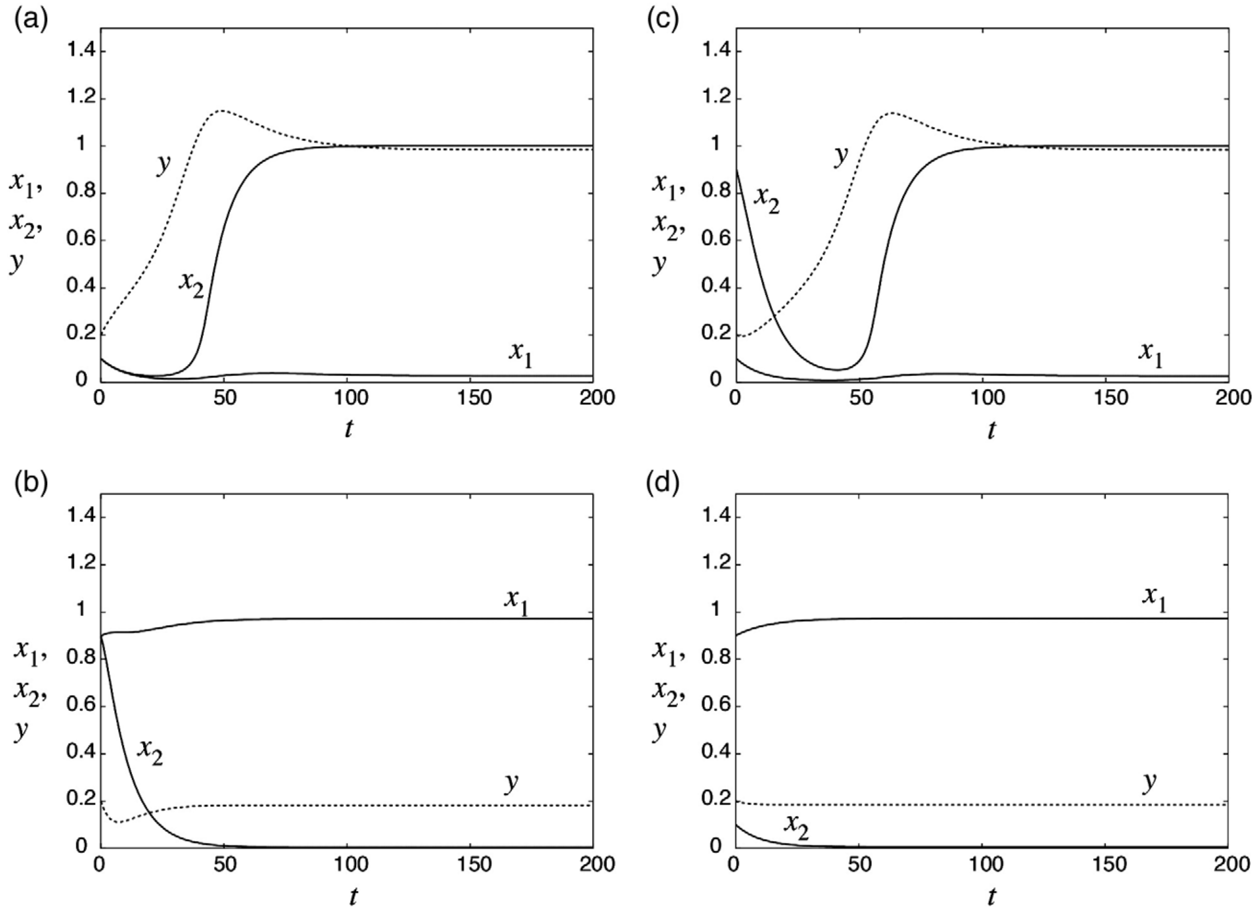

Fig. 5 – Dynamics of cooperation levels in two groups having different conformist tendencies and social concerns. $\xi_1=4$, $\xi_2=2$, $\kappa_1=1$, $\kappa_2=2$. (a) Initial cooperation levels are $x_1(0)=0.1$, $x_2(0)=0.1$. (b) $x_1(0)=0.9$, $x_2=0.9$. (c) $x_1(0)=0.1$, $x_2(0)=0.9$. (d) $x_1(0)=0.9$, $x_2(0)=0.1$. The initial pollution level is $y(0)=0.2$ for all cases. The other parameter settings are the same as those in Fig. 4.

4.1. Two groups with the same parameters (symmetrical case)

We analyzed the equilibria of the cooperation levels of two groups when the individuals in both groups had the same values of parameters ($c_1=c_2$, $\xi_1=\xi_2$, $\kappa_1=\kappa_2$, $p_{H1}=p_{H2}$, $p_{L1}=p_{L2}$, and $\xi_{12}=\xi_{21}$). When the cross-group conformist tendency was exactly the same as the within-group conformist tendency ($\xi_1=\xi_2=\xi_{12}=\xi_{21}$), x_1 and x_2 always became equal, which implied that there was no conflict regardless of the degrees of these conformist tendencies.

In the symmetrical case, the cooperation levels differed only when the cross-group conformist tendency was small and different from the within-group conformist tendency. As illustrated in Fig. 6, the domain of attraction to conflict equilibria (E_1 and E_2) became small drastically as the cross-group conformist tendency increased. This was in sharp contrast with the cases without the cross-group conformity reported in the last section (see Appendix A).

4.2. Two groups with different parameters (asymmetrical case)

When two groups had different cross-group conformist tendencies, different cooperation levels or conflict between the groups arose. However, if both ξ_{12} and ξ_{21} were the same and large, it could resolve the conflict caused by differences in the other social factors (i.e., different c_i, ξ_i, and κ_i) (Fig. 7). Compared with the model without the cross-group conformist tendency, the cooperation levels in both groups tended to be high because a high cooperation level in one group increased the cooperation level in the other group (Fig. 7). High cooperation levels in both groups decreased the pollution level dramatically.

5. Discussion

We extended the single-group model of Suzuki and Iwasa (in press) to two groups and examined the magnitude of the difference in the cooperation levels between two groups in the problem of lake water pollution. In our model, a large difference in cooperation levels was a relatively general phenomenon. Once one group is divided into two groups without the cross-group conformist tendency, the cooperation levels in these groups may become very different even when these groups have the same social and ecological backgrounds. In the symmetrical case where both groups had the same social factors and there was no cross-group conformist tendency, the difference in cooperation levels depended on the initial cooperation levels and on the initial pollution level

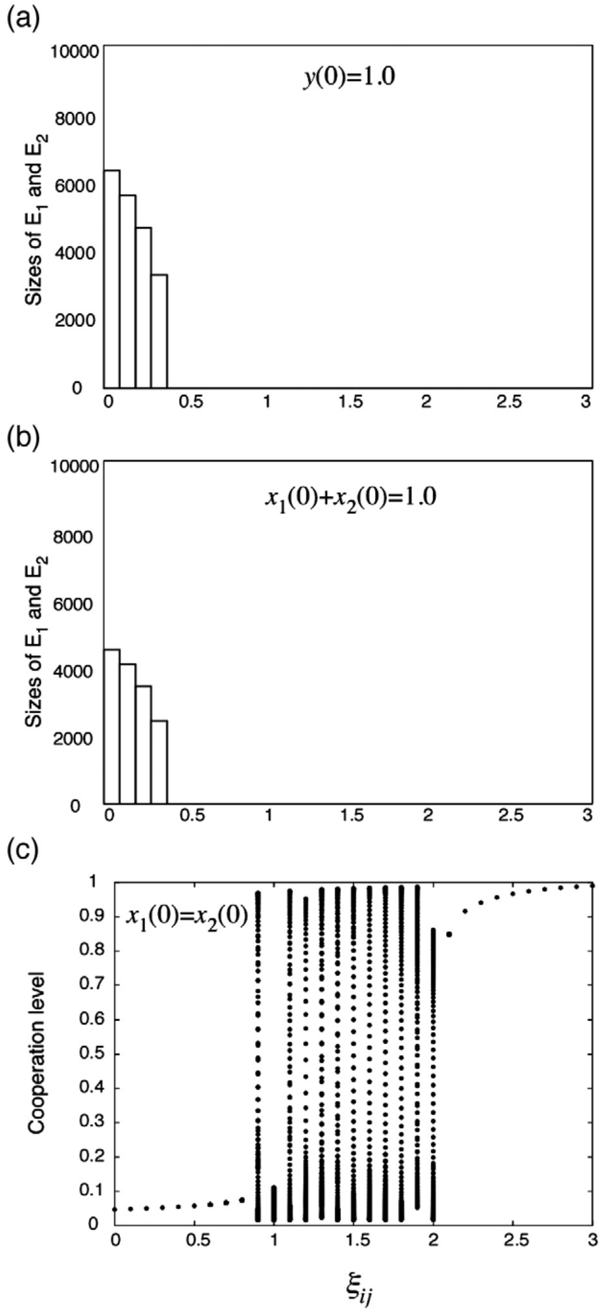

Fig. 6 – The effect of cross-group conformist tendency ξ_{ij} on the area of domains of attraction to conflict equilibria (E_1 and E_2). (a) Sizes of E_1 and E_2 in the initial condition space in Fig. 3(a). (b) Sizes of E_1 and E_2 in the initial condition space in Fig. 3(b). (c) Cooperation levels starting from $x_1(0)=x_2(0)$ with different ξ_{ij}. The parameter settings are the same as those in Fig. 2 except for $c_1=c_2=8$ and ξ_{ij}.

(Figs. 2 and 3). Groups with different social factors have different cooperation levels more readily than in the symmetrical case. The conflict equilibrium emerged when the economic cost of cooperation was lower (Fig. 4(a)), when the conformist tendency was stronger (Fig. 4(b)), when one group was more concerned than the other about the pollution level (Fig. 4(c)), and when the groups differed in both conformist tendency and social concern (Fig. 5).

The cross-group conformist tendency can increase cooperation levels and reduce differences in those levels. In the symmetrical case with the cross-group conformist tendency, that tendency very effectively reduced conflict (Fig. 6). In the asymmetrical case with the cross-group conformist tendency, both groups tended to maintain high cooperation levels because the high level in one group increased the level in the other group (Fig. 7). High cooperation levels in both groups decreased the pollution level dramatically. In the following subsections, we discuss factors that create conflict between groups and how to reduce the conflict in more detail.

5.1. *Factors creating conflict between two groups*

Differences in social factors may cause a serious conflict. In the real world, the economic cost (c_i) may differ between groups due to difference in subsidies for ecological conservation. The decision on the amount of the subsidy is likely to depend on the general public opinion in the local community. The net economic cost of the cooperative option should be smaller if the local community provides a larger subsidy to cooperators. The cost c_i may also be time, inconvenience, and reduced quality of pro-environmental products (Dresner et al., 2007). The change in lifestyle that results from choosing to cooperate would add the cost of that option.

The magnitude of the conformist tendency within a group (ξ_i) would be affected by the strength of the social network. The core members of the local community and people who have lived there for many years tend to have stronger conformist tendencies than others. The degree of social concern about the pollution level (κ_i) may depend on many factors. People who engage in economic activity on the lake may concern about the pollution level more than others because they will benefit more from an improved water quality. They also might have more information on the pollution level in the lake and stronger concern about that level. In addition, when people learned about the environment, their degree of social concern increases. We also considered the situation where the players in group 1 had a stronger conformist tendency ($\xi_1>\xi_2$) whereas

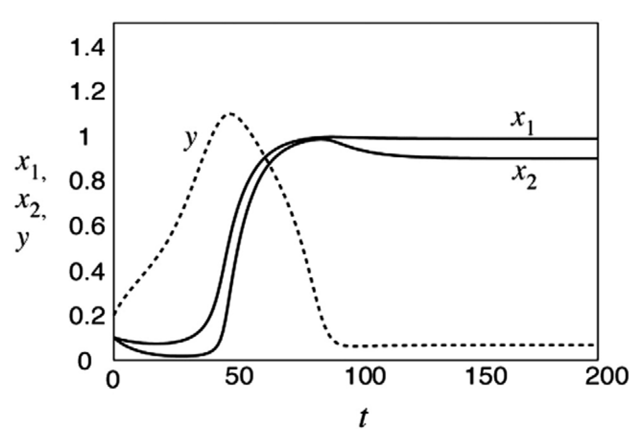

Fig. 7 – Effect of common cross-group conformist tendency ξ_{ij} on conflict. (a) Dynamics of cooperation levels and pollution level. Initial cooperation levels and pollution level are $x_1(0)=0.1$, $x_2(0)=0.1$, and $y(0)=0.2$. Parameter settings are the same as in Fig. 4(a), except for $\xi_{12}=\xi_{21}=2$.

players in group 2 had greater social concern ($\kappa_1 < \kappa_2$) (Fig. 5). It is often the case that people who live in cities tend to value a healthy environment more than people who live near the environment (Y. Mitani, personal communication, 2007). People living in cities would have a higher concern about pollution level than people living near the lake. However, city people may have a low conformist tendency because they do not make frequent contact with each other.

Multiple social factors are likely to have complex effect on the relative tendency to cooperate. Recent studies have developed methods of measuring the effects of social factors on the tendency to cooperate (e.g., Mitani et al., in press). If the effects of social factors become known better, we will be able to revise the model in order to describe the social–ecological dynamics more accurately and to make predictions that can be tested by quantitative data.

5.2. *How to reduce the conflict*

One way commonly adopted to reduce the conflict is to decrease the difference of social factors (i.e., the economic cost (c_i), the conformist tendency (ξ_i), and the social concern (κ_i)). However, as stated above, if the cross-conformist tendency is very small, equal cooperation levels are not always reached even when all the parameters are exactly the same between two groups (Figs. 2, 3, A1, A2, and A3).

An effective way to increase cooperation levels and to reduce conflict is to create a cross-group conformist tendency between groups (Figs. 6 and 7). According to Pretty (2003), four features are important for maintaining cooperation in environmental conservation: [1] trust, [2] reciprocity, [3] sanctions, and [4] connectedness in networks and groups. These features may correspond to increased conformity to cooperative people within a group as well as between groups in our model. Global and national environmental policies have often ignored community-based governance and traditional tools, such as informal communication and sanctions, but they can significantly affect the success of a policy (Dietz et al., 2003). Informal communication between groups enhances the cross-group conformist tendency, which increases cooperation levels. If groups conflict, increasing cross-group conformist tendency through informal communication, through inter-group projects or traditional festivals may reduce the conflict and solve the water pollution problem in the lake.

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Appendix A

Here we explain the effect of changing the economic cost c_i, the conformist tendency ξ_i, and the social concern κ_i on the sizes of E_1 and E_2. To estimate the sizes of E_1 and E_2 numerically, we counted the number of initial conditions under which the system converged to one of conflict equilibrium points. Fig. A1 illustrates how the sizes of E_1 and E_2 change with c_i. When $4.6 \le c_i \le 5.2$, all initial conditions satisfying $y(0)=1$ or $x_1(0)+x_2(0)=1$ except for $x_1(0)=x_2(0)$ belonged to the domain of attraction to conflict equilibria. In contrast, when $5.4 \le c_i \le 6.4$, all initial conditions satisfying $y(0)=1$ or $x_1(0)+x_2(0)=1$ belonged to the domain of attraction to

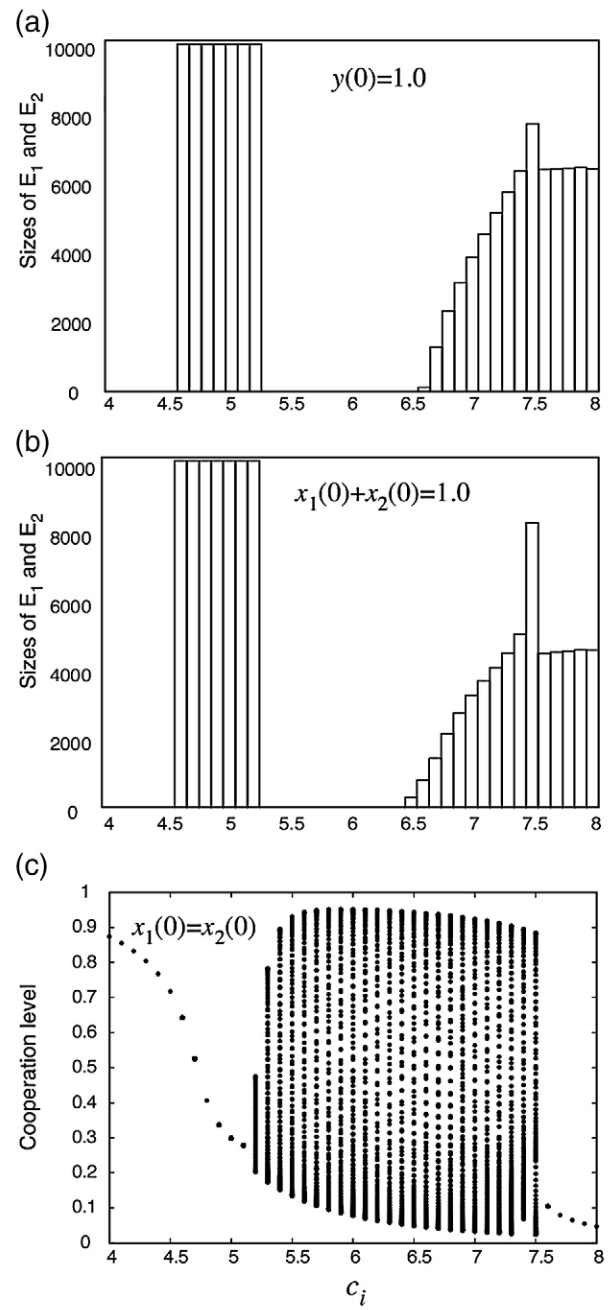

Fig. A1 – The effect of economic cost c_i on the area of domains of attraction to conflict equilibria (E_1 and E_2). (a) Sizes of E_1 and E_2 in the initial condition space in Fig. 3(a). (b) Sizes of E_1 and E_2 in the initial condition space in Fig. 3(b). (c) Cooperation levels starting from $x_1(0)=x_2(0)$ with different c_i. The parameter settings are the same as those in Fig. 2 except for c_i.

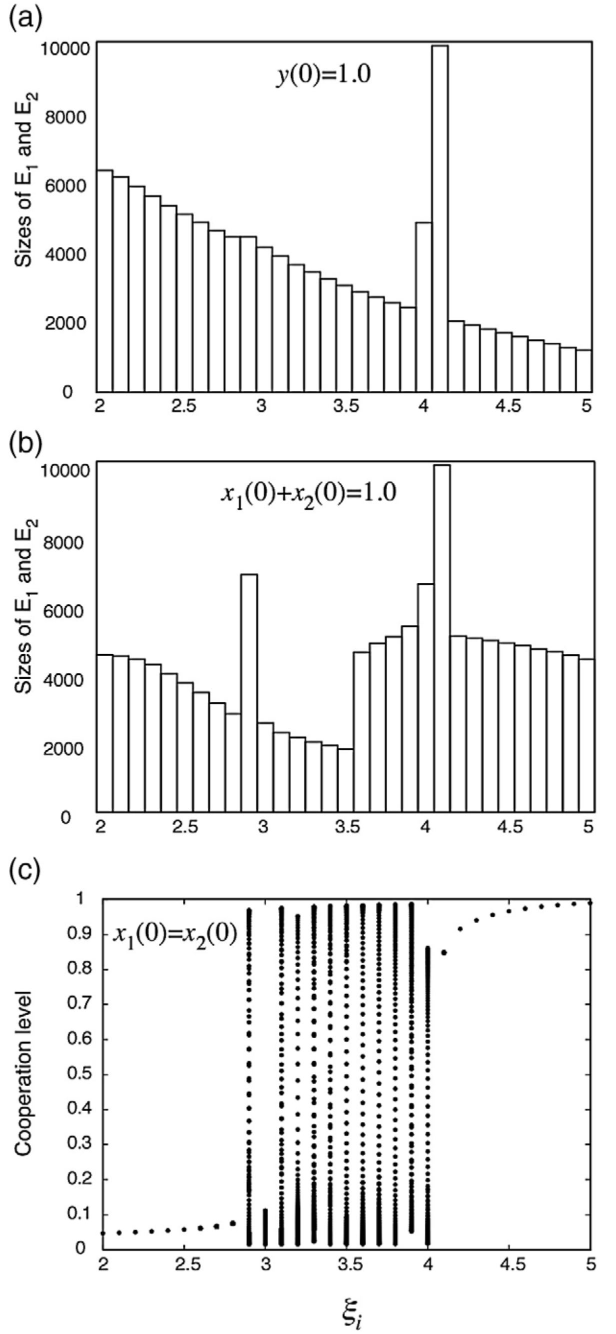

Fig. A2 – The effect of conformist tendency ξ_i on the area of domains of attraction to conflict equilibria (E_1 and E_2). (a) Sizes of E_1 and E_2 in the initial condition space in Fig. 3(a). (b) Sizes of E_1 and E_2 in the initial condition space in Fig. 3(b). (c) Cooperation levels starting from $x_1(0)=x_2(0)$ with different ξ_i. The parameter settings are the same as those in Fig. 2 except for $c_1=c_2=8$ and ξ_i.

synchronous oscillation. E_1 and E_2 emerged again in $c_i \geq 6.6$ in Fig. A1(a) and in $c_i \geq 6.5$ in Fig. A1(b). Those domains grew as c_i increased in the range of $6.5 \leq c_i \leq 7.5$.

In a similar manner as Fig. A1, we analyzed the effects of changing ξ_i and κ_i. When we changed ξ_i with the same parameter setting in Fig. A1 except for $c_i=8.0$, E_1 and E_2 tended to become smaller as ξ_i increased (Fig. A2). When κ_i increased, the domains of attraction to conflict equilibria became smaller in $1.0 \leq \kappa_i \leq 1.6$ (Fig. A3). When $1.7 \leq \kappa_i \leq 3.1$, all initial conditions satisfying $y(0)=1$ or $x_1(0)+x_2(0)=1$ belonged to the domain of attraction to synchronous oscillation. In the range of $3.9 \leq \kappa_i \leq 6.0$, all initial conditions except for $x_1(0)=x_2(0)$ belonged to E_1 and E_2 (Fig. A3(a) and (b)).

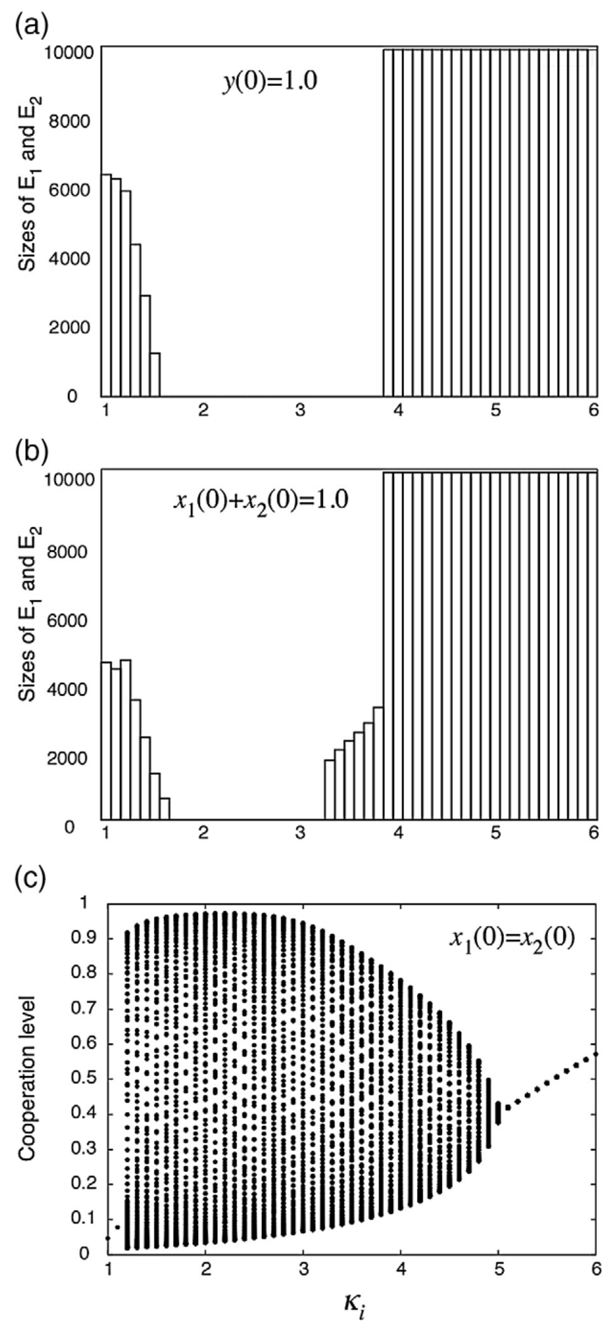

Fig. A3 – The effect of social concern κ_i on E_1 and E_2. (a) Sizes of E_1 and E_2 in the initial condition space in Fig. 3(a). (b) Sizes of E_1 and E_2 in the initial condition space in Fig. 3(b). (c) Cooperation levels starting from $x_1(0)=x_2(0)$. The parameter settings are the same as those in Fig. 2 except for $c_1=c_2=8$ and κ_i.

REFERENCES

Adams, W.M., Brockington, D., Dyson, J., Vira, B., 2003. Managing tragedies: understanding conflict over common pool resources. Science 302, 1915–1916.

Boyd, R., Richerson, P.J., 1996. Why culture is common, but cultural evolution is rare. Proceedings of the British Academy 88, 77–93.

Brekke, K.A., Kverndokk, S., Nyborg, K., 2003. An economic model of moral motivation. Journal of Public Economics 87, 1967–1983.

Brock, W.A., de Zeeuw, A., 2002. The repeated lake game. Economics Letters 76, 109–114.

Carpenter, S.R., Ludwig, D., Brock, W.A., 1999a. Management of eutrophication for lakes subject to potentially irreversible change. Ecological Applications 9, 751–771.

Carpenter, S.R., Brock, W.A., Hanson, P., 1999b. Ecological and social dynamics in simple models of ecosystem management. Conservation Ecology 3 [online] URL: http://www.consecol.org/vol3/iss2/art4/.

Dechert, W.D., O'Donnell, S.I., 2006. The stochastic lake game: a numerical solution. Journal of Economic Dynamics and Control 30, 1569–1587.

Dietz, T., Ostrom, E., Stern, P.C., 2003. The struggle to govern the commons. Science 302, 1907–1912.

Dresner, S., McGeevor, K., Tomei, J., 2007. Public understanding synthesis report: a report to the Department for Environment, Food and Rural Affairs. Policy Studies Institute, Defra, London.

Fehr, E., Gächter, S., 2000. Cooperation and punishment in public goods experiments. American Economic Review 90 (4), 980–994.

Fischbacher, U., Gächter, S., Fehr, E., 2001. Are people conditionally cooperative? Evidence from a public goods experiment. Economics Letters 71, 397–404.

Gunderson, L.H., Holling, C.S., 2001. Panarchy. Island Press, Washington, DC.

Hardin, G., 1968. The tragedy of the commons. Science 162, 1243–1248.

Henrich, J., Boyd, R., 1998. The evolution of conformist transmission and the emergence of between-group differences. Evolution of Human Behavior 19, 215–241.

Hofbauer, J., Sigmund, K., 2003. Evolutionary game dynamics. Bulletin of the American Mathematical Society 40, 479–519.

Iwasa, Y., Uchida, T., Yokomizo, H., 2007. Nonlinear behavior of the socio-economic dynamics for lake eutrophication control. Ecological Economics 63, 219–229.

McFadden, D., 1981. Econometric models of probabilistic choice. In: Manski, C., McFadden, D. (Eds.), Structural analysis of discrete data. MIT Press, Cambridge, pp. 198–272.

Mckelvey, R.D., Palfrey, T.R., 1995. Quantal response equilibria for normal form games. Games and Economic Behavior 10, 6–38.

Milinski, M., Semmann, D., Krambeck, H., Marotzke, J., 2006. Stabilizing the earth's climate is not a losing game: supporting evidence from public goods experiments. Proceedings of the National Academy of Sciences of the USA 103, 3994–3998.

Mitani, Y., Shoji, Y., Kuriyama, K., in press. Estimating economic values of vegetation restoration with choice experiments: a case study of endangered species in lake Kasumigaura, Japan. Landscape and Ecological Engineering.

Nyborg, K., Rege, M., 2003. On social norms: the evolution of considerate smoking behavior. Journal of Economic Behavior and Organization 52, 323–340.

Ostrom, E., 1990. Governing the commons. Cambridge University Press, Cambridge.

Pillutla, M.M., Chen, X.-P., 1999. Social norms and cooperation in social dilemmas: the effects of context and feedback. Organizational Behavior and Human Decision Processes 78, 81–103.

Pretty, J., 2003. Social capital and the collective management of resources. Science 302, 1912–1914.

Satake, A., Janssen, M., Levin, S.A., Iwasa, Y., 2007. Synchronized deforestation induced by social learning under uncertainty of forest-use value. Ecological Economics 63, 452–462.

Scheffer, M., 2004. Ecology of shallow lakes. Kluwer Academic Publishers, Dordrecht.

Scheffer, M., Carpenter, S.R., 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. Trends in Ecology and Evolution 18, 648–656.

Suzuki, Y. and Iwasa, Y., in press. The coupled dynamics of human socio-economic choice and lake water system: the interaction of two sources of nonlinearity. Ecological Research.