The effect of sanctions on the evolution of cooperation in linear division of labor

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Authors' contributions

MN conceived of the study, designed the study, coordinated the study, analyzed the mathematical model, carried out the numerical simulations, and drafted the manuscript; HS analyzed mathematical models, carried out the numerical simulations, and helped draft the manuscript; YK and OS participated in the design of the study, helped coordinate the study and helped draft the manuscript; All authors gave final approval for publication.

Abstract

The evolution of cooperation is an unsolved research topic and has been investigated from the viewpoint of not only biology and other natural sciences but also social sciences. Much extant research has focused on the evolution of cooperation among peers. While, different players belonging to different organizations play different social roles, and players playing different social roles cooperate together to achieve their goals.

We focus on the evolution of cooperation in linear division of labor that is defined as follows: a player in the i-th role interacts with a player in the i+1-th role, and a player in the n-th role achieves their goal ($1 \leq i < n$) if there are n roles in the division of labor. We take the industrial waste treatment process as an example for illustration. We consider three organizational roles and B_i is the i-th role. The player of B_i can choose two strategies: legal treatment or illegal dumping, which can be interpreted as cooperation or defection (i = 1−3). With legally required treatment, the player of B_j pays a cost to ask the player of B_{j+1} to treat the waste (j = 1, 2). Then, the cooperator of B_{j+1} pays a cost to treat the waste properly. With illegal dumping, the player of B_i dumps the waste and does not pay any cost (i = 1−3). However, the waste dumped by the defector has negative environmental consequences, which all players in all roles suffer from. This situation is equivalent to a social dilemma encountered in common-pool resource management contexts.

The administrative organ in Japan introduces two sanction systems to address the illegal dumping problem: the actor responsibility system and the producer responsibility system. In the actor responsibility system, if players in any role who choose defection are monitored and discovered, they are penalized via a fine. However, it is difficult to monitor and detect the violators, and this system does not work well. While, in the producer responsibility system, the player in B_1 is fined if the player cannot hand the manifest to the local administrative organ because the players of B_i (i = 1−3) who choose defection do not hand the manifest to the player of B_1.

We analyze this situation using the replicator equation. We reveal that (1) the three-role model has more empirical credibility than the two-role model including B_1 and B_3, and (2) the producer responsibility system promotes the evolution of cooperation more than the system without sanctioning. (3) the actor responsibility system does not promote the evolution of cooperation if monitoring and detecting defectors is unsuccessful.

Keywords: illegal dumping, social dilemma, common-pool resource management, monitoring, replicator equation for asymmetric games

Introduction

Our society is based on cooperation. The evolution of cooperation remains a challenging problem from the viewpoint of not only evolutionary theory but also the social sciences: the evolution of cooperation is not an easy problem to solve. We consider the prisoner's dilemma (PD) game. Two players play the prisoner's dilemma game and there are two types of players: cooperators and defectors. If both cooperators play the PD game, they obtain the payoff, R. If a cooperator plays the PD game with a defector, the cooperator obtains S and the defector obtains T. If both are defectors, they obtain the payoff, P. It is often assumed that the cooperator gives a benefit, b, to the opponent, incurring a cooperation cost, $-c$ (b, $c > 0$), but the defector does not give anything. Therefore, $T = b$, $R = b-c$, $P = 0$ and $S = -c$. As one of the definitions satisfying the PD game is $T > R > P > S$, defectors obtains a greater payoff than cooperators regardless of the opponent's type. As a result, players choose to be defectors and thus cooperation is unachievable. Therefore, previous studies on evolutionary game theory have investigated conditions whereby cooperation can evolve. “Evolution” here has two meanings: one is biological evolution in which genetic changes occur, and the other is social learning in which players change their behavior according to their own and their opponents' payoffs. Studies from social science perspectives often use evolutionary game theory as social learning (Sigmund et al., 2010).

Five conditions for the evolution of cooperation can be posited (Nowak, 2006): kin selection (Hamilton, 1964), group selection (Sober and Wilson, 1999), direct reciprocity (Axelrod and Hamilton, 1981), indirect reciprocity (Sugden, 1986; Nowak and Sigmund, 1998), and network reciprocity (Nowak and May, 1992; Nakamaru et al., 1997; Nakamaru et al., 1998). Besides these five categories, the effect of punishment on the evolution of cooperation has also been studied (Axelrod, 1986; Sigmund et al., 2001; Boyd et al., 2003; Nakamaru and Iwasa, 2005; Nakamaru and Iwasa, 2006; Rand et al., 2010; Sigmund et al., 2010; Shimao and Nakamaru, 2013; Chen et al., 2014; Chen et al., 2015b; Sasaki et al., 2015). Many previous studies assume players are peers. In actual, empirical contexts we cooperate not only with peers, but also among players with different social roles, between a leader and a subordinate, within groups under hierarchy, or among groups which exhibit hierarchical relationships (Henrich and Boyd, 2008; Powers and Lehmann, 2014; Roithmayr et al., 2015). In this paper, we focus on cooperation in the division of labor.

Various animals, such as social insects and naked mole rats, developed division of labor and different individuals have different roles. In social insects, each individual plays various roles such as attending the mother queen, grooming larvae, guarding the nest entrance, and foraging, and which role s/he plays depends on his/her aging; an individual attends mother queen when s/he is younger than 10 days old, rolls and carries mature larvae at the age of 10 days, then defends nest when s/he is older than 14 days old, which is termed temporal division of labor (Hölldobler and Wilson, 1990). We consider the basic structure of the division of labor in animals, where individuals belonging to a specific role (A_1, … or A_n) can work independently and cooperate together for the purposes of goal attainment (Figure 1A). If some of them are not cooperators, all cannot achieve the goal. We humans have also developed division of labor (Kuhn and Stiner, 2006; Henrich and Boyd, 2008; Nakahashi and Feldman, 2014). Humans differ from other animals in terms of their approach to the division of labor because they can innovate and create new styles of division of labor suitable for group, institutional or societal goals. Powers et al. (2016) noted that natural selection has shaped our cognitive ability in terms of language usage, a theory of mind, shared intentionality; these abilities then facilitate the development of institutions (Powers et al., 2016). The same logic can be applied to human division of labor since some institutions are equipped with the division of labor to run or manage institutions efficiently. We can consider that not the division of labor but the cognitive ability to innovate new styles of the division of labor is involved with natural selection. Cognitive anthropologists have discussed that episodic memory, one of high cognitive ability typically evolved and developed in humans, but not in Neanderthals, is required to innovate age and gender divisions thereof. It is because episodic memory not only stores and retrieves past events but also makes future planning or simulating future scenarios possible; to innovate or maintain the division of labor requires such ability (Coolidge and Wynn, 2008). Cognitive sciences, some branches of anthropology, and natural selection fall under the domain of biology, and therefore, the division of labor in human society can be studied from the perspective of biology.

There are various types of division of labor existing in our society and we focus on one such type, illustrated in Figure 1B, the linear division of labor. Well-known examples thereof include the car assembling process and the manufacturing process of some traditional crafts such as kimonos and Buddhist alters in Japan (Ohnuma, personal communication). In Figure 1B, a player in role B_1 cooperates to achieve the goal and works towards that goal accordingly. After s/he completes his/her work, s/he brings the product to a player in role B_2. Then, the player in B_2 completes further goal-oriented work. After s/he finishes it, s/he brings it to a player in role B_3. Role B_j is dependent on role B_i ($n \geq j > i$). This process is repeated and then a player in role B_n produces the final product. The final product is a goal of the division of labor and the quality influences all players in all roles. For example, if the quality is good, the price is expensive and the group members obtain a good reputation. However, if players are not cooperative and the final product is bad, they cannot accrue the desirable benefits. However, cooperation is costly; if a player in B_i is not a cooperator, a player in B_j is a cooperator and these two roles are similar, the player in B_j can compensate for the imperfection of the player in B_i ($j > i$), and the final product may be good. As a result, the player in B_i does not need to pay a cost for doing a good job and get a high benefit from the good final product. While, if a cooperative player in B_j cannot compensate for the imperfection of a player in B_i because of the high specialty in each role, the final product may not be good. As a result, no players accrue desirable benefits from the final product.

If a player in B_i knows the reputation of players in B_{i+1}, a player in B_i can choose a cooperator in B_{i+1}. Then, players in both B_i and B_{i+1} would accrue desirable benefits. However, if a player in B_j ($j > i+1$) does not choose a cooperator in B_{j+1}, the quality of the final product becomes low and then all players in all roles do not accrue desirable benefits even though the player in B_i chose a cooperator in B_{i+1}.

What kinds of system promote the evolution of cooperation in linear division of labor? We focus on the effect of sanctions and monitoring. Previous empirical and theoretical studies have shown that monitoring and/or sanctions inhibit the violators who break institutional rules in common-pool resource management contexts, such as with forest logging, in order to run the institution efficiently (Ostrom, 1990; Rustagi et al., 2010; Chen et al., 2015a; Lee et al., 2015). After successful monitoring detects violators, sanctions can be imposed on them. Monitoring is effective in small villages where people have knowledge of the behavior of others, through direct observation and gossip. However, detecting violators is sometimes hard work and it is very costly in larger societies because it is almost impossible to have knowledge of the behavior of all members in society. Then, sanctions cannot be imposed on the violators. Consequently, both monitoring and sanctions are not meaningful anymore. For example, detecting illegal logging far from human habitation deep in the mountains to which there are neither roads nor transportation to access is almost impossible and monitoring does not work. How do we deal with this situation?

In this paper, we take the industrial waste treatment process in Japan as an example of the linear type of division of labor, and then investigate the effect of sanctions and monitoring on the evolution of cooperation, using the industrial waste illegal dumping game which Ohnuma and Kitakaji proposed based on their field survey and government publications (Ohnuma and Kitakaji, 2007; Kitakaji and Ohnuma, 2014; Kitakaji and Ohnuma, 2016). In what follows, the industrial waste treatment process in Japan based on their experimental works (Ohnuma and Kitakaji, 2007; Kitakaji and Ohnuma, 2014; Kitakaji and Ohnuma, 2016) is explained. The industrial waste treatment process consists of five roles: generators (B_1), the 1st waste haulers (B_2), the intermediate treatment facilities (B_3), the 2nd waste haulers (B_4) and the landfill sites (B_5). The generators produce industrial waste as a secondary product, and commit the waste to the 1st waste haulers. When the 1st waste haulers can commit the waste to the intermediate treatment facilities, the 1st waste haulers bring it to the intermediate treatment facilities. The intermediate treatment facilities crush the waste, treat it chemically, or incinerate it. Then, the intermediate treatment facilities decide to commit it to the 2nd waste hauler. When the 2nd waste haulers can commit it to the landfill sites, they bring it to the landfill sites. The landfill sites dispose of it in sanitary land-fills. In the industrial waste treatment process, cooperation means that a player in B_i commits the waste to a player in B_{i+1}, paying a commission cost, or a player in B_3 also treats waste paying a treatment cost. If all players in all roles cooperate, the volume of waste is reduced and its risk, such as its toxicity, is removed and then the waste is landfilled safely and does not deleteriously impact the natural environment. Therefore, the final product is the safely landfilled waste in the industrial waste treatment process. Defection means that a player in B_i

does not commit the waste to a player in B_{i+1} but illegally dumps the waste far from human habitation deep in the mountains which is hard to access ($1 \leq i \leq 4$). Defectors do not need to pay a commission cost or a treatment cost. Once defection occurs, illegal dumped waste damages the natural environment. Hence, the final product in this case is the environmental damage and all players suffer from the damage. Actually, if the local administrative organ detects the damage caused by the illegal dumped waste but cannot know which player dumped the waste, the organ forces all players in all roles to pay for restoration. Players in all roles reserve a fund in advance to pay for future restoration.

This situation in the industrial waste treatment process is interpreted as a social dilemma (Ohnuma and Kitakaji, 2007; Kitakaji and Ohnuma, 2014; Kitakaji and Ohnuma, 2016). We explain the reason as follows. If all players in all roles are cooperators, they pay a cost, such as a commission cost and a treatment cost, but do not need to pay for restoration. While, a player in B_1 chooses defection, the player does not need to pay a commission cost. Not only the defector in B_1 but also other players in B_j ($j > 1$) have to pay for restoration. If players in B_1 and B_2 are cooperators and a player in B_3 is a defector, players in B_1 and B_2 have to pay a commission cost as well as for restoration. Players in B_4 and B_5 also have to pay for restoration even though they are cooperators. If the restoration cost is expensive, the payoff when all players choose cooperation can be higher than the payoff when a player in B_1 chooses defection. However, if a player changes behavior from cooperation to defection in B_i ($1 \leq i \leq 5$), the defector gets a higher payoff than the cooperator because the defector does not need to pay for a cost such as a commission cost or a treatment cost.

To inhibit illegal dumping, two sanction systems are put into effect in Japan (Ohnuma and Kitakaji, 2007; Kitakaji and Ohnuma, 2014; Kitakaji and Ohnuma, 2016). In this paper, we term these two systems the actor responsibility system and the producer responsibility system. In the actor responsibility system, the local administrative organ challenges to detect the illegal dumping. As many firms illegally dump the industrial waste deep in the mountains or in rivers far from habitation, the organ hardly detects the waste. When the organ luckily detects the waste, s/he has to detect who illegally dumped it. To detect who dumped it is very hard work. If the organ detects who dumped it, the firm is fined; the maximum fine in Japan is one hundred million yen, which is equivalent to one million US dollars. Previous theoretical studies concerning the evolution of pool-punishment also make the same assumption: pool-punishers detect the violators and punish them, and pool-punishers do not fail to detect these violators (Sigmund et al., 2010).

However, as the local administrative organ had difficulty in monitoring and detecting the illegal dumping, a new system was introduced in 1990, which we call the producer responsibility system herein. In this system, a manifest is important. The local administrative organ prepares the manifest, which all players in all roles have to fill in when committing waste. Then, after the generator fills the manifest, it is handed to the 1st waste hauler. After the 1st waste hauler fills in the manifest, it is handed to the intermediate treatment facility. Then, after the intermediate treatment facility hands it to the 2nd waste hauler, the 2nd waste hauler fills in it and hands it to the landfill site. Next, the landfill site fills in it and hands it back to the 2nd waste hauler, which also hands it back to the intermediate treatment facility. This process continues and finally the generator hands it to the local administrative organ. If the generator fails to hand it back to the local administrative organ, the local administrative organ punishes the generator and the generator has to pay a fine, even though another player in another role does not fill in it and hand it back.

Data from the Ministry of the Environment in Japan shows that the total number of illegal dumping activities detected annually increased directly after introducing the manifest system; the number has subsequently decreased since 2000 (see http://www.env.go.jp/press/103219.html). Does the data show that the new system inhibits the number of illegal dumping activities? Or, does the data only show that monitoring fails to detect illegal dumping because illegal dumping is more secret than before? Consecutive experimental works by Ohnuma and Kitakaji tackled this question (Ohnuma and Kitakaji, 2007; Kitakaji and Ohnuma, 2014; Kitakaji and Ohnuma, 2016). They showed that either monitoring or sanctions in the actor responsibility system did not prevent illegal dumping under the producer responsibility system (Kitakaji and Ohnuma, 2014). In this paper, using the replicator equation in evolutionary game theory, we investigate the effect of either of two sanction systems on the evolution of cooperation in the industrial waste process in Japan as an example of linear division of labor. Generally, firms pursue profits and change tactics or strategy based on profit considerations. They may imitate the strategy of others to accrue more profits. Therefore, the replicator dynamics, which can be interpreted as a social learning model, is a useful tool to describe the behavior of firms.

Model Assumptions

It is a complex task to construct a mathematical model assuming five roles in linear division of labor. We consider three cases. (i) There are only generators which can treat the industrial waste after producing the product. We call this model the no-role model. See Appendix A for model assumptions and results. (ii) There are generators and landfill sites; this is the two-role model. Appendix B contains assumptions and results for this model. (iii) There are generators, intermediate treatment facilities, and landfill sites; this is the three-role model.

In the following, we delineate the assumptions of three systems in the three-role model: the baseline system, the actor responsibility system, and the producer responsibility system. The reason that we consider the baseline system, which has no sanctions, is to facilitate examination and comparison of the effects of two sanction types on the evolution of cooperation in linear division of labor.

Baseline system in the three-role model

We consider that there are three roles: the generator group, the intermediate treatment facility (ITF) group, and landfill site (LS) group. The player is the firm. A player in the generator group, called a generator, plays a generator's role. One in the ITF group, called an ITF, plays an ITF's role. One in the LS group, called an LS, plays an LS's role. Each group has an infinite number of players.

The generator is either a cooperator or a defector. The cooperator commits industrial waste to the ITF, and the defectors dump the waste illegally. The generator's benefit from production is b. If the generator is a cooperator, the commission cost is $-x_1$ ($b > x_1 > 0$). Hereafter, the cooperators and defectors in the generator group are termed g-cooperators and g-defectors, respectively.

The ITF obtains the commission cost of the g-cooperator, x_1, as his/her benefit. Then, the ITF has to choose either cooperation or defection in each of two stages. S/he can choose either cooperation or defection in the first stage. Cooperation in the first stage (cooperation-1) indicates that s/he treats the industrial wastes brought from the generator by paying an intermediate treatment cost, c_{mid}. The example of cooperation-1 is breaking waste into pieces, treating it chemically, and rendering it harmless. Defection in the first stage (defection-1) means that the ITF does not treat the waste. After the ITF makes the decision in the first stage, s/he chooses either cooperation or defection in the second stage. Cooperation in the second stage (cooperation-2) means committing the industrial waste to a landfill site, and defection in the second stage (defection-2) means illegal dumping. Let the C-C player, the C-D player, the D-C player and the D-D player be defined as the ITF choosing cooperation-1 and cooperation-2, one choosing cooperation 1 and defection 2, one choosing defection-1 and cooperation-2, and one choosing defection-1 and defection-2, respectively The C-C player pays the commission cost, $-x_2$. The commission cost of the D-C player is $-x_2'$. We assume $x_2' \geq x_2$, because the D-C player does not treat industrial waste at all, and the LS pays a greater cost for treating the waste than the waste from the C-C player. The C-D or D-D player does not pay any commission cost.

The LS can harness the commission cost of ITF (x_2 or x_2') as his/her profit. The LS can be either a cooperator or a defector. Defectors dump the waste illegally and do not pay any cost for treatment. The cooperator buries the waste in the landfill that the LS possesses, paying a treatment cost (c_t or c_t'; $x_1 > c_t$, c_t'). If the ITF has treated the waste, the treatment cost is c_t. If not, the treatment cost is c_t'. The cooperator incurs a greater cost in burying non-treated waste than treated waste because non-treated waste is larger or more dangerous than treated waste. Therefore we assume that $c_t' \geq c_t > 0$. Hereafter, cooperators and defectors in the LS group are termed ls-cooperators and ls-defectors, respectively.

The g-defectors, a C-D and D-D players or ls-defectors illegally dump industrial waste in places such as rivers, seas, mountains, forests, and they do damage to the environment in the form of water pollution, soil pollution, and other types of pollution. Consequently, the population size of animals and plants will decrease in the future. As a result, all players equally suffer from the damage. To prevent future environmental damage, the local administrative organ mandates all players to pay an environmental restoration fee. Illegal dumping by a g-defector damages the natural environment and g_0 is defined as the amount of industrial waste dumped by a g-defector. Illegal dumping by a C-D player damages the natural environment and g_1 is defined as the amount of industrial waste dumped by a C-D player. The amount of industrial wastes dumped by a D-D player is g_0 because the D-D player has not treated the industrial waste from the g-cooperator. We assume that $g_0 \geq g_1$, because treatment by the ITF can reduce the amount of waste. If the industrial waste has not been treated at all, the amount of waste dumped by an ls-defector is still g_0. If the industrial waste has been treated, the amount of waste dumped by an ls-defector is g_1. Let r be defined as the environmental restoration fee or damage per unit of waste. Therefore, rg_i is the restoration fee (i = 0 or 1) to restore the damaged environment. We consider that the local administrative organ determines that the generator group is forced to pay a fee s times as high as the ITF and the LS group ($s \geq 1$). If a player dumps industrial waste illegally, srg_i is imposed on a generator and rg_i is imposed on an ITF or a LS. As illegal dumping damages all players' utility or health, the problem of illegal dumping can be interpreted as a social dilemma problem. The parameters in the system are listed in Table 1.

The payoff matrix of generators when the LS is an ls-cooperator is:

$$A_1 = \begin{pmatrix} b - x_1 & b - x_1 - srg_1 & b - x_1 & b - x_1 - srg_0 \\ b - srg_0 & b - srg_0 & b - srg_0 & b - srg_0 \end{pmatrix} ,$$

in which the element a_{1j} in A_1 is the payoff of g-cooperators committing the industrial waste to the ITF whose type is j (j = 1−4). The ITF's strategy 1, 2, 3, and 4 correspond to a C-C player, a C-D player, a D-C player, and a D-D player, respectively. The element a_{2j} is the payoff of g-defectors (j = 1−4). The payoff matrix of generators when the LS is an ls-defector is:

$$A_2 = \begin{pmatrix} b - x_1 - srg_1 & b - x_1 - srg_1 & b - x_1 - srg_0 & b - x_1 - srg_0 \\ b - srg_0 & b - srg_0 & b - srg_0 & b - srg_0 \end{pmatrix} ,$$

in which the element a_{1j} in A_2 is the payoff of cooperators of the generator committing the industrial waste to the ITF whose type is j (j = 1−4). The element a_{2j} in A_2 is the payoff of defectors in the generator (j = 1−4).

The payoff matrix of the ITF interacting with the ls-cooperator is C_1, and that of the ITF interacting with the ls-defector is C_2. They present:

$$C_1 = \begin{pmatrix} x_1 - c_{mid} - x_2 & -rg_0 \\ x_1 - c_{mid} - rg_1 & -rg_0 \\ x_1 - x_2' & -rg_0 \\ x_1 - rg_0 & -rg_0 \end{pmatrix}, \qquad C_2 = \begin{pmatrix} x_1 - c_{mid} - x_2 - rg_1 & -rg_0 \\ x_1 - c_{mid} - rg_1 & -rg_0 \\ x_1 - x_2' - rg_0 & -rg_0 \\ x_1 - rg_0 & -rg_0 \end{pmatrix},$$

in which the (i, 1) element in C_1 and C_2 is the payoff of ITF's strategy i interacting with a g-cooperator and the (i, 2) element in C_1 and C_2 is the payoff of ITF's strategy i interacting with a g-defector.

The payoff matrices of landfill sites when the generator chooses cooperation (committing the waste to ITF) and defection (illegal dumping) are B_1 and B_2, respectively, which presents;

$$B_1 = \begin{pmatrix} x_2 - c_t & -rg_1 & x_2' - c_t' & -rg_0 \\ x_2 - rg_1 & -rg_1 & x_2' - rg_0 & -rg_0 \end{pmatrix}, \qquad B_2 = \begin{pmatrix} -rg_0 & -rg_0 & -rg_0 & -rg_0 \\ -rg_0 & -rg_0 & -rg_0 & -rg_0 \end{pmatrix},$$

in which the (1, j) element in B_1 and B_2 is the payoff of the ls-cooperator interacting with ITF's strategy j and the (2, j) element in B_1 and B_2 is the payoff of the ls-defector interacting with ITF's strategy j.

Here we assume that each group size is infinite. One generator is chosen randomly from the generator group and interacts with one ITF chosen randomly from the ITF group, following the model assumptions. Then, the ITF interacts with one LS chosen randomly from the LS group, following the model assumptions. We assume an absence of intra-group interaction. Therefore we can apply the replicator equation of an asymmetric game to our model, and the time-differential equations can be described as:

$$\frac{du_1}{dt} = v_1 u_1 \left[\left(A_1 \vec{z} \right)_1 - \vec{u} A_1 \vec{z} \right] + \left(1 - v_1 \right) u_1 \left[\left(A_2 \vec{z} \right)_1 - \vec{u} A_2 \vec{z} \right] \quad , \text{(1a)}$$

$$\frac{dz_i}{dt} = v_1 z_i \left[\left(C_1 \vec{u} \right)_i - \vec{z} C_1 \vec{u} \right] + \left(1 - v_1 \right) z_i \left[\left(C_2 \vec{u} \right)_i - \vec{z} C_2 \vec{u} \right] \quad (i = 1-3) \quad , \text{(1b)}$$

$$\frac{dv_1}{dt} = u_1 v_1 \left[\left(B_1 \vec{z} \right)_1 - \vec{v} B_1 \vec{z} \right] + \left(1 - u_1 \right) v_1 \left[\left(B_2 \vec{z} \right)_1 - \vec{v} B_2 \vec{z} \right] \quad , \text{(1c)}$$

in which let u_1 be the frequencies of the g-cooperators in the generator group; u_2, the frequencies of the g-defectors ($u_1 + u_2 = 1$; $u_1, u_2 \geq 0$). Let z_i be the frequency of players with the ITF's strategy i ($i = 1-4$; $z_1 + z_2 + z_3 + z_4 = 1$; $z_1, z_2, z_3, z_4 \geq 0$). Let v_1 be the frequencies of the ls-cooperators in the landfill site group; v_2, the frequencies of the ls-defectors in the landfill site group ($v_1 + v_2 = 1$; $v_1, v_2 \geq 0$). We assume that $\vec{u} = (u_1 \quad u_2)^t$, $\vec{z} = (z_1 \quad z_2 \quad z_3 \quad z_4)^t$, and $\vec{v} = (v_1 \quad v_2)^t$.

Actor responsibility system in the three-role model

If the local administrative organ successfully monitors and detects the illegal dumping and the illegal dumper, the local administrative organ punishes the dumper and then forces the dumper to pay a fine, f. Let d be the probability of being monitored and detected by the local administrative organ. We call this sanction the actor responsibility system. The parameters in the system are listed in Table 1.

The local administrative organ has difficulty in monitoring perfectly and detecting the illegal dumping and the illegal dumper because the illegal dumper dumps the waste in inconspicuous places such as deep in the mountains, destroying evidence. As a result, perfect-monitoring is very costly and *d* is very low. While, the fine *f* is very expensive. For example, *f* can be one hundred million yen which is roughly equivalent to one million US dollar.

The expected value of the fine which the dumper has to pay for, *df*, is added to the baseline system, and then the payoff matrices in eq. (1) are replaced by:

$$A_1 = \begin{pmatrix} b-x_1 & b-x_1-srg_1 & b-x_1 & b-x_1-srg_0 \\ b-srg_0-df & b-srg_0-df & b-srg_0-df & b-srg_0-df \end{pmatrix} ,$$

$$A_2 = \begin{pmatrix} b-x_1-srg_1 & b-x_1-srg_1 & b-x_1-srg_0 & b-x_1-srg_0 \\ b-srg_0-df & b-srg_0-df & b-srg_0-df & b-srg_0-df \end{pmatrix} ,$$

$$C_1 = \begin{pmatrix} x_1-c_{mid}-x_2 & -rg_0 \\ x_1-c_{mid}-rg_1-df & -rg_0 \\ x_1-x_2' & -rg_0 \\ x_1-rg_0-df & -rg_0 \end{pmatrix}, \quad C_2 = \begin{pmatrix} x_1-c_{mid}-x_2-rg_1 & -rg_0 \\ x_1-c_{mid}-rg_1-df & -rg_0 \\ x_1-x_2'-rg_0 & -rg_0 \\ x_1-rg_0-df & -rg_0 \end{pmatrix} ,$$

$$B_1 = \begin{pmatrix} x_2-c_t & -rg_1 & x_2'-c_t' & -rg_0 \\ x_2-rg_1-df & -rg_1 & x_2'-rg_0-df & -rg_0 \end{pmatrix} , \text{ and}$$

$$B_2 = \begin{pmatrix} -rg_0 & -rg_0 & -rg_0 & -rg_0 \\ -rg_0 & -rg_0 & -rg_0 & -rg_0 \end{pmatrix} .$$

Producer responsibility system in the three-role model

Herein, the local administrative organ prepares the manifest, which all industries have to fill in. Then after the producer or the generator fill the manifest, it is handed to the ITF. After the ITF fills the manifest, it is hand to the LS. Then, the LS hands it back to the ITF, which also hands it back to the generator. Next, the generator hands it to the local administrative organ. If the generator fails to hand it back to the local administrative organ, the local administrative organ punishes the generator and s/he has to pay for a fine, f_1.

Following are the reasons why the generator cannot hand the manifest back to the local administrative organ. (i) The generator is a g-defector, and then s/he cannot hand the manifest to the ITF because there is no transaction between him/her and the ITF. Let p_2 be the probability that the g-defector does not hand the manifest to the local administrative organ. The probability, $1-p_2$, means that the g-defector hands the fictitious manifest to the local administrative organ. (ii) The ITF is a C-D or D-D player and the generator does not receive the manifest from the ITF. Let p_3 be the probability that the C-D or D-D player does not hand the manifest back to the generator. The probability, $1-p_3$, means that the C-D or D-D player hands the fictitious manifest to the generator. (iii) The LS is an ls-defector and does not hand the manifest back to the ITF. As a result, the generator does not receive the manifest. Let p_4 be the probability that the ls-defector does not hand the manifest back to the ITF. The probability, $1-p_4$, means that the ls-defector hands the fictitious manifest to the ITF. For simplicity, we assume that the local administrative organ does not distinguish the honest manifest from the fictitious one.

We also consider that the g-cooperator always hands the manifest back to the local administrative organ, and that the cooperator in the ITF or LS group accidentally fails to hand the manifest. (i) Let q_3 ($1-q_3$) be the probability that the C-C or D-C player does not (does) hand the manifest back to the generator. (ii) Let q_4 ($1-q_4$) be the probability that the ls-cooperator does not (does) hand the manifest back to the ITF.

We can calculate the probabilities that the g-cooperator does not hand the manifest back to the local administrative organ. (i) $q_4 + (1- q_4)q_3$ is the probability that the g-cooperator does not receive the manifest when there is a transaction with a C-C or D-C player and the ls-cooperator. (ii) $p_4 + (1- p_4)q_3$ is the probability that the g-cooperator does not receive the manifest when there is a transaction with a C-C or D-C player and the ls-defector. (iii) p_3 is the probability that the g-cooperator does not receive the manifest from the C-D or D-D player when there is a transaction between them. If (i)−(iii) occur, the local administrative organ punishes the g-cooperator, who has to pay a fine, f_1. The parameters in the system are listed in Table 1.

The expected value of the fine which the generator has to pay is added to the baseline system, and then the payoff matrices in eq. (1) are replaced by:

$$A_1 = \begin{pmatrix} b - x_1 - F_1 & b - x_1 - srg_1 - f_1 p_3 & b - x_1 - F_1 & b - x_1 - srg_0 - f_1 p_3 \\ b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 \end{pmatrix},$$

in which $F_1 = f_1(q_4 + (1 - q_4)q_3)$,

$$A_2 = \begin{pmatrix} b - x_1 - srg_1 - F_2 & b - x_1 - srg_1 - f_1 p_3 & b - x_1 - srg_0 - F_2 & b - x_1 - srg_0 - f_1 p_3 \\ b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 \end{pmatrix},$$

in which $F_2 = f_1(p_4 + (1 - p_4)q_3)$,

$$C_1 = \begin{pmatrix} x_1 - c_{mid} - x_2 & -rg_0 \\ x_1 - c_{mid} - rg_1 & -rg_0 \\ x_1 - x_2' & -rg_0 \\ x_1 - rg_0 & -rg_0 \end{pmatrix}, \qquad C_2 = \begin{pmatrix} x_1 - c_{mid} - x_2 - rg_1 & -rg_0 \\ x_1 - c_{mid} - rg_1 & -rg_0 \\ x_1 - x_2' - rg_0 & -rg_0 \\ x_1 - rg_0 & -rg_0 \end{pmatrix},$$

$$B_1 = \begin{pmatrix} x_2 - c_t & -rg_1 & x_2' - c_t' & -rg_0 \\ x_2 - rg_1 & -rg_1 & x_2' - rg_0 & -rg_0 \end{pmatrix}, \text{ and}$$

$$B_2 = \begin{pmatrix} -rg_0 & -rg_0 & -rg_0 & -rg_0 \\ -rg_0 & -rg_0 & -rg_0 & -rg_0 \end{pmatrix}.$$

Next we calculate the equilibrium points in three systems and conduct the local stability analysis. We also did Monte Carlo simulations and then we obtain almost the same results to our following analysis of the replicator dynamics.

Results

We analyze eqs. (1) and obtain the equilibrium points in three systems, which are categorized into seven types:

$$(u_1, z_1, z_2, z_3, v) = (1, 1, 0, 0, 1), (1, 0, 0, 1, 1), (0, *, *, *, *), (1, 0, 1, 0, *),$$

$$(1, 0, 0, 0, *), (1, 0, 0, 1, 0), (1, 1, 0, 0, 0),$$

in which the asterisk "*" means any value between 0 and 1. We also obtain one unstable inner equilibrium point in each system (see Appendix C). These seven equilibrium points indicate that all members adopt the same strategy in each industry in equilibrium, and then (u_1, z_1, z_2, z_3, v) can be represented by (G, ITF, LS) which is the strategy of the G, the ITF and the LS, respectively. For example, (1, 1, 0, 0, 1) is equivalent to (C, C-C, C), in which the first column denotes the generator is a g-cooperator, the second that the ITF is a C-C player, and the third that the LS is an ls-cooperator. Table 2 shows the seven equilibrium points and the corresponding strategies. Out of seven equilibrium points, two points, (1, 1, 0, 0, 1) and (1, 0, 0, 1, 1) are interpreted as cooperation evolving in the division of labor (see Table 2). (0, *, *,

*, *) is interpreted as illegal dumping by G; two points, (1, 0, 1, 0, *) and (1, 0, 0, 0, *), illegal dumping by ITF; two points, (1, 0, 0, 1, 0), (1, 1, 0, 0, 0), illegal dumping by LS.

We conducted the local stability analysis of the seven points. Appendix C shows the condition of the local stability of each point. In (1, 1, 0, 0, 1) = (C, C-C, C) and (1, 0, 0, 1, 1) = (C, D-C, C), the actor responsibility system promotes the local stability if *df* is large enough to influence the dynamics (see Tables C1 and C2). Table C1 and C2 also show that, if (1, 1, 0, 0, 1) = (C, C-C, C) is locally stable, (1, 0, 0, 1, 1) = (C, D-C, C) is not locally stable, and vice versa. It is natural to assume that p_2 is high, q_3 is low, and q_4 is low, and then $q_3 - p_2 + q_4(1 - q_3)$ can be negative. This indicates that the producer responsibility system also favors the evolution of cooperation in the division of labor more than the baseline system (see Tables C1 and C2). In (0, *, *, *, *) = (D, *, *), both sanction systems discourage the stability and then both disfavor illegal dumping by the generator more than the baseline system. In (1, 0, 1, 0, *) = (C, C-D, *), the effect of the sanction systems on the stability of illegal dumping by ITF depends on the parameter values (see Table C4). As $x_1 < 0$ does not hold due to our assumption that $x_1 > 0$ (see Table C5), the equilibrium point, (1, 0, 0, 0, *) = (C, D-D, *), is always unstable in the baseline system. While, both sanction systems promote the stability of this equilibrium point (see Table C5). Therefore both sanction systems promote illegal dumping by ITF. In (1, 0, 0, 1, 0) = (C, D-C, D) and (1, 1, 0, 0, 0) = (C, C-C, D), as three inequalities, $x_1 < 0$, $x_2 < 0$ and $x_2' < 0$, do not hold because of our assumption that $x_1 > 0$, $x_2 > 0$ and $x_2' > 0$, this equilibrium point is always unstable in both the baseline system and the producer responsibility system. While, the actor responsibility system promotes illegal dumping by LS (see Tables C6 and C7).

Table 2 summarizes the stability conditions of the seven equilibrium points. (i) Both sanction systems promote the evolution of cooperation in the division of labor, and inhibit illegal dumping by generators. (ii) There are two types of illegal ITF dumping: ITF is either a C-D player or a D-D player in equilibrium. Illegal dumping by a D-D player does not occur in the absence of a sanction system because the equilibrium point, (C, D-D, *), is not stable. However, both sanction systems promote illegal dumping by a D-D player. (iii) Illegal dumping by LS does not occur in the absence of a sanction system and in the producer responsibility system, while the actor responsibility system promotes illegal dumping by LS.

In the producer responsibility system, when any defector never hands back the fake manifest ($p_i = 1$, $i = 2, 3, 4$) and any cooperator always hands back the manifest ($q_i = 0$, $i = 3, 4$), the sanction promotes (C, C-C, C) and (C, D-C, C), and the sanction inhibits (D, *, *). However, the sanction does not influence the other four types of equilibrium point resulting in illegal dumping, as per the baseline system.

Comparison with the results of Kitakaji and Ohnuma (2014)

Following Kitakaji and Ohnuma (2014) and their personal communication, model parameters can be estimated. “s” is used as the currency in their experiment and 1s is equivalent to one million yen or ten thousand US dollars. In their experiment, when the generator produces 100 tons of industrial waste, b = 65s, x_1 = 45s, c_{mid} = 10s, x_2 = 20s, x_2' = 40s, c_t = 10s, c_t' = 20s, g_0 = 100 tons, g_1 = 50 tons, r = 0.1s/ton, s = 4 in which “*s*” is not the same as the currency “s” here, f = 30s, d = 0.0065, and f_1 = 100s or 50s (Table 1). For simplicity, $p_2 = p_3 = p_4 = 1$ and $q_3 = q_4 = 0$.

Using these parameter values, we obtain that (D, *, *) is locally stable, and other equilibrium points are locally unstable not only in the baseline model but also in both sanction systems.

Now we investigate which sanction system promotes the evolution of cooperation based on parameters used in Kitakaji and Ohnuma (2014). The local administrative organ has difficulty in monitoring perfectly and detecting the illegal dumping and the illegal dumper because the illegal dumper dumps waste in inconspicuous places such as deep in the mountains, destroying evidence. As a result, perfect-monitoring is very costly. The experimental results from Kitakaji and Ohnuma (2014) indicate that the probability of being monitored and detected by the local administrative organ (d) is very low and they estimated d at 0.0065. In reality, d is considered to be much smaller than their experimental observation because monitoring and detecting illegal dumping is not as difficult in the experimental space as in real space. Even though the fine f is very expensive, the value df is very small relative to other parameters. Then, the actor responsibility system converges near the baseline model (see Table C); the actor responsibility system hardly promotes the evolution of cooperation. If monitoring and detecting illegal dumping were straightforward and df were not neglected, (C, C-C, C) would be stable when $df > 20$ and other parameters are as per Kitakaji and Ohnuma (2014).

Here we consider the producer responsibility system. The value r can be controlled by the local administrative organ and Ishiwata (2002) suggests that x_1 is much higher than x_2 (Ishiwata, 2002). We examine in which value of r and x_1 the producer responsibility system promotes the evolution of cooperation based on the local stability conditions in Table C. Our calculations show that, if both inequalities, $r > 0.4$ and $400r < x_1 < 400r + f_1p_2$, hold, (C, C-C, C) is locally unstable in the baseline model, and locally stable in the producer responsibility system (see Figures 2 and 3). Figure 2 shows the initial frequencies influence the dynamics when $r = 0.5$, $x_1 = 250$, which satisfy $r > 0.4$ and $400r < x_1 < 400r + f_1p_2$, and other parameters are as per Kitakaji and Ohnuma (2014). Numerical simulations show that (u, z_1, v) almost converges to (1, 1, 1) even in the low initial value of u when the initial values of z_1 and v are high (Figure 2(A) and (B)). When the initial value of u is higher, the area where (u, z_1, v) almost converges to (1, 1, 1) is wider (see Figure 2(A) and (B)). In Figure 3(A), the value of u increases and converges to one. When the initial value of v is 0.75, the value of u decreases and then increases until u becomes one (Figure 3(B)). When the initial value of v is 0.7, the value of u immediately converges to zero. Figure 3(B) indicates that the frequency of g-cooperators (u) decreases at the beginning and then increases before the dynamics finally converge to (C, C-C, C) even though the producer responsibility system is effective.

Kitakaji and Ohnuma (2014) showed that sanctioning increased the number of defectors. While, our analysis only shows that (D, *, *) is stable in the baseline model and two sanction systems using their parameters, and does not show that sanctions increase the number of defectors. Instead, we can indicate that, if those authors use the parameters we estimated in the previous paragraph, the producer responsibility system may promote cooperation. However, our model assumptions do not perfectly match the experimental design in Kitakaji and Ohnuma (2014), and the behavior of examinees in their experiment was not identical to those of the players in our case: some examinees formed a coalition, the examinees monitored each other in the same role, or examinees divided the waste into pieces and committed them to some examinees. Therefore, our suggestion is tentative, it may not work well in their experimental design.

Comparison with empirical reality

We can compare these equilibrium points with Japanese field survey data, captured by our coauthors, Ohnuma and Katakaji. (1, 0, 0, 1, 1) = (C, D-C, C) applies in Hokkaido, the second largest of Japan's principal islands. The land which the LS has is abundant and real estate is very inexpensive relative to Tokyo. As a result, LS has a huge and inexpensive land and does not mind landfilling the waste which ITF does not treat properly prior to it being landfilled by LS. By contrast, (1, 0, 1, 0, *) = (C, C-D, *) applies in the Kanto area including the Tokyo metropolitan area. There is little room in this area and real estate is very expensive. Thus the land of the LS is very limited. As a result, LS cannot accept the offer from the ITF. ITF has no choice but to dump the waste. Before illegal dumping, ITF treats the waste properly following the reasons; (i) if extracting valuable things such as precious metals from the waste successfully through the treatment process, ITF can transact them and obtain benefits in the metropolitan area in which there are big markets for reuse. It is easy for ITF to access the market and then the transportation cost is low for ITF. (ii) the amount of treated waste is smaller than that of untreated one, and the smaller waste is not easily found if dumped. We denote this as the Kanto type.

According to data from the Ministry of the Environment in Japan, in 1998 (2015) 60% (56.6%) of illegal dumping resulted from generators, 10% (2.1%) from unlicensed dealers, and 8% (4.9%) from licensed dealers. The data shows that the ratio of generators' illegal dumping is much higher than others. If we consider that *df* is too small to influence the dynamics and $p_2 = p_3 = p_4 = 1$ and $q_3 = q_4 = 0$,illegal dumping by generators occurs, but illegal dumping by firms in other roles does not occur, except the Kanto type. Our theoretical model is supported by empirical data suggesting that generators exhibit a high propensity to engage in illegal dumping activities.

Data from the Ministry of the Environment in Japan also shows that, directly following the introduction of the producer responsibility system in 1990, illegal dumping first increased and then decreased. The dynamics illustrated in Figure 3(B) may explain this empirical phenomenon.

Comparison between the three-role and two-role models

We presented results in the previous section whereby the number of industry types was reduced from five to three types. We also constructed a simpler model called the two-role model, constituted by the generator and the landfill site (see Appendix B for specification equations and analytical results). Appendix B shows that there are three equilibrium points in the three systems: $(u_1, v_1) = (1, 1), (1, 0), (0, *)$. $(u_1, v_1) = (1, 1)$ corresponds to $(u_1, z_1, z_2, z_3, v) = (1, 1, 0, 0, 1)$ and $(1, 0, 0, 1, 1)$; $(u_1, v_1) = (1, 0)$, $(u_1, z_1, z_2, z_3, v) = (1, 0, 0, 1, 0)$ and $(1, 1, 0, 0, 0)$; $(u_1, v_1) = (0, *)$ corresponds to $(u_1, z_1, z_2, z_3, v) = (0, *, *, *, *)$. However, other equilibrium points in the three-role model, such as (1, 0, 1, 0, *) which is interpreted as the Kanto type, cannot be described by the results of the two-role model. Therefore, we conclude that the three-role model has greater empirical credibility than the two-role model.

Discussion and conclusion

We investigate the effect of sanctions on the evolution of cooperation in linear division of labor. As an example, we institute the replicator dynamics in the context of an industrial waste illegal dumping game proposed by Ohnuma and Kitakaji (2007). We introduce two sanction systems, the actor responsibility system and the producer responsibility system, and then compare each of these two systems with a baseline model devoid of sanctions. Our main conclusion is that both sanction systems seem to promote the evolution of cooperation and inhibit illegal dumping by generators. However, where fines do not influence evolutionary dynamics because monitoring is ineffective, the actor responsibility system no longer promotes the evolution of cooperation.

Monitoring violators is arduous not only in the case of illegal industrial waste but in other contexts too, such as illegal logging and overfishing. The industrial waste treatment process in Japan embodies linear division of labor; and the sanction system which does not require monitoring violators can be put into practice rather than the sanction system with monitoring. Our analysis also shows that the producer responsibility system, which does not require monitoring, promotes the evolution of cooperation and inhibits illegal dumping more than the actor responsibility system. If logging or fishing in some areas are configured according to linear division of labor, sanction systems like the producer responsibility system may work to inhibit illegal logging or overfishing.

In the producer responsibility system, the generator is sanctioned if the manifest is not handed to the local administrative organ. There is another possible sanction system derived from the producer responsibility system; not a generator but an intermediate treatment facility or a landfill site is punished when the manifest is not handed to the local administrative organ. However, generators are expected to choose illegal dumping more if intermediate treatment facilities or landfill sites are punished, and then the amount of illegal dumping is larger. It is because g-defectors do not need to pay not only the cost of cooperation but also the fine. To confirm our guess, we will analyze the model with the new sanction system as our future study.

Sanctions are only one of a number of potential interventions. Following are other potential solutions which may promote the evolution of cooperation. If we can configure a group who chooses good players in all roles, the members maximize their efforts towards goal attainment, and produce a final good product. In this case, how to choose group members and/or to choose a group is crucial. Nakamaru and Yokoyama (2014) examined how choosing a new member, or choosing a good group influence the evolution of group cooperation when players are peers or on an equal footing in a group consisting of more than three members. We may apply Nakamaru and Yokoyama (2014) to the linear division of labor context. However, if players in role B_i do not interact with players in role B_j and then cannot evaluate the quality of players in B_j correctly ($j > i + 1$), the group fails to choose optimal players and the evolution of cooperation in linear division of labor does not occur. Or, without choosing group members, we can consider that a player in role B_i chooses a player with good reputation in role B_{i+1} and then the player in role B_{i+1} can accept the player's offer if s/he has a good reputation. In this case, we guess that the evolution of cooperation in linear division of labor is promoted and we will analyze the model as our future work.

Linear division of labor (Figure 1B) has a similar structure to the centipede game (Rosenthal, 1981). In the standard setting, two players play the centipede game alternately and repeatedly. The player can choose “Right” or “Down” on his/her turn. If the player chooses Down, the game is over and then both players can receive the payoff. If the player chooses Right, the game is continued and the other player can choose either of the two options. This is repeated. It is assumed that (i) The payoff of player A who chooses Down in the *i*-th stage, $s_{A,i}$, is higher than that of player A who chooses Right when the other player B chooses Down in the i+1-th stage, $s_{A,i+1}$, and (ii) $s_{A,i+2}$ is higher than $s_{A,i}$., and (iii) If two players always choose Right, they achieve the final stage. The payoff in the final stage is higher than in any previous stage. There is one study, Smead (2008), from the viewpoint of evolutionary game theory; this showed that a finite population promotes the evolution of cooperation in the quasi-centipede game, where two players choose their tactics simultaneously and the payoff is symmetric. It is often assumed that two players repeatedly and alternately play in the centipede game. While, in our assumptions, players in different roles play the game in different stages and the same players do not play the game repeatedly. As a result, we can describe the model through the replicator dynamics for asymmetric games.

We only assumed players or organizations in three roles, and did not assume a local administrative organ player. If we introduce such a player, which also maximizes payoff in evolutionary game theory, the player may prefer the producer responsibility system to the actor responsibility system because the latter is very costly. Further exploration thereof remains for future research.

In this paper, we assumed the generators, the intermediate treatment facilities, and the landfill sites as the three-role model in linear division of labor. We can consider another combination of the three roles, which are the generators, the haulers, and the landfill sites.

The model assumption in the new three roles is different from our current model, and we will investigate which three-role model promotes the evolution of cooperation in linear division of labor as our future work. Then, we will challenge to analyze the five-role model. It is complicated to analyze the equations and the analytical results may be complicated. To understand the complicated results and obtain the general conclusion, we will compare the results in the five-role model with our current results and results in the new three-role model.

In empirical contexts, there are many types of division of labor besides the linear variant; the structure of the division of labor may influence the efficiency of the institution or the social goal. The division of labor has long been studied in sociology and organization theory, especially industrial ecology (Durkheim, 1893; Frosch and Gallopoulos, 1989; Milgrom and Roberts, 1992; Axtell et al., 2001; Giddens, 2006). We studied the division of labor from the viewpoint of evolutionary game theory and then showed that a special sanction such as the producer responsibility system can promote cooperation among organizations with linear division of labor. Network structure among roles is also key from the viewpoint of evolutionary game theory. In this paper, we assumed the simplest network: the linear type network or one-dimensional lattice structure. The network structures among organization or roles in other institutions are more complicated than what we dealt with here. We can proffer a new possibility that organizations can be studied from the viewpoint of the evolution of cooperation and complex networks by means of replicator dynamics.

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Appendix A

Model assumptions and results in the no-role model:

In the baseline system, we consider the simplest and, thus, unrealistic scenario: generators can dispose of industrial waste and then the division of labor does not exist. Each of generators is either a g-cooperator or a g-defector in the population. We assume that the benefit from a generator's production is b and the treatment cost is $-c$ ($b > c > 0$). Let g be defined as the amount of industrial waste dumped by a g-defector and let r be defined as the environmental restoration expense or damage per unit of waste (g, $r > 0$). The frequency of g-cooperators and g-defectors is u and $1-u$, respectively. The environmental load of each generator is $-gr(1-u)$. Therefore, the payoffs of a g-cooperator ($E_C(u)$) and a g-defector ($E_D(u)$) are $b - c - gr(1-u)$ and $b - gr(1-u)$, respectively. The assumption satisfies the tragedy of the commons when $c/r < g$ which is derived from the situation that the payoff of a cooperator when all generators are cooperators is higher than that of a defector when all generators are defectors ($E_C(1) > E_D(0)$).

The replicator equation can be written as;

$$\frac{d}{dt}u = u(1-u)\left(E_C(u) - E_D(u)\right) \quad . \qquad \text{(A1)}$$

As $E_C(u) - E_D(u) = -c < 0$, $u = 0$ is stable regardless of any parameters.

We introduce the actor responsibility system to the baseline system in the no-role model. In this system, the local administrative organ imposes a fine (f) on the g-defector if the g-defector is monitored and detected. Let d be the probability of monitoring and detecting illegal dumping ($d > 0$). The probability d is very small because it is almost impossible for the local administration organ to detect illegal dumping. The payoff of a defector, $E_D(u)$, is $b - gr(1-u) - df$. Then, putting the payoff of the g-cooperators and the g-defectors into eq. (A1), we obtain that $u = 1$ is stable in $df > c$, and $u = 0$ is stable otherwise.

We introduce the producer responsibility system to the baseline system in the no-role model. It is assumed that a g-cooperator always submits the manifest. If a g-defector does not submit it, s/he has to pay a fine defined as f_1 (> 0). The probability of g-defectors not submitting a manifest is p; the probability of them submitting a fake manifest is $1-p$. The probability p is high because g-defectors cannot submit unless they concoct a fake manifest. The local administration organ may accept the fake manifest because it is almost impossible for the local administration organ to monitor illegal dumping to distinguish between honest and fake manifests. Therefore, the payoff of a defector is $b - gr(1-u) - pf_1$. Then, putting the payoffs of the g-cooperators and the g-defectors into eq. (A1), we obtain that $u = 1$ is stable in $pf_1 > c$, and $u = 0$ is stable otherwise.

Comparison of the baseline system with the actor responsibility system and the proucer responsibility system indicates that a fine imposed by a local administrator increases the incentive to choose legal treatment. Basically, the results show there is no difference between the actor responsibility system and the producer responsibility system in the no-role model. If we assume $df < pf_1$ because d is very small and p is high, the producer responsibility system promotes the evolution of cooperation more than the actor responsibility system.

Appendix B

Model assumptions and results in the two-role model:

We consider that there are two types of industries: generators and landfill sites. The group size of each industry is infinite. Each generator is either a g-cooperator or a g-defector. The generator's benefit from production is b. When a g-cooperator commits industrial waste to the landfill site, the commission cost is $-x_1$ ($b > x_1 > 0$). The landfill site can capture the commission cost as his/her profit, x_1. The landfill site is either an ls-cooperator or an ls-defector. The ls-cooperator pays a treatment cost, c_t ($x_1 > c_t > 0$). The definition of the environmental load caused by g-defectors and ls-defectors is the same as per the three-role model. Let g_0 be defined as the amount of industrial waste dumped by a g-defector. We consider that the local administrative organ determines that the generator group be forced to pay an expense s times as high as the LS group ($s \geq 1$). Here let r be defined as the environmental restoration expense or damage per unit of waste. If a player dumps industrial waste illegally, srg_0 is imposed on a generator and rg_0 is imposed on an LS.

The payoff of a generator and a landfill site are presented by the payoff matrices A and B as follows:

$$A = \begin{bmatrix} b - x_1 & b - x_1 - g_0 sr \\ b - g_0 sr & b - g_0 sr \end{bmatrix} \text{ and } B = \begin{bmatrix} x_1 - c_t & -g_0 r \\ x_1 - g_0 r & -g_0 r \end{bmatrix} \quad . \qquad \text{(B1)}$$

Let u_1 and u_2 be the frequencies of g-cooperators and g-defectors in the generator group ($u_1 + u_2 = 1$), and v_1 and v_2 be the frequencies of ls-cooperators and ls-defectors in the landfill site group ($v_1 + v_2 = 1$). We assume that one player is randomly chosen from the generator's group and the other is chosen from the landfill site's group, and then the two interact together, following our assumptions. We also assume that there are no dealings between generators or between landfill sites. We can apply this model to replicator dynamics of asymmetric games (Hofbauer and Sigmund, 1998):

$$\frac{d}{dt}u_i = u_i\left(\left(Av\right)_i - u \cdot Av\right) \text{ and } \frac{d}{dt}v_i = v_i\left(\left(Bu\right)_i - v \cdot Bu\right) \qquad (i = 1 \text{ or } 2), \qquad \text{(B2)}$$

in which $u = (u_1, u_2)^t$ and $v = (v_1, v_2)^t$. The equation below can be derived from eq. (B2):

$$\frac{d}{dt}u_1 = u_1\left(1 - u_1\right)\left(g_0 srv_1 - x_1\right) \quad , \qquad \text{(B3a)}$$

$$\frac{d}{dt}v_1 = u_1 v_1\left(1 - v_1\right)\left(g_0 r - c_t\right) \quad . \qquad \text{(B3b)}$$

The equilibrium points are: $(u_1, v_1) = (1, 1), (1, 0), (0, v_1^*)$, in which v_1^* means any value between 0 and 1. When $x_1/(sr) < g_0$ and $c_t/r < g_0$, (1, 1) is locally stable. (1, 0) is locally stable when $x_1 < 0$ and $c_t/r > g_0$. (0, *) is unstable if $g_0 rsv_1^* < x_1$, as the other eigenvalue is zero.

When the actor responsibility system is introduced, the payoff matrices are:

$$A = \begin{bmatrix} b - x_1 & b - x_1 - g_0 sr \\ b - g_0 sr - df & b - g_0 sr - df \end{bmatrix} \text{ and } B = \begin{bmatrix} x_1 - c_t & -g_0 r_2 \\ x_1 - g_0 r_2 - df & -g_0 r_2 \end{bmatrix} , \qquad \text{(B4)}$$

in which the local administrative organ punishes the dumper and then forces the dumper to pay a fine, f if the local administrative organ successfully monitors and detects the illegal dumping and the illegal dumper. Let d be the probability of being detected by the local administrative organ. The matrices in eq.(B2) are replaced with those in eq.(B4), thus:

$$\begin{aligned} \frac{d}{dt}u_1 &= u_1(1-u_1)(g_0 srv_1 + df - x_2) , \\ \frac{d}{dt}v_1 &= u_1 v_1 (1-v_1)(g_0 r + df - c_t) . \end{aligned} \qquad \text{(B5)}$$

We obtain the equilibrium points: (1, 0), (1, 1), (0, v_1*). The local stability conditions of (1, 1) are: $(c_t - df)/r < g_0$ and $(x_1 - df)/(sr) < g_0$. Those of (1, 0) are: $(c_t - df)/r > g_0$ and $x_1 - df < 0$. (0, v_1*) is unstable if $g_0 rsv_1^* + df < x_1$ as the other eigenvalue is zero.

When the producer responsibility system is introduced, the payoff matrices are:

$$A = \begin{bmatrix} b - x_1 - f_1 q_1 & b - x_1 - g_0 sr - f_1 p_1 \\ b - g_0 sr - f_1 p_2 & b - g_0 sr - f_1 p_2 \end{bmatrix} \text{ and } B = \begin{bmatrix} x_1 - c_t & -g_0 r \\ x_1 - g_0 r & -g_0 r \end{bmatrix} , \qquad \text{(B6)}$$

in which let p_1 be the probability that the ls-defector does not hand the manifest back to the g-cooperator. $1-p_1$ is the probability that the ls-defector hands in a fictitious manifest. Let p_2 be the probability that the g-defector does not hand the manifest back to the local administrative organ. $1-p_2$ is the probability that the g-defector hands in a fictitious manifest.

Let q_1 be the probability that the ls-cooperator does not hand the manifest back to the g-cooperator. The matrices in eq. (B2) are replaced with those in eq.(B6) and then the equations are:

$$\frac{d}{dt}u_1 = u_1\left(1-u_1\right)\left(\left(g_0 sr + f_1 p_1 - f_1 q_1\right)v_1 - \left(x_1 + f_1(p_1 - p_2)\right)\right) ,$$

$$\frac{d}{dt}v_1 = u_1 v_1\left(1-v_1\right)\left(g_0 r - c_t\right) .$$

We obtain the equilibrium points: (u_1, v_1) = (1, 0), (1, 1), (0, v_1*). The local stability conditions of (1, 1) are: $c_t/r < g_0$ and $(x_1 - f_1(p_2 - q_1))/(sr) < g_0$. Those of (1, 0) are: $c_t/r > g_0$ and $x_1 + f_1(p_1 - p_2) < 0$. (0, v_1*) is unstable if $g_0 rs v_1^* + f_1(-p_1 + p_2) + f_1 v_1^*(-q_1 + p_1) < x_1$ as the other eigenvalue is zero.

Appendix C

Eq. (1) shows that there is one inner equilibrium point besides seven types of equilibrium points in either the baseline system or the producer responsibility system:

$$(u_1, z_1, z_2, z_3, v) = (1,\ \frac{rg_0 - c_t'}{r(g_0 - g_1) + c_t - c_t'},\ 0,\ \frac{-rg_1 + c_t}{r(g_0 - g_1) + c_t - c_t'},\ 1 - \frac{c_{mid} + x_2 - x_2'}{r(g_0 - g_1)}).$$

One inner equilibrium point in the actor responsibility system is:

$$(u_1, z_1, z_2, z_3, v) = (1,\ \frac{df + rg_0 - c_t'}{r(g_0 - g_1) + c_t - c_t'},\ 0,\ \frac{-df - rg_1 + c_t}{r(g_0 - g_1) + c_t - c_t'},\ 1 - \frac{c_{mid} + x_2 - x_2'}{r(g_0 - g_1)}).$$

The numerical calculations show they are unstable.

The stability condition of seven equilibrium points in the baseline model, the actor responsibility system model, and the producer responsibility system model (see Table 2) are calculated using eq. (1); we calculate the eigenvalues for each equilibrium point, and they are real numbers. Therefore, when all eigenvalues for one equilibrium point are negative, the equilibrium is locally stable. Table C shows the condition that all eigenvalues are negative, which is the local stability condition of each equilibrium point. The local stability conditions of (1, 1, 0, 0, 1) are listed in Table C1; (1, 0, 0, 1, 1), Table C2; (0, *, *, *, *), Table C3; (1, 0, 1, 0, *), Table C4; (1, 0, 0, 0, *), Table C5; (1, 0, 0, 1, 0), Table C6; (1, 1, 0, 0, 0), Table C7.

Figure legends

Figure 1

The division of labor:

(A) shows general division of labor. Players in each role A_i (i = 1, …, n) work to achieve their goal. (B) shows linear division of labor. Players in role B_i interact with those in role B_{i+1} (i < n). Then, players in the final role B_n achieve the goal.

Figure 2

The initial frequency dependency of the dynamics:

These graphs present the effect of the initial frequencies on the dynamics. The horizontal axis is the initial frequency of C-C players (z_1) and the vertical is the initial frequency of ls-cooperators (v). The initial values of z_2 and z_3 are (1 − (the initial value of z_1))/3. The black point signifies that the dynamics converge to (C, C-C, C); the gray point signifies that the dynamics converge to (D, *, *). (A) The initial frequency of g-cooperators (u) is 0.95, and we executed numerical simulations through 500 time steps (the interval between time steps is 0.01 time). (B) The initial frequency of g-cooperators is 0.05, and we executed numerical simulations through 1,000 time steps. In both (A) and (B), $r = 0.5$, $x_1 = 250$, and other values are as per Kitakaji and Ohnuma (2014).

Figure 3

The time-change of the frequencies:

These graphs present the numerical simulation outcomes. The horizontal axis is time, and the vertical is the frequencies of u, z_1, z_2, z_3, and v. The thick black line is u; the thick gray, z_1; the thick dotted gray line, z_2; the thin dotted gray line, z_3; the thin black line, v. (A) the initial values of (u_1, z_1, z_2, z_3, v) are (0.5, 0.8, 0.066, 0.066, 0.95); (B), (0.5, 0.8, 0.066, 0.066, 0.75); (C), (0.5, 0.8, 0.066, 0.066, 0.7). In (A) − (C), $r = 0.5$, $x_1 = 250$, and other values are as per Kitakaji and Ohnuma (2014).

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The effect of sanctions on the evolution of cooperation in linear division of labor

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Authors' contributions

MN conceived of the study, designed the study, coordinated the study, analyzed the mathematical model, carried out the numerical simulations, and drafted the manuscript; HS analyzed mathematical models, carried out the numerical simulations, and helped draft the manuscript; YK and OS participated in the design of the study, helped coordinate the study and helped draft the manuscript; All authors gave final approval for publication.

Abstract

The evolution of cooperation is an unsolved research topic and has been investigated from the viewpoint of not only biology and other natural sciences but also social sciences. Much extant research has focused on the evolution of cooperation among peers. While, different players belonging to different organizations play different social roles, and players playing different social roles cooperate together to achieve their goals.

We focus on the evolution of cooperation in linear division of labor that is defined as follows: a player in the i-th role interacts with a player in the i+1-th role, and a player in the n-th role achieves their goal ($1 \leq i < n$) if there are n roles in the division of labor. We take the industrial waste treatment process as an example for illustration. We consider three organizational roles and B_i is the i-th role. The player of B_i can choose two strategies: legal treatment or illegal dumping, which can be interpreted as cooperation or defection (i = 1−3). With legally required treatment, the player of B_j pays a cost to ask the player of B_{j+1} to treat the waste (j = 1, 2). Then, the cooperator of B_{j+1} pays a cost to treat the waste properly. With illegal dumping, the player of B_i dumps the waste and does not pay any cost (i = 1−3). However, the waste dumped by the defector has negative environmental consequences, which all players in all roles suffer from. This situation is equivalent to a social dilemma encountered in common-pool resource management contexts.

The administrative organ in Japan introduces two sanction systems to address the illegal dumping problem: the actor responsibility system and the producer responsibility system. In the actor responsibility system, if players in any role who choose defection are monitored and discovered, they are penalized via a fine. However, it is difficult to monitor and detect the violators, and this system does not work well. While, in the producer responsibility system, the player in B_1 is fined if the player cannot hand the manifest to the local administrative organ because the players of B_i (i = 1−3) who choose defection do not hand the manifest to the player of B_1.

We analyze this situation using the replicator equation. We reveal that (1) the three-role model has more empirical credibility than the two-role model including B_1 and B_3, and (2) the producer responsibility system promotes the evolution of cooperation more than the system without sanctioning. (3) the actor responsibility system does not promote the evolution of cooperation if monitoring and detecting defectors is unsuccessful.

Keywords: illegal dumping, social dilemma, common-pool resource management, monitoring, replicator equation for asymmetric games

Introduction

Our society is based on cooperation. The evolution of cooperation remains a challenging problem from the viewpoint of not only evolutionary theory but also the social sciences: the evolution of cooperation is not an easy problem to solve. We consider the prisoner's dilemma (PD) game. Two players play the prisoner's dilemma game and there are two types of players: cooperators and defectors. If both cooperators play the PD game, they obtain the payoff, R. If a cooperator plays the PD game with a defector, the cooperator obtains S and the defector obtains T. If both are defectors, they obtain the payoff, P. It is often assumed that the cooperator gives a benefit, b, to the opponent, incurring a cooperation cost, $-c$ (b, $c > 0$), but the defector does not give anything. Therefore, $T = b$, $R = b-c$, $P = 0$ and $S = -c$. As one of the definitions satisfying the PD game is $T > R > P > S$, defectors obtains a greater payoff than cooperators regardless of the opponent's type. As a result, players choose to be defectors and thus cooperation is unachievable. Therefore, previous studies on evolutionary game theory have investigated conditions whereby cooperation can evolve. “Evolution” here has two meanings: one is biological evolution in which genetic changes occur, and the other is social learning in which players change their behavior according to their own and their opponents' payoffs. Studies from social science perspectives often use evolutionary game theory as social learning (Sigmund et al., 2010).

Five conditions for the evolution of cooperation can be posited (Nowak, 2006): kin selection (Hamilton, 1964), group selection (Sober and Wilson, 1999), direct reciprocity (Axelrod and Hamilton, 1981), indirect reciprocity (Sugden, 1986; Nowak and Sigmund, 1998), and network reciprocity (Nowak and May, 1992; Nakamaru et al., 1997; Nakamaru et al., 1998). Besides these five categories, the effect of punishment on the evolution of cooperation has also been studied (Axelrod, 1986; Sigmund et al., 2001; Boyd et al., 2003; Nakamaru and Iwasa, 2005; Nakamaru and Iwasa, 2006; Rand et al., 2010; Sigmund et al., 2010; Shimao and Nakamaru, 2013; Chen et al., 2014; Chen et al., 2015b; Sasaki et al., 2015). Many previous studies assume players are peers. In actual, empirical contexts we cooperate not only with peers, but also among players with different social roles, between a leader and a subordinate, within groups under hierarchy, or among groups which exhibit hierarchical relationships (Henrich and Boyd, 2008; Powers and Lehmann, 2014; Roithmayr et al., 2015). In this paper, we focus on cooperation in the division of labor.

Various animals, such as social insects and naked mole rats, developed division of labor and different individuals have different roles. In social insects, each individual plays various roles such as attending the mother queen, grooming larvae, guarding the nest entrance, and foraging, and which role s/he plays depends on his/her aging; an individual attends mother queen when s/he is younger than 10 days old, rolls and carries mature larvae at the age of 10 days, then defends nest when s/he is older than 14 days old, which is termed temporal division of labor (Hölldobler and Wilson, 1990). We consider the basic structure of the division of labor in animals, where individuals belonging to a specific role (A_1, … or A_n) can work independently and cooperate together for the purposes of goal attainment (Figure 1A). If some of them are not cooperators, all cannot achieve the goal. We humans have also developed division of labor (Kuhn and Stiner, 2006; Henrich and Boyd, 2008; Nakahashi and Feldman, 2014). Humans differ from other animals in terms of their approach to the division of labor because they can innovate and create new styles of division of labor suitable for group, institutional or societal goals. Powers et al. (2016) noted that natural selection has shaped our cognitive ability in terms of language usage, a theory of mind, shared intentionality; these abilities then facilitate the development of institutions (Powers et al., 2016). The same logic can be applied to human division of labor since some institutions are equipped with the division of labor to run or manage institutions efficiently. We can consider that not the division of labor but the cognitive ability to innovate new styles of the division of labor is involved with natural selection. Cognitive anthropologists have discussed that episodic memory, one of high cognitive ability typically evolved and developed in humans, but not in Neanderthals, is required to innovate age and gender divisions thereof. It is because episodic memory not only stores and retrieves past events but also makes future planning or simulating future scenarios possible; to innovate or maintain the division of labor requires such ability (Coolidge and Wynn, 2008). Cognitive sciences, some branches of anthropology, and natural selection fall under the domain of biology, and therefore, the division of labor in human society can be studied from the perspective of biology.

There are various types of division of labor existing in our society and we focus on one such type, illustrated in Figure 1B, the linear division of labor. Well-known examples thereof include the car assembling process and the manufacturing process of some traditional crafts such as kimonos and Buddhist alters in Japan (Ohnuma, personal communication). In Figure 1B, a player in role B_1 cooperates to achieve the goal and works towards that goal accordingly. After s/he completes his/her work, s/he brings the product to a player in role B_2. Then, the player in B_2 completes further goal-oriented work. After s/he finishes it, s/he brings it to a player in role B_3. Role B_j is dependent on role B_i ($n \geq j > i$). This process is repeated and then a player in role B_n produces the final product. The final product is a goal of the division of labor and the quality influences all players in all roles. For example, if the quality is good, the price is expensive and the group members obtain a good reputation. However, if players are not cooperative and the final product is bad, they cannot accrue the desirable benefits. However, cooperation is costly; if a player in B_i is not a cooperator, a player in B_j is a cooperator and these two roles are similar, the player in B_j can compensate for the imperfection of the player in B_i ($j > i$), and the final product may be good. As a result, the player in B_i does not need to pay a cost for doing a good job and get a high benefit from the good final product. While, if a cooperative player in B_j cannot compensate for the imperfection of a player in B_i because of the high specialty in each role, the final product may not be good. As a result, no players accrue desirable benefits from the final product.

If a player in B_i knows the reputation of players in B_{i+1}, a player in B_i can choose a cooperator in B_{i+1}. Then, players in both B_i and B_{i+1} would accrue desirable benefits. However, if a player in B_j ($j > i+1$) does not choose a cooperator in B_{j+1}, the quality of the final product becomes low and then all players in all roles do not accrue desirable benefits even though the player in B_i chose a cooperator in B_{i+1}.

What kinds of system promote the evolution of cooperation in linear division of labor? We focus on the effect of sanctions and monitoring. Previous empirical and theoretical studies have shown that monitoring and/or sanctions inhibit the violators who break institutional rules in common-pool resource management contexts, such as with forest logging, in order to run the institution efficiently (Ostrom, 1990; Rustagi et al., 2010; Chen et al., 2015a; Lee et al., 2015). After successful monitoring detects violators, sanctions can be imposed on them. Monitoring is effective in small villages where people have knowledge of the behavior of others, through direct observation and gossip. However, detecting violators is sometimes hard work and it is very costly in larger societies because it is almost impossible to have knowledge of the behavior of all members in society. Then, sanctions cannot be imposed on the violators. Consequently, both monitoring and sanctions are not meaningful anymore. For example, detecting illegal logging far from human habitation deep in the mountains to which there are neither roads nor transportation to access is almost impossible and monitoring does not work. How do we deal with this situation?

In this paper, we take the industrial waste treatment process in Japan as an example of the linear type of division of labor, and then investigate the effect of sanctions and monitoring on the evolution of cooperation, using the industrial waste illegal dumping game which Ohnuma and Kitakaji proposed based on their field survey and government publications (Ohnuma and Kitakaji, 2007; Kitakaji and Ohnuma, 2014; Kitakaji and Ohnuma, 2016). In what follows, the industrial waste treatment process in Japan based on their experimental works (Ohnuma and Kitakaji, 2007; Kitakaji and Ohnuma, 2014; Kitakaji and Ohnuma, 2016) is explained. The industrial waste treatment process consists of five roles: generators (B_1), the 1st waste haulers (B_2), the intermediate treatment facilities (B_3), the 2nd waste haulers (B_4) and the landfill sites (B_5). The generators produce industrial waste as a secondary product, and commit the waste to the 1st waste haulers. When the 1st waste haulers can commit the waste to the intermediate treatment facilities, the 1st waste haulers bring it to the intermediate treatment facilities. The intermediate treatment facilities crush the waste, treat it chemically, or incinerate it. Then, the intermediate treatment facilities decide to commit it to the 2nd waste hauler. When the 2nd waste haulers can commit it to the landfill sites, they bring it to the landfill sites. The landfill sites dispose of it in sanitary land-fills. In the industrial waste treatment process, cooperation means that a player in B_i commits the waste to a player in B_{i+1}, paying a commission cost, or a player in B_3 also treats waste paying a treatment cost. If all players in all roles cooperate, the volume of waste is reduced and its risk, such as its toxicity, is removed and then the waste is landfilled safely and does not deleteriously impact the natural environment. Therefore, the final product is the safely landfilled waste in the industrial waste treatment process. Defection means that a player in B_i

does not commit the waste to a player in B_{i+1} but illegally dumps the waste far from human habitation deep in the mountains which is hard to access ($1 \le i \le 4$). Defectors do not need to pay a commission cost or a treatment cost. Once defection occurs, illegal dumped waste damages the natural environment. Hence, the final product in this case is the environmental damage and all players suffer from the damage. Actually, if the local administrative organ detects the damage caused by the illegal dumped waste but cannot know which player dumped the waste, the organ forces all players in all roles to pay for restoration. Players in all roles reserve a fund in advance to pay for future restoration.

This situation in the industrial waste treatment process is interpreted as a social dilemma (Ohnuma and Kitakaji, 2007; Kitakaji and Ohnuma, 2014; Kitakaji and Ohnuma, 2016). We explain the reason as follows. If all players in all roles are cooperators, they pay a cost, such as a commission cost and a treatment cost, but do not need to pay for restoration. While, a player in B_1 chooses defection, the player does not need to pay a commission cost. Not only the defector in B_1 but also other players in B_j ($j > 1$) have to pay for restoration. If players in B_1 and B_2 are cooperators and a player in B_3 is a defector, players in B_1 and B_2 have to pay a commission cost as well as for restoration. Players in B_4 and B_5 also have to pay for restoration even though they are cooperators. If the restoration cost is expensive, the payoff when all players choose cooperation can be higher than the payoff when a player in B_1 chooses defection. However, if a player changes behavior from cooperation to defection in B_i ($1 \leq i \leq 5$), the defector gets a higher payoff than the cooperator because the defector does not need to pay for a cost such as a commission cost or a treatment cost.

To inhibit illegal dumping, two sanction systems are put into effect in Japan (Ohnuma and Kitakaji, 2007; Kitakaji and Ohnuma, 2014; Kitakaji and Ohnuma, 2016). In this paper, we term these two systems the actor responsibility system and the producer responsibility system. In the actor responsibility system, the local administrative organ challenges to detect the illegal dumping. As many firms illegally dump the industrial waste deep in the mountains or in rivers far from habitation, the organ hardly detects the waste. When the organ luckily detects the waste, s/he has to detect who illegally dumped it. To detect who dumped it is very hard work. If the organ detects who dumped it, the firm is fined; the maximum fine in Japan is one hundred million yen, which is equivalent to one million US dollars. Previous theoretical studies concerning the evolution of pool-punishment also make the same assumption: pool-punishers detect the violators and punish them, and pool-punishers do not fail to detect these violators (Sigmund et al., 2010).

However, as the local administrative organ had difficulty in monitoring and detecting the illegal dumping, a new system was introduced in 1990, which we call the producer responsibility system herein. In this system, a manifest is important. The local administrative organ prepares the manifest, which all players in all roles have to fill in when committing waste. Then, after the generator fills the manifest, it is handed to the 1st waste hauler. After the 1st waste hauler fills in the manifest, it is handed to the intermediate treatment facility. Then, after the intermediate treatment facility hands it to the 2nd waste hauler, the 2nd waste hauler fills in it and hands it to the landfill site. Next, the landfill site fills in it and hands it back to the 2nd waste hauler, which also hands it back to the intermediate treatment facility. This process continues and finally the generator hands it to the local administrative organ. If the generator fails to hand it back to the local administrative organ, the local administrative organ punishes the generator and the generator has to pay a fine, even though another player in another role does not fill in it and hand it back.

Data from the Ministry of the Environment in Japan shows that the total number of illegal dumping activities detected annually increased directly after introducing the manifest system; the number has subsequently decreased since 2000 (see http://www.env.go.jp/press/103219.html). Does the data show that the new system inhibits the number of illegal dumping activities? Or, does the data only show that monitoring fails to detect illegal dumping because illegal dumping is more secret than before? Consecutive experimental works by Ohnuma and Kitakaji tackled this question (Ohnuma and Kitakaji, 2007; Kitakaji and Ohnuma, 2014; Kitakaji and Ohnuma, 2016). They showed that either monitoring or sanctions in the actor responsibility system did not prevent illegal dumping under the producer responsibility system (Kitakaji and Ohnuma, 2014). In this paper, using the replicator equation in evolutionary game theory, we investigate the effect of either of two sanction systems on the evolution of cooperation in the industrial waste process in Japan as an example of linear division of labor. Generally, firms pursue profits and change tactics or strategy based on profit considerations. They may imitate the strategy of others to accrue more profits. Therefore, the replicator dynamics, which can be interpreted as a social learning model, is a useful tool to describe the behavior of firms.

Model Assumptions

It is a complex task to construct a mathematical model assuming five roles in linear division of labor. We consider three cases. (i) There are only generators which can treat the industrial waste after producing the product. We call this model the no-role model. See Appendix A for model assumptions and results. (ii) There are generators and landfill sites; this is the two-role model. Appendix B contains assumptions and results for this model. (iii) There are generators, intermediate treatment facilities, and landfill sites; this is the three-role model.

In the following, we delineate the assumptions of three systems in the three-role model: the baseline system, the actor responsibility system, and the producer responsibility system. The reason that we consider the baseline system, which has no sanctions, is to facilitate examination and comparison of the effects of two sanction types on the evolution of cooperation in linear division of labor.

Baseline system in the three-role model

We consider that there are three roles: the generator group, the intermediate treatment facility (ITF) group, and landfill site (LS) group. The player is the firm. A player in the generator group, called a generator, plays a generator's role. One in the ITF group, called an ITF, plays an ITF's role. One in the LS group, called an LS, plays an LS's role. Each group has an infinite number of players.

The generator is either a cooperator or a defector. The cooperator commits industrial waste to the ITF, and the defectors dump the waste illegally. The generator's benefit from production is b. If the generator is a cooperator, the commission cost is $-x_1$ ($b > x_1 > 0$). Hereafter, the cooperators and defectors in the generator group are termed g-cooperators and g-defectors, respectively.

The ITF obtains the commission cost of the g-cooperator, x_1, as his/her benefit. Then, the ITF has to choose either cooperation or defection in each of two stages. S/he can choose either cooperation or defection in the first stage. Cooperation in the first stage (cooperation-1) indicates that s/he treats the industrial wastes brought from the generator by paying an intermediate treatment cost, c_{mid}. The example of cooperation-1 is breaking waste into pieces, treating it chemically, and rendering it harmless. Defection in the first stage (defection-1) means that the ITF does not treat the waste. After the ITF makes the decision in the first stage, s/he chooses either cooperation or defection in the second stage. Cooperation in the second stage (cooperation-2) means committing the industrial waste to a landfill site, and defection in the second stage (defection-2) means illegal dumping. Let the C-C player, the C-D player, the D-C player and the D-D player be defined as the ITF choosing cooperation-1 and cooperation-2, one choosing cooperation 1 and defection 2, one choosing defection-1 and cooperation-2, and one choosing defection-1 and defection-2, respectively The C-C player pays the commission cost, $-x_2$. The commission cost of the D-C player is $-x_2'$. We assume $x_2' \geq x_2$, because the D-C player does not treat industrial waste at all, and the LS pays a greater cost for treating the waste than the waste from the C-C player. The C-D or D-D player does not pay any commission cost.

The LS can harness the commission cost of ITF (x_2 or x_2') as his/her profit. The LS can be either a cooperator or a defector. Defectors dump the waste illegally and do not pay any cost for treatment. The cooperator buries the waste in the landfill that the LS possesses, paying a treatment cost (c_t or c_t'; $x_1 > c_t$, c_t'). If the ITF has treated the waste, the treatment cost is c_t. If not, the treatment cost is c_t'. The cooperator incurs a greater cost in burying non-treated waste than treated waste because non-treated waste is larger or more dangerous than treated waste. Therefore we assume that $c_t' \geq c_t > 0$. Hereafter, cooperators and defectors in the LS group are termed ls-cooperators and ls-defectors, respectively.

The g-defectors, a C-D and D-D players or ls-defectors illegally dump industrial waste in places such as rivers, seas, mountains, forests, and they do damage to the environment in the form of water pollution, soil pollution, and other types of pollution. Consequently, the population size of animals and plants will decrease in the future. As a result, all players equally suffer from the damage. To prevent future environmental damage, the local administrative organ mandates all players to pay an environmental restoration fee. Illegal dumping by a g-defector damages the natural environment and g_0 is defined as the amount of industrial waste dumped by a g-defector. Illegal dumping by a C-D player damages the natural environment and g_1 is defined as the amount of industrial waste dumped by a C-D player. The amount of industrial wastes dumped by a D-D player is g_0 because the D-D player has not treated the industrial waste from the g-cooperator. We assume that $g_0 \geq g_1$, because treatment by the ITF can reduce the amount of waste. If the industrial waste has not been treated at all, the amount of waste dumped by an ls-defector is still g_0. If the industrial waste has been treated, the amount of waste dumped by an ls-defector is g_1. Let r be defined as the environmental restoration fee or damage per unit of waste. Therefore, rg_i is the restoration fee (i = 0 or 1) to restore the damaged environment. We consider that the local administrative organ determines that the generator group is forced to pay a fee s times as high as the ITF and the LS group ($s \geq 1$). If a player dumps industrial waste illegally, srg_i is imposed on a generator and rg_i is imposed on an ITF or a LS. As illegal dumping damages all players' utility or health, the problem of illegal dumping can be interpreted as a social dilemma problem. The parameters in the system are listed in Table 1.

The payoff matrix of generators when the LS is an ls-cooperator is:

$$A_1 = \begin{pmatrix} b - x_1 & b - x_1 - srg_1 & b - x_1 & b - x_1 - srg_0 \\ b - srg_0 & b - srg_0 & b - srg_0 & b - srg_0 \end{pmatrix} ,$$

in which the element a_{1j} in A_1 is the payoff of g-cooperators committing the industrial waste to the ITF whose type is j (j = 1−4). The ITF's strategy 1, 2, 3, and 4 correspond to a C-C player, a C-D player, a D-C player, and a D-D player, respectively. The element a_{2j} is the payoff of g-defectors (j = 1−4). The payoff matrix of generators when the LS is an ls-defector is:

$$A_2 = \begin{pmatrix} b - x_1 - srg_1 & b - x_1 - srg_1 & b - x_1 - srg_0 & b - x_1 - srg_0 \\ b - srg_0 & b - srg_0 & b - srg_0 & b - srg_0 \end{pmatrix} ,$$

in which the element a_{1j} in A_2 is the payoff of cooperators of the generator committing the industrial waste to the ITF whose type is j (j = 1−4). The element a_{2j} in A_2 is the payoff of defectors in the generator (j = 1−4).

The payoff matrix of the ITF interacting with the ls-cooperator is C_1, and that of the ITF interacting with the ls-defector is C_2. They present:

$$C_1 = \begin{pmatrix} x_1 - c_{mid} - x_2 & -rg_0 \\ x_1 - c_{mid} - rg_1 & -rg_0 \\ x_1 - x_2' & -rg_0 \\ x_1 - rg_0 & -rg_0 \end{pmatrix}, \qquad C_2 = \begin{pmatrix} x_1 - c_{mid} - x_2 - rg_1 & -rg_0 \\ x_1 - c_{mid} - rg_1 & -rg_0 \\ x_1 - x_2' - rg_0 & -rg_0 \\ x_1 - rg_0 & -rg_0 \end{pmatrix},$$

in which the (i, 1) element in C_1 and C_2 is the payoff of ITF's strategy i interacting with a g-cooperator and the (i, 2) element in C_1 and C_2 is the payoff of ITF's strategy i interacting with a g-defector.

The payoff matrices of landfill sites when the generator chooses cooperation (committing the waste to ITF) and defection (illegal dumping) are B_1 and B_2, respectively, which presents;

$$B_1 = \begin{pmatrix} x_2 - c_t & -rg_1 & x_2' - c_t' & -rg_0 \\ x_2 - rg_1 & -rg_1 & x_2' - rg_0 & -rg_0 \end{pmatrix}, \qquad B_2 = \begin{pmatrix} -rg_0 & -rg_0 & -rg_0 & -rg_0 \\ -rg_0 & -rg_0 & -rg_0 & -rg_0 \end{pmatrix},$$

in which the (1, j) element in B_1 and B_2 is the payoff of the ls-cooperator interacting with ITF's strategy j and the (2, j) element in B_1 and B_2 is the payoff of the ls-defector interacting with ITF's strategy j.

Here we assume that each group size is infinite. One generator is chosen randomly from the generator group and interacts with one ITF chosen randomly from the ITF group, following the model assumptions. Then, the ITF interacts with one LS chosen randomly from the LS group, following the model assumptions. We assume an absence of intra-group interaction. Therefore we can apply the replicator equation of an asymmetric game to our model, and the time-differential equations can be described as:

$$\frac{du_1}{dt} = v_1 u_1 \left[\left(A_1 \vec{z} \right)_1 - \vec{u} A_1 \vec{z} \right] + \left(1 - v_1 \right) u_1 \left[\left(A_2 \vec{z} \right)_1 - \vec{u} A_2 \vec{z} \right] \quad , \text{(1a)}$$

$$\frac{dz_i}{dt} = v_1 z_i \left[\left(C_1 \vec{u} \right)_i - \vec{z} C_1 \vec{u} \right] + \left(1 - v_1 \right) z_i \left[\left(C_2 \vec{u} \right)_i - \vec{z} C_2 \vec{u} \right] \quad (i = 1\text{–}3) \quad , \text{(1b)}$$

$$\frac{dv_1}{dt} = u_1 v_1 \left[\left(B_1 \vec{z} \right)_1 - \vec{v} B_1 \vec{z} \right] + \left(1 - u_1 \right) v_1 \left[\left(B_2 \vec{z} \right)_1 - \vec{v} B_2 \vec{z} \right] \quad , \text{(1c)}$$

in which let u_1 be the frequencies of the g-cooperators in the generator group; u_2, the frequencies of the g-defectors ($u_1 + u_2 = 1$; $u_1, u_2 \geq 0$). Let z_i be the frequency of players with the ITF's strategy i ($i = 1–4$; $z_1 + z_2 + z_3 + z_4 = 1$; $z_1, z_2, z_3, z_4 \geq 0$). Let v_1 be the frequencies of the ls-cooperators in the landfill site group; v_2, the frequencies of the ls-defectors in the landfill site group ($v_1 + v_2 = 1$; $v_1, v_2 \geq 0$). We assume that $\vec{u} = (u_1 \quad u_2)^t$, $\vec{z} = (z_1 \quad z_2 \quad z_3 \quad z_4)^t$, and $\vec{v} = (v_1 \quad v_2)^t$.

Actor responsibility system in the three-role model

If the local administrative organ successfully monitors and detects the illegal dumping and the illegal dumper, the local administrative organ punishes the dumper and then forces the dumper to pay a fine, f. Let d be the probability of being monitored and detected by the local administrative organ. We call this sanction the actor responsibility system. The parameters in the system are listed in Table 1.

The local administrative organ has difficulty in monitoring perfectly and detecting the illegal dumping and the illegal dumper because the illegal dumper dumps the waste in inconspicuous places such as deep in the mountains, destroying evidence. As a result, perfect-monitoring is very costly and *d* is very low. While, the fine *f* is very expensive. For example, *f* can be one hundred million yen which is roughly equivalent to one million US dollar.

The expected value of the fine which the dumper has to pay for, *df*, is added to the baseline system, and then the payoff matrices in eq. (1) are replaced by:

$$A_1 = \begin{pmatrix} b-x_1 & b-x_1-srg_1 & b-x_1 & b-x_1-srg_0 \\ b-srg_0-df & b-srg_0-df & b-srg_0-df & b-srg_0-df \end{pmatrix},$$

$$A_2 = \begin{pmatrix} b-x_1-srg_1 & b-x_1-srg_1 & b-x_1-srg_0 & b-x_1-srg_0 \\ b-srg_0-df & b-srg_0-df & b-srg_0-df & b-srg_0-df \end{pmatrix},$$

$$C_1 = \begin{pmatrix} x_1-c_{mid}-x_2 & -rg_0 \\ x_1-c_{mid}-rg_1-df & -rg_0 \\ x_1-x_2' & -rg_0 \\ x_1-rg_0-df & -rg_0 \end{pmatrix}, \quad C_2 = \begin{pmatrix} x_1-c_{mid}-x_2-rg_1 & -rg_0 \\ x_1-c_{mid}-rg_1-df & -rg_0 \\ x_1-x_2'-rg_0 & -rg_0 \\ x_1-rg_0-df & -rg_0 \end{pmatrix},$$

$$B_1 = \begin{pmatrix} x_2-c_t & -rg_1 & x_2'-c_t' & -rg_0 \\ x_2-rg_1-df & -rg_1 & x_2'-rg_0-df & -rg_0 \end{pmatrix}, \text{ and}$$

$$B_2 = \begin{pmatrix} -rg_0 & -rg_0 & -rg_0 & -rg_0 \\ -rg_0 & -rg_0 & -rg_0 & -rg_0 \end{pmatrix}.$$

Producer responsibility system in the three-role model

Herein, the local administrative organ prepares the manifest, which all industries have to fill in. Then after the producer or the generator fill the manifest, it is handed to the ITF. After the ITF fills the manifest, it is hand to the LS. Then, the LS hands it back to the ITF, which also hands it back to the generator. Next, the generator hands it to the local administrative organ. If the generator fails to hand it back to the local administrative organ, the local administrative organ punishes the generator and s/he has to pay for a fine, f_1.

Following are the reasons why the generator cannot hand the manifest back to the local administrative organ. (i) The generator is a g-defector, and then s/he cannot hand the manifest to the ITF because there is no transaction between him/her and the ITF. Let p_2 be the probability that the g-defector does not hand the manifest to the local administrative organ. The probability, $1-p_2$, means that the g-defector hands the fictitious manifest to the local administrative organ. (ii) The ITF is a C-D or D-D player and the generator does not receive the manifest from the ITF. Let p_3 be the probability that the C-D or D-D player does not hand the manifest back to the generator. The probability, $1-p_3$, means that the C-D or D-D player hands the fictitious manifest to the generator. (iii) The LS is an ls-defector and does not hand the manifest back to the ITF. As a result, the generator does not receive the manifest. Let p_4 be the probability that the ls-defector does not hand the manifest back to the ITF. The probability, $1-p_4$, means that the ls-defector hands the fictitious manifest to the ITF. For simplicity, we assume that the local administrative organ does not distinguish the honest manifest from the fictitious one.

We also consider that the g-cooperator always hands the manifest back to the local administrative organ, and that the cooperator in the ITF or LS group accidentally fails to hand the manifest. (i) Let q_3 ($1-q_3$) be the probability that the C-C or D-C player does not (does) hand the manifest back to the generator. (ii) Let q_4 ($1-q_4$) be the probability that the ls-cooperator does not (does) hand the manifest back to the ITF.

We can calculate the probabilities that the g-cooperator does not hand the manifest back to the local administrative organ. (i) $q_4 + (1- q_4)q_3$ is the probability that the g-cooperator does not receive the manifest when there is a transaction with a C-C or D-C player and the ls-cooperator. (ii) $p_4 + (1- p_4)q_3$ is the probability that the g-cooperator does not receive the manifest when there is a transaction with a C-C or D-C player and the ls-defector. (iii) p_3 is the probability that the g-cooperator does not receive the manifest from the C-D or D-D player when there is a transaction between them. If (i)−(iii) occur, the local administrative organ punishes the g-cooperator, who has to pay a fine, f_1. The parameters in the system are listed in Table 1.

The expected value of the fine which the generator has to pay is added to the baseline system, and then the payoff matrices in eq. (1) are replaced by:

$$A_1 = \begin{pmatrix} b - x_1 - F_1 & b - x_1 - srg_1 - f_1 p_3 & b - x_1 - F_1 & b - x_1 - srg_0 - f_1 p_3 \\ b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 \end{pmatrix},$$

in which $F_1 = f_1(q_4 + (1 - q_4)q_3)$,

$$A_2 = \begin{pmatrix} b - x_1 - srg_1 - F_2 & b - x_1 - srg_1 - f_1 p_3 & b - x_1 - srg_0 - F_2 & b - x_1 - srg_0 - f_1 p_3 \\ b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 & b - srg_0 - f_1 p_2 \end{pmatrix},$$

in which $F_2 = f_1(p_4 + (1 - p_4)q_3)$,

$$C_1 = \begin{pmatrix} x_1 - c_{mid} - x_2 & -rg_0 \\ x_1 - c_{mid} - rg_1 & -rg_0 \\ x_1 - x_2' & -rg_0 \\ x_1 - rg_0 & -rg_0 \end{pmatrix}, \qquad C_2 = \begin{pmatrix} x_1 - c_{mid} - x_2 - rg_1 & -rg_0 \\ x_1 - c_{mid} - rg_1 & -rg_0 \\ x_1 - x_2' - rg_0 & -rg_0 \\ x_1 - rg_0 & -rg_0 \end{pmatrix},$$

$$B_1 = \begin{pmatrix} x_2 - c_t & -rg_1 & x_2' - c_t' & -rg_0 \\ x_2 - rg_1 & -rg_1 & x_2' - rg_0 & -rg_0 \end{pmatrix}$$, and

$$B_2 = \begin{pmatrix} -rg_0 & -rg_0 & -rg_0 & -rg_0 \\ -rg_0 & -rg_0 & -rg_0 & -rg_0 \end{pmatrix} .$$

Next we calculate the equilibrium points in three systems and conduct the local stability analysis. We also did Monte Carlo simulations and then we obtain almost the same results to our following analysis of the replicator dynamics.

Results

We analyze eqs. (1) and obtain the equilibrium points in three systems, which are categorized into seven types:

$$(u_1, z_1, z_2, z_3, v) = (1, 1, 0, 0, 1), (1, 0, 0, 1, 1), (0, *, *, *, *), (1, 0, 1, 0, *),$$

$$(1, 0, 0, 0, *), (1, 0, 0, 1, 0), (1, 1, 0, 0, 0),$$

in which the asterisk "*" means any value between 0 and 1. We also obtain one unstable inner equilibrium point in each system (see Appendix C). These seven equilibrium points indicate that all members adopt the same strategy in each industry in equilibrium, and then (u_1, z_1, z_2, z_3, v) can be represented by (G, ITF, LS) which is the strategy of the G, the ITF and the LS, respectively. For example, (1, 1, 0, 0, 1) is equivalent to (C, C-C, C), in which the first column denotes the generator is a g-cooperator, the second that the ITF is a C-C player, and the third that the LS is an ls-cooperator. Table 2 shows the seven equilibrium points and the corresponding strategies. Out of seven equilibrium points, two points, (1, 1, 0, 0, 1) and (1, 0, 0, 1, 1) are interpreted as cooperation evolving in the division of labor (see Table 2). (0, *, *,

*, *) is interpreted as illegal dumping by G; two points, (1, 0, 1, 0, *) and (1, 0, 0, 0, *), illegal dumping by ITF; two points, (1, 0, 0, 1, 0), (1, 1, 0, 0, 0), illegal dumping by LS.

We conducted the local stability analysis of the seven points. Appendix C shows the condition of the local stability of each point. In (1, 1, 0, 0, 1) = (C, C-C, C) and (1, 0, 0, 1, 1) = (C, D-C, C), the actor responsibility system promotes the local stability if *df* is large enough to influence the dynamics (see Tables C1 and C2). Table C1 and C2 also show that, if (1, 1, 0, 0, 1) = (C, C-C, C) is locally stable, (1, 0, 0, 1, 1) = (C, D-C, C) is not locally stable, and vice versa. It is natural to assume that p_2 is high, q_3 is low, and q_4 is low, and then $q_3 - p_2 + q_4(1 - q_3)$ can be negative. This indicates that the producer responsibility system also favors the evolution of cooperation in the division of labor more than the baseline system (see Tables C1 and C2). In (0, *, *, *, *) = (D, *, *), both sanction systems discourage the stability and then both disfavor illegal dumping by the generator more than the baseline system. In (1, 0, 1, 0, *) = (C, C-D, *), the effect of the sanction systems on the stability of illegal dumping by ITF depends on the parameter values (see Table C4). As $x_1 < 0$ does not hold due to our assumption that $x_1 > 0$ (see Table C5), the equilibrium point, (1, 0, 0, 0, *) = (C, D-D, *), is always unstable in the baseline system. While, both sanction systems promote the stability of this equilibrium point (see Table C5). Therefore both sanction systems promote illegal dumping by ITF. In (1, 0, 0, 1, 0) = (C, D-C, D) and (1, 1, 0, 0, 0) = (C, C-C, D), as three inequalities, $x_1 < 0$, $x_2 < 0$ and $x_2' < 0$, do not hold because of our assumption that $x_1 > 0$, $x_2 > 0$ and $x_2' > 0$, this equilibrium point is always unstable in both the baseline system and the producer responsibility system. While, the actor responsibility system promotes illegal dumping by LS (see Tables C6 and C7).

Table 2 summarizes the stability conditions of the seven equilibrium points. (i) Both sanction systems promote the evolution of cooperation in the division of labor, and inhibit illegal dumping by generators. (ii) There are two types of illegal ITF dumping: ITF is either a C-D player or a D-D player in equilibrium. Illegal dumping by a D-D player does not occur in the absence of a sanction system because the equilibrium point, (C, D-D, *), is not stable. However, both sanction systems promote illegal dumping by a D-D player. (iii) Illegal dumping by LS does not occur in the absence of a sanction system and in the producer responsibility system, while the actor responsibility system promotes illegal dumping by LS.

In the producer responsibility system, when any defector never hands back the fake manifest ($p_i = 1$, $i = 2, 3, 4$) and any cooperator always hands back the manifest ($q_i = 0$, $i = 3, 4$), the sanction promotes (C, C-C, C) and (C, D-C, C), and the sanction inhibits (D, *, *). However, the sanction does not influence the other four types of equilibrium point resulting in illegal dumping, as per the baseline system.

<u>Comparison with the results of Kitakaji and Ohnuma (2014)</u>

Following Kitakaji and Ohnuma (2014) and their personal communication, model parameters can be estimated. “s” is used as the currency in their experiment and 1s is equivalent to one million yen or ten thousand US dollars. In their experiment, when the generator produces 100 tons of industrial waste, b = 65s, x_1 = 45s, c_{mid} = 10s, x_2 = 20s, x_2' = 40s, c_t = 10s, c_t' = 20s, g_0 = 100 tons, g_1 = 50 tons, r = 0.1s/ton, s = 4 in which “*s*” is not the same as the currency “s” here, f = 30s, d = 0.0065, and f_1 = 100s or 50s (Table 1). For simplicity, $p_2 = p_3 = p_4 = 1$ and $q_3 = q_4 = 0$.

Using these parameter values, we obtain that (D, *, *) is locally stable, and other equilibrium points are locally unstable not only in the baseline model but also in both sanction systems.

Now we investigate which sanction system promotes the evolution of cooperation based on parameters used in Kitakaji and Ohnuma (2014). The local administrative organ has difficulty in monitoring perfectly and detecting the illegal dumping and the illegal dumper because the illegal dumper dumps waste in inconspicuous places such as deep in the mountains, destroying evidence. As a result, perfect-monitoring is very costly. The experimental results from Kitakaji and Ohnuma (2014) indicate that the probability of being monitored and detected by the local administrative organ (d) is very low and they estimated d at 0.0065. In reality, d is considered to be much smaller than their experimental observation because monitoring and detecting illegal dumping is not as difficult in the experimental space as in real space. Even though the fine f is very expensive, the value df is very small relative to other parameters. Then, the actor responsibility system converges near the baseline model (see Table C); the actor responsibility system hardly promotes the evolution of cooperation. If monitoring and detecting illegal dumping were straightforward and df were not neglected, (C, C-C, C) would be stable when $df > 20$ and other parameters are as per Kitakaji and Ohnuma (2014).

Here we consider the producer responsibility system. The value r can be controlled by the local administrative organ and Ishiwata (2002) suggests that x_1 is much higher than x_2 (Ishiwata, 2002). We examine in which value of r and x_1 the producer responsibility system promotes the evolution of cooperation based on the local stability conditions in Table C. Our calculations show that, if both inequalities, $r > 0.4$ and $400r < x_1 < 400r + f_1p_2$, hold, (C, C-C, C) is locally unstable in the baseline model, and locally stable in the producer responsibility system (see Figures 2 and 3). Figure 2 shows the initial frequencies influence the dynamics when $r = 0.5$, $x_1 = 250$, which satisfy $r > 0.4$ and $400r < x_1 < 400r + f_1p_2$, and other parameters are as per Kitakaji and Ohnuma (2014). Numerical simulations show that (u, z_1, v) almost converges to (1, 1, 1) even in the low initial value of u when the initial values of z_1 and v are high (Figure 2(A) and (B)). When the initial value of u is higher, the area where (u, z_1, v) almost converges to (1, 1, 1) is wider (see Figure 2(A) and (B)). In Figure 3(A), the value of u increases and converges to one. When the initial value of v is 0.75, the value of u decreases and then increases until u becomes one (Figure 3(B)). When the initial value of v is 0.7, the value of u immediately converges to zero. Figure 3(B) indicates that the frequency of g-cooperators (u) decreases at the beginning and then increases before the dynamics finally converge to (C, C-C, C) even though the producer responsibility system is effective.

Kitakaji and Ohnuma (2014) showed that sanctioning increased the number of defectors. While, our analysis only shows that (D, *, *) is stable in the baseline model and two sanction systems using their parameters, and does not show that sanctions increase the number of defectors. Instead, we can indicate that, if those authors use the parameters we estimated in the previous paragraph, the producer responsibility system may promote cooperation. However, our model assumptions do not perfectly match the experimental design in Kitakaji and Ohnuma (2014), and the behavior of examinees in their experiment was not identical to those of the players in our case: some examinees formed a coalition, the examinees monitored each other in the same role, or examinees divided the waste into pieces and committed them to some examinees. Therefore, our suggestion is tentative, it may not work well in their experimental design.

Comparison with empirical reality

We can compare these equilibrium points with Japanese field survey data, captured by our coauthors, Ohnuma and Katakaji. (1, 0, 0, 1, 1) = (C, D-C, C) applies in Hokkaido, the second largest of Japan's principal islands. The land which the LS has is abundant and real estate is very inexpensive relative to Tokyo. As a result, LS has a huge and inexpensive land and does not mind landfilling the waste which ITF does not treat properly prior to it being landfilled by LS. By contrast, (1, 0, 1, 0, *) = (C, C-D, *) applies in the Kanto area including the Tokyo metropolitan area. There is little room in this area and real estate is very expensive. Thus the land of the LS is very limited. As a result, LS cannot accept the offer from the ITF. ITF has no choice but to dump the waste. Before illegal dumping, ITF treats the waste properly following the reasons; (i) if extracting valuable things such as precious metals from the waste successfully through the treatment process, ITF can transact them and obtain benefits in the metropolitan area in which there are big markets for reuse. It is easy for ITF to access the market and then the transportation cost is low for ITF. (ii) the amount of treated waste is smaller than that of untreated one, and the smaller waste is not easily found if dumped. We denote this as the Kanto type.

According to data from the Ministry of the Environment in Japan, in 1998 (2015) 60% (56.6%) of illegal dumping resulted from generators, 10% (2.1%) from unlicensed dealers, and 8% (4.9%) from licensed dealers. The data shows that the ratio of generators' illegal dumping is much higher than others. If we consider that *df* is too small to influence the dynamics and $p_2 = p_3 = p_4 = 1$ and $q_3 = q_4 = 0$,illegal dumping by generators occurs, but illegal dumping by firms in other roles does not occur, except the Kanto type. Our theoretical model is supported by empirical data suggesting that generators exhibit a high propensity to engage in illegal dumping activities.

Data from the Ministry of the Environment in Japan also shows that, directly following the introduction of the producer responsibility system in 1990, illegal dumping first increased and then decreased. The dynamics illustrated in Figure 3(B) may explain this empirical phenomenon.

Comparison between the three-role and two-role models

We presented results in the previous section whereby the number of industry types was reduced from five to three types. We also constructed a simpler model called the two-role model, constituted by the generator and the landfill site (see Appendix B for specification equations and analytical results). Appendix B shows that there are three equilibrium points in the three systems: $(u_1, v_1) = (1, 1), (1, 0), (0, *)$. $(u_1, v_1) = (1, 1)$ corresponds to $(u_1, z_1, z_2, z_3, v) = (1, 1, 0, 0, 1)$ and $(1, 0, 0, 1, 1)$; $(u_1, v_1) = (1, 0)$, $(u_1, z_1, z_2, z_3, v) = (1, 0, 0, 1, 0)$ and $(1, 1, 0, 0, 0)$; $(u_1, v_1) = (0, *)$ corresponds to $(u_1, z_1, z_2, z_3, v) = (0, *, *, *, *)$. However, other equilibrium points in the three-role model, such as (1, 0, 1, 0, *) which is interpreted as the Kanto type, cannot be described by the results of the two-role model. Therefore, we conclude that the three-role model has greater empirical credibility than the two-role model.

Discussion and conclusion

We investigate the effect of sanctions on the evolution of cooperation in linear division of labor. As an example, we institute the replicator dynamics in the context of an industrial waste illegal dumping game proposed by Ohnuma and Kitakaji (2007). We introduce two sanction systems, the actor responsibility system and the producer responsibility system, and then compare each of these two systems with a baseline model devoid of sanctions. Our main conclusion is that both sanction systems seem to promote the evolution of cooperation and inhibit illegal dumping by generators. However, where fines do not influence evolutionary dynamics because monitoring is ineffective, the actor responsibility system no longer promotes the evolution of cooperation.

Monitoring violators is arduous not only in the case of illegal industrial waste but in other contexts too, such as illegal logging and overfishing. The industrial waste treatment process in Japan embodies linear division of labor; and the sanction system which does not require monitoring violators can be put into practice rather than the sanction system with monitoring. Our analysis also shows that the producer responsibility system, which does not require monitoring, promotes the evolution of cooperation and inhibits illegal dumping more than the actor responsibility system. If logging or fishing in some areas are configured according to linear division of labor, sanction systems like the producer responsibility system may work to inhibit illegal logging or overfishing.

In the producer responsibility system, the generator is sanctioned if the manifest is not handed to the local administrative organ. There is another possible sanction system derived from the producer responsibility system; not a generator but an intermediate treatment facility or a landfill site is punished when the manifest is not handed to the local administrative organ. However, generators are expected to choose illegal dumping more if intermediate treatment facilities or landfill sites are punished, and then the amount of illegal dumping is larger. It is because g-defectors do not need to pay not only the cost of cooperation but also the fine. To confirm our guess, we will analyze the model with the new sanction system as our future study.

Sanctions are only one of a number of potential interventions. Following are other potential solutions which may promote the evolution of cooperation. If we can configure a group who chooses good players in all roles, the members maximize their efforts towards goal attainment, and produce a final good product. In this case, how to choose group members and/or to choose a group is crucial. Nakamaru and Yokoyama (2014) examined how choosing a new member, or choosing a good group influence the evolution of group cooperation when players are peers or on an equal footing in a group consisting of more than three members. We may apply Nakamaru and Yokoyama (2014) to the linear division of labor context. However, if players in role B_i do not interact with players in role B_j and then cannot evaluate the quality of players in B_j correctly ($j > i + 1$), the group fails to choose optimal players and the evolution of cooperation in linear division of labor does not occur. Or, without choosing group members, we can consider that a player in role B_i chooses a player with good reputation in role B_{i+1} and then the player in role B_{i+1} can accept the player's offer if s/he has a good reputation. In this case, we guess that the evolution of cooperation in linear division of labor is promoted and we will analyze the model as our future work.

Linear division of labor (Figure 1B) has a similar structure to the centipede game (Rosenthal, 1981). In the standard setting, two players play the centipede game alternately and repeatedly. The player can choose "Right" or "Down" on his/her turn. If the player chooses Down, the game is over and then both players can receive the payoff. If the player chooses Right, the game is continued and the other player can choose either of the two options. This is repeated. It is assumed that (i) The payoff of player A who chooses Down in the *i*-th stage, $s_{A,i}$, is higher than that of player A who chooses Right when the other player B chooses Down in the i+1-th stage, $s_{A,i+1}$, and (ii) $s_{A,i+2}$ is higher than $s_{A,i,}$, and (iii) If two players always choose Right, they achieve the final stage. The payoff in the final stage is higher than in any previous stage. There is one study, Smead (2008), from the viewpoint of evolutionary game theory; this showed that a finite population promotes the evolution of cooperation in the quasi-centipede game, where two players choose their tactics simultaneously and the payoff is symmetric. It is often assumed that two players repeatedly and alternately play in the centipede game. While, in our assumptions, players in different roles play the game in different stages and the same players do not play the game repeatedly. As a result, we can describe the model through the replicator dynamics for asymmetric games.

We only assumed players or organizations in three roles, and did not assume a local administrative organ player. If we introduce such a player, which also maximizes payoff in evolutionary game theory, the player may prefer the producer responsibility system to the actor responsibility system because the latter is very costly. Further exploration thereof remains for future research.

In this paper, we assumed the generators, the intermediate treatment facilities, and the landfill sites as the three-role model in linear division of labor. We can consider another combination of the three roles, which are the generators, the haulers, and the landfill sites.

The model assumption in the new three roles is different from our current model, and we will investigate which three-role model promotes the evolution of cooperation in linear division of labor as our future work. Then, we will challenge to analyze the five-role model. It is complicated to analyze the equations and the analytical results may be complicated. To understand the complicated results and obtain the general conclusion, we will compare the results in the five-role model with our current results and results in the new three-role model.

In empirical contexts, there are many types of division of labor besides the linear variant; the structure of the division of labor may influence the efficiency of the institution or the social goal. The division of labor has long been studied in sociology and organization theory, especially industrial ecology (Durkheim, 1893; Frosch and Gallopoulos, 1989; Milgrom and Roberts, 1992; Axtell et al., 2001; Giddens, 2006). We studied the division of labor from the viewpoint of evolutionary game theory and then showed that a special sanction such as the producer responsibility system can promote cooperation among organizations with linear division of labor. Network structure among roles is also key from the viewpoint of evolutionary game theory. In this paper, we assumed the simplest network: the linear type network or one-dimensional lattice structure. The network structures among organization or roles in other institutions are more complicated than what we dealt with here. We can proffer a new possibility that organizations can be studied from the viewpoint of the evolution of cooperation and complex networks by means of replicator dynamics.

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Appendix A

Model assumptions and results in the no-role model:

In the baseline system, we consider the simplest and, thus, unrealistic scenario: generators can dispose of industrial waste and then the division of labor does not exist. Each of generators is either a g-cooperator or a g-defector in the population. We assume that the benefit from a generator's production is b and the treatment cost is $-c$ ($b > c > 0$). Let g be defined as the amount of industrial waste dumped by a g-defector and let r be defined as the environmental restoration expense or damage per unit of waste (g, $r > 0$). The frequency of g-cooperators and g-defectors is u and $1-u$, respectively. The environmental load of each generator is $-gr(1-u)$. Therefore, the payoffs of a g-cooperator ($E_C(u)$) and a g-defector ($E_D(u)$) are $b - c - gr(1-u)$ and $b - gr(1-u)$, respectively. The assumption satisfies the tragedy of the commons when $c/r < g$ which is derived from the situation that the payoff of a cooperator when all generators are cooperators is higher than that of a defector when all generators are defectors ($E_C(1) > E_D(0)$).

The replicator equation can be written as;

$$\frac{d}{dt}u = u(1-u)\left(E_C(u) - E_D(u)\right) \quad . \qquad \text{(A1)}$$

As $E_C(u) - E_D(u) = -c < 0$, $u = 0$ is stable regardless of any parameters.

We introduce the actor responsibility system to the baseline system in the no-role model. In this system, the local administrative organ imposes a fine (f) on the g-defector if the g-defector is monitored and detected. Let d be the probability of monitoring and detecting illegal dumping ($d > 0$). The probability d is very small because it is almost impossible for the local administration organ to detect illegal dumping. The payoff of a defector, $E_D(u)$, is $b - gr(1-u) - df$. Then, putting the payoff of the g-cooperators and the g-defectors into eq. (A1), we obtain that $u = 1$ is stable in $df > c$, and $u = 0$ is stable otherwise.

We introduce the producer responsibility system to the baseline system in the no-role model. It is assumed that a g-cooperator always submits the manifest. If a g-defector does not submit it, s/he has to pay a fine defined as f_1 (> 0). The probability of g-defectors not submitting a manifest is p; the probability of them submitting a fake manifest is $1-p$. The probability p is high because g-defectors cannot submit unless they concoct a fake manifest. The local administration organ may accept the fake manifest because it is almost impossible for the local administration organ to monitor illegal dumping to distinguish between honest and fake manifests. Therefore, the payoff of a defector is $b - gr(1-u) - pf_1$. Then, putting the payoffs of the g-cooperators and the g-defectors into eq. (A1), we obtain that $u = 1$ is stable in $pf_1 > c$, and $u = 0$ is stable otherwise.

Comparison of the baseline system with the actor responsibility system and the proucer responsibility system indicates that a fine imposed by a local administrator increases the incentive to choose legal treatment. Basically, the results show there is no difference between the actor responsibility system and the producer responsibility system in the no-role model. If we assume $df < pf_1$ because d is very small and p is high, the producer responsibility system promotes the evolution of cooperation more than the actor responsibility system.

Appendix B

Model assumptions and results in the two-role model:

We consider that there are two types of industries: generators and landfill sites. The group size of each industry is infinite. Each generator is either a g-cooperator or a g-defector. The generator's benefit from production is b. When a g-cooperator commits industrial waste to the landfill site, the commission cost is $-x_1$ ($b > x_1 > 0$). The landfill site can capture the commission cost as his/her profit, x_1. The landfill site is either an ls-cooperator or an ls-defector. The ls-cooperator pays a treatment cost, c_t ($x_1 > c_t > 0$). The definition of the environmental load caused by g-defectors and ls-defectors is the same as per the three-role model. Let g_0 be defined as the amount of industrial waste dumped by a g-defector. We consider that the local administrative organ determines that the generator group be forced to pay an expense s times as high as the LS group ($s \geq 1$). Here let r be defined as the environmental restoration expense or damage per unit of waste. If a player dumps industrial waste illegally, srg_0 is imposed on a generator and rg_0 is imposed on an LS.

The payoff of a generator and a landfill site are presented by the payoff matrices A and B as follows:

$$A = \begin{bmatrix} b - x_1 & b - x_1 - g_0 sr \\ b - g_0 sr & b - g_0 sr \end{bmatrix} \text{ and } B = \begin{bmatrix} x_1 - c_t & -g_0 r \\ x_1 - g_0 r & -g_0 r \end{bmatrix} \quad . \qquad \text{(B1)}$$

Let u_1 and u_2 be the frequencies of g-cooperators and g-defectors in the generator group ($u_1 + u_2 = 1$), and v_1 and v_2 be the frequencies of ls-cooperators and ls-defectors in the landfill site group ($v_1 + v_2 = 1$). We assume that one player is randomly chosen from the generator's group and the other is chosen from the landfill site's group, and then the two interact together, following our assumptions. We also assume that there are no dealings between generators or between landfill sites. We can apply this model to replicator dynamics of asymmetric games (Hofbauer and Sigmund, 1998):

$$\frac{d}{dt}u_i = u_i\left((Av)_i - u \cdot Av\right) \text{ and } \frac{d}{dt}v_i = v_i\left((Bu)_i - v \cdot Bu\right) \qquad (i = 1 \text{ or } 2), \qquad \text{(B2)}$$

in which $u = (u_1, u_2)^t$ and $v = (v_1, v_2)^t$. The equation below can be derived from eq. (B2):

$$\frac{d}{dt}u_1 = u_1(1 - u_1)(g_0 srv_1 - x_1) \quad , \qquad \text{(B3a)}$$

$$\frac{d}{dt}v_1 = u_1 v_1(1 - v_1)(g_0 r - c_t) \quad . \qquad \text{(B3b)}$$

The equilibrium points are: $(u_1, v_1) = (1, 1), (1, 0), (0, v_1^*)$, in which v_1^* means any value between 0 and 1. When $x_1/(sr) < g_0$ and $c_t/r < g_0$, (1, 1) is locally stable. (1, 0) is locally stable when $x_1 < 0$ and $c_t/r > g_0$. (0, *) is unstable if $g_0 rsv_1^* < x_1$, as the other eigenvalue is zero.

When the actor responsibility system is introduced, the payoff matrices are:

$$A = \begin{bmatrix} b-x_1 & b-x_1-g_0sr \\ b-g_0sr-df & b-g_0sr-df \end{bmatrix} \text{ and } B = \begin{bmatrix} x_1-c_t & -g_0r_2 \\ x_1-g_0r_2-df & -g_0r_2 \end{bmatrix} , \quad \text{(B4)}$$

in which the local administrative organ punishes the dumper and then forces the dumper to pay a fine, f if the local administrative organ successfully monitors and detects the illegal dumping and the illegal dumper. Let d be the probability of being detected by the local administrative organ. The matrices in eq.(B2) are replaced with those in eq.(B4), thus:

$$\frac{d}{dt}u_1 = u_1(1-u_1)(g_0srv_1+df-x_2) , \quad \text{(B5)}$$
$$\frac{d}{dt}v_1 = u_1v_1(1-v_1)(g_0r+df-c_t) .$$

We obtain the equilibrium points: (1, 0), (1, 1), (0, v_1*). The local stability conditions of (1, 1) are: $(c_t - df)/r < g_0$ and $(x_1 - df)/(sr) < g_0$. Those of (1, 0) are: $(c_t - df)/r > g_0$ and $x_1 - df < 0$. (0, v_1*) is unstable if $g_0rsv_1^* + df < x_1$ as the other eigenvalue is zero.

When the producer responsibility system is introduced, the payoff matrices are:

$$A = \begin{bmatrix} b-x_1-f_1q_1 & b-x_1-g_0sr-f_1p_1 \\ b-g_0sr-f_1p_2 & b-g_0sr-f_1p_2 \end{bmatrix} \text{ and } B = \begin{bmatrix} x_1-c_t & -g_0r \\ x_1-g_0r & -g_0r \end{bmatrix} , \quad \text{(B6)}$$

in which let p_1 be the probability that the ls-defector does not hand the manifest back to the g-cooperator. $1-p_1$ is the probability that the ls-defector hands in a fictitious manifest. Let p_2 be the probability that the g-defector does not hand the manifest back to the local administrative organ. $1-p_2$ is the probability that the g-defector hands in a fictitious manifest.

Let q_1 be the probability that the ls-cooperator does not hand the manifest back to the g-cooperator. The matrices in eq. (B2) are replaced with those in eq.(B6) and then the equations are:

$$\frac{d}{dt}u_1 = u_1(1-u_1)\left(\left(g_0 sr + f_1 p_1 - f_1 q_1\right)v_1 - \left(x_1 + f_1(p_1 - p_2)\right)\right),$$

$$\frac{d}{dt}v_1 = u_1 v_1 (1-v_1)(g_0 r - c_t).$$

We obtain the equilibrium points: $(u_1, v_1) = (1, 0), (1, 1), (0, v_1^*)$. The local stability conditions of (1, 1) are: $c_t/r < g_0$ and $(x_1 - f_1(p_2 - q_1))/(sr) < g_0$. Those of (1, 0) are: $c_t/r > g_0$ and $x_1 + f_1(p_1 - p_2) < 0$. $(0, v_1^*)$ is unstable if $g_0 rsv_1^* + f_1(-p_1 + p_2) + f_1 v_1^*(-q_1 + p_1) < x_1$ as the other eigenvalue is zero.

Appendix C

Eq. (1) shows that there is one inner equilibrium point besides seven types of equilibrium points in either the baseline system or the producer responsibility system:

$$(u_1, z_1, z_2, z_3, v) = (1, \frac{rg_0 - c_t'}{r(g_0 - g_1) + c_t - c_t'}, 0, \frac{-rg_1 + c_t}{r(g_0 - g_1) + c_t - c_t'}, 1 - \frac{c_{mid} + x_2 - x_2'}{r(g_0 - g_1)}).$$

One inner equilibrium point in the actor responsibility system is:

$$(u_1, z_1, z_2, z_3, v) = (1, \frac{df + rg_0 - c_t'}{r(g_0 - g_1) + c_t - c_t'}, 0, \frac{-df - rg_1 + c_t}{r(g_0 - g_1) + c_t - c_t'}, 1 - \frac{c_{mid} + x_2 - x_2'}{r(g_0 - g_1)}).$$

The numerical calculations show they are unstable.

The stability condition of seven equilibrium points in the baseline model, the actor responsibility system model, and the producer responsibility system model (see Table 2) are calculated using eq. (1); we calculate the eigenvalues for each equilibrium point, and they are real numbers. Therefore, when all eigenvalues for one equilibrium point are negative, the equilibrium is locally stable. Table C shows the condition that all eigenvalues are negative, which is the local stability condition of each equilibrium point. The local stability conditions of (1, 1, 0, 0, 1) are listed in Table C1; (1, 0, 0, 1, 1), Table C2; (0, *, *, *, *), Table C3; (1, 0, 1, 0, *), Table C4; (1, 0, 0, 0, *), Table C5; (1, 0, 0, 1, 0), Table C6; (1, 1, 0, 0, 0), Table C7.

Figure legends

Figure 1

The division of labor:

(A) shows general division of labor. Players in each role A_i (i = 1, …, n) work to achieve their goal. (B) shows linear division of labor. Players in role B_i interact with those in role B_{i+1} (i < n). Then, players in the final role B_n achieve the goal.

Figure 2

The initial frequency dependency of the dynamics:

These graphs present the effect of the initial frequencies on the dynamics. The horizontal axis is the initial frequency of C-C players (z_1) and the vertical is the initial frequency of ls-cooperators (v). The initial values of z_2 and z_3 are (1 − (the initial value of z_1))/3. The black point signifies that the dynamics converge to (C, C-C, C); the gray point signifies that the dynamics converge to (D, *, *). (A) The initial frequency of g-cooperators (u) is 0.95, and we executed numerical simulations through 500 time steps (the interval between time steps is 0.01 time). (B) The initial frequency of g-cooperators is 0.05, and we executed numerical simulations through 1,000 time steps. In both (A) and (B), $r = 0.5$, $x_1 = 250$, and other values are as per Kitakaji and Ohnuma (2014).

Figure 3

The time-change of the frequencies:

These graphs present the numerical simulation outcomes. The horizontal axis is time, and the vertical is the frequencies of u, z_1, z_2, z_3, and v. The thick black line is u; the thick gray, z_1; the thick dotted gray line, z_2; the thin dotted gray line, z_3; the thin black line, v. (A) the initial values of (u_1, z_1, z_2, z_3, v) are (0.5, 0.8, 0.066, 0.066, 0.95); (B), (0.5, 0.8, 0.066, 0.066, 0.75); (C), (0.5, 0.8, 0.066, 0.066, 0.7). In (A) − (C), $r = 0.5$, $x_1 = 250$, and other values are as per Kitakaji and Ohnuma (2014).

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4. Figure
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Figure 1

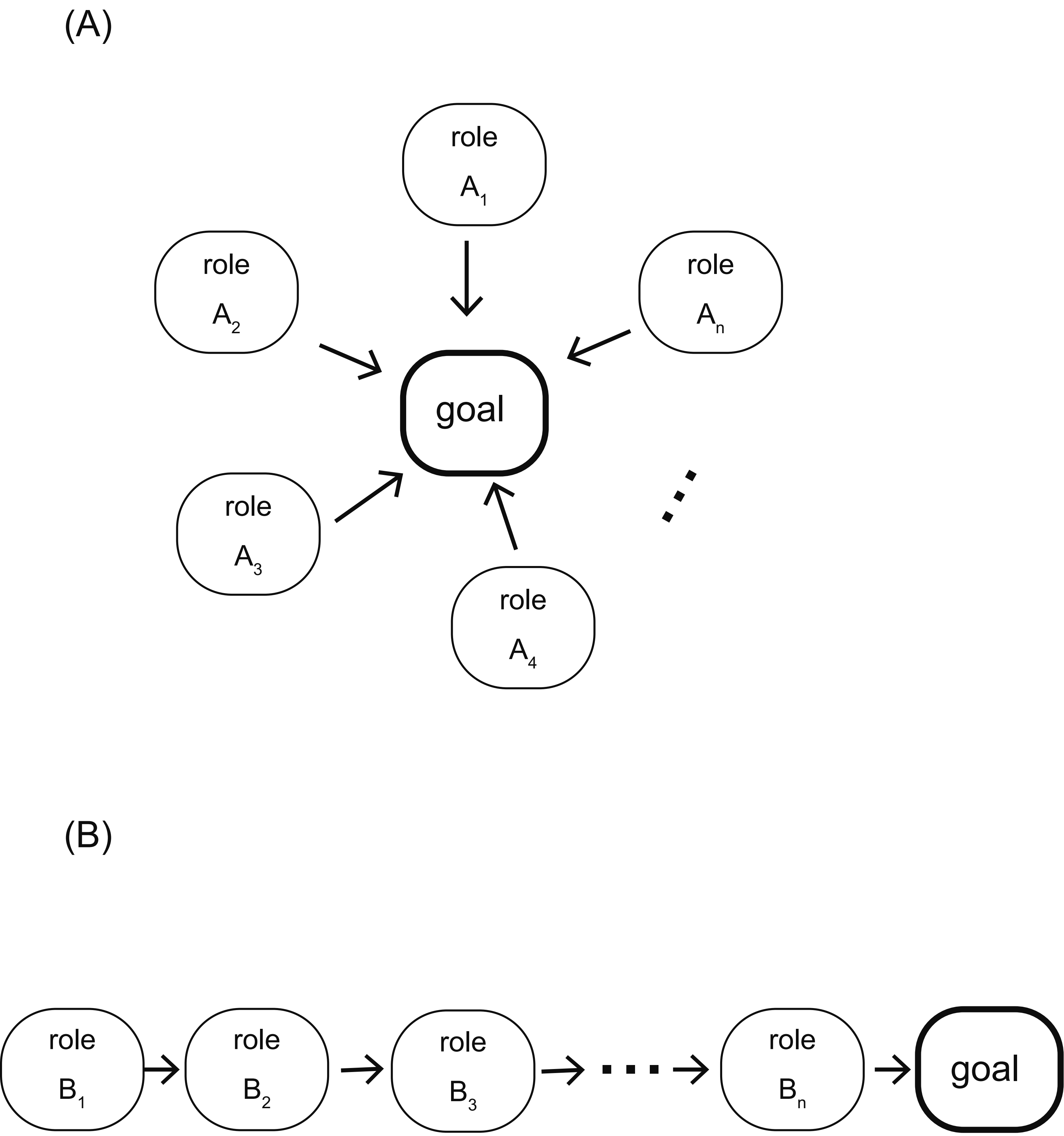
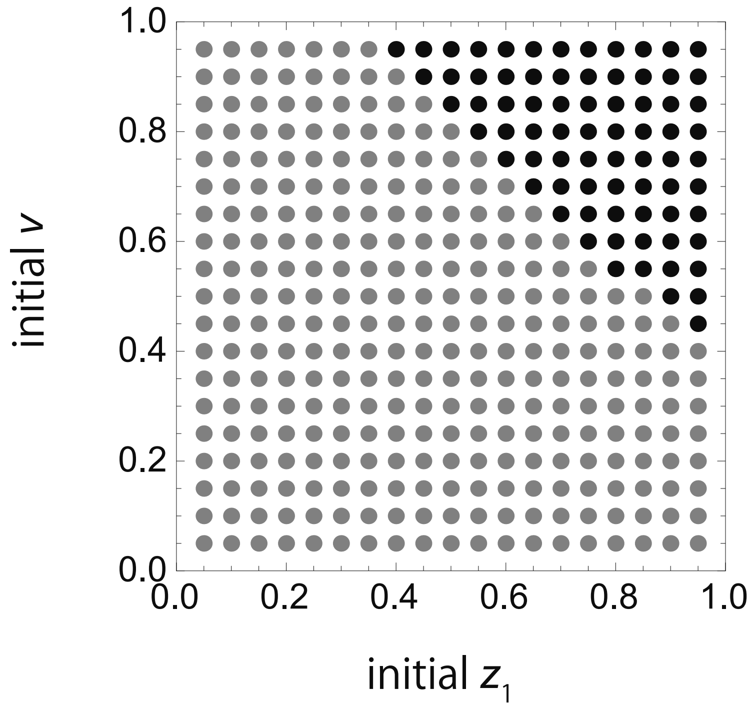


Figure 2

(A)


1.0
0.8
0.6
0.4
0.2
0.0
initial v
0.0
0.2
0.4
0.6
0.8
1.0
initial z1

(B)

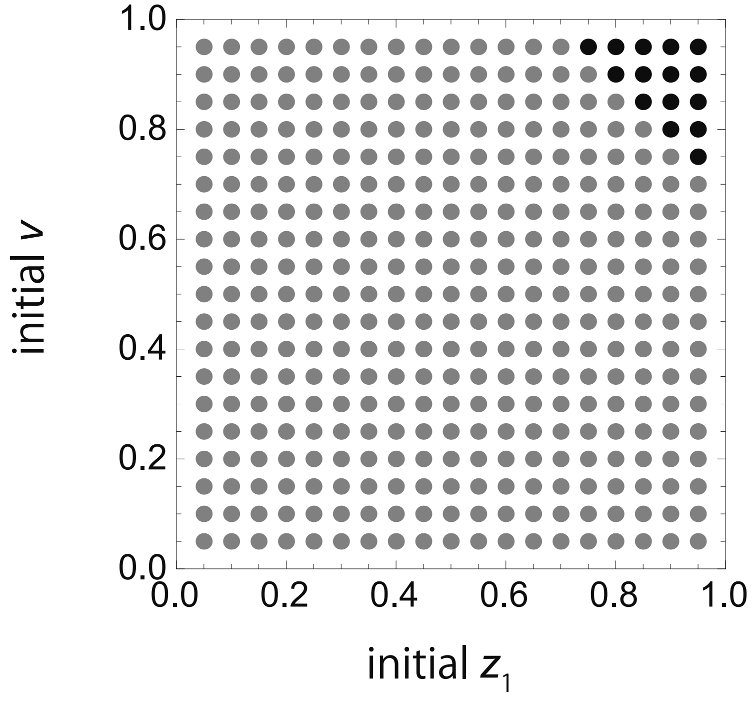
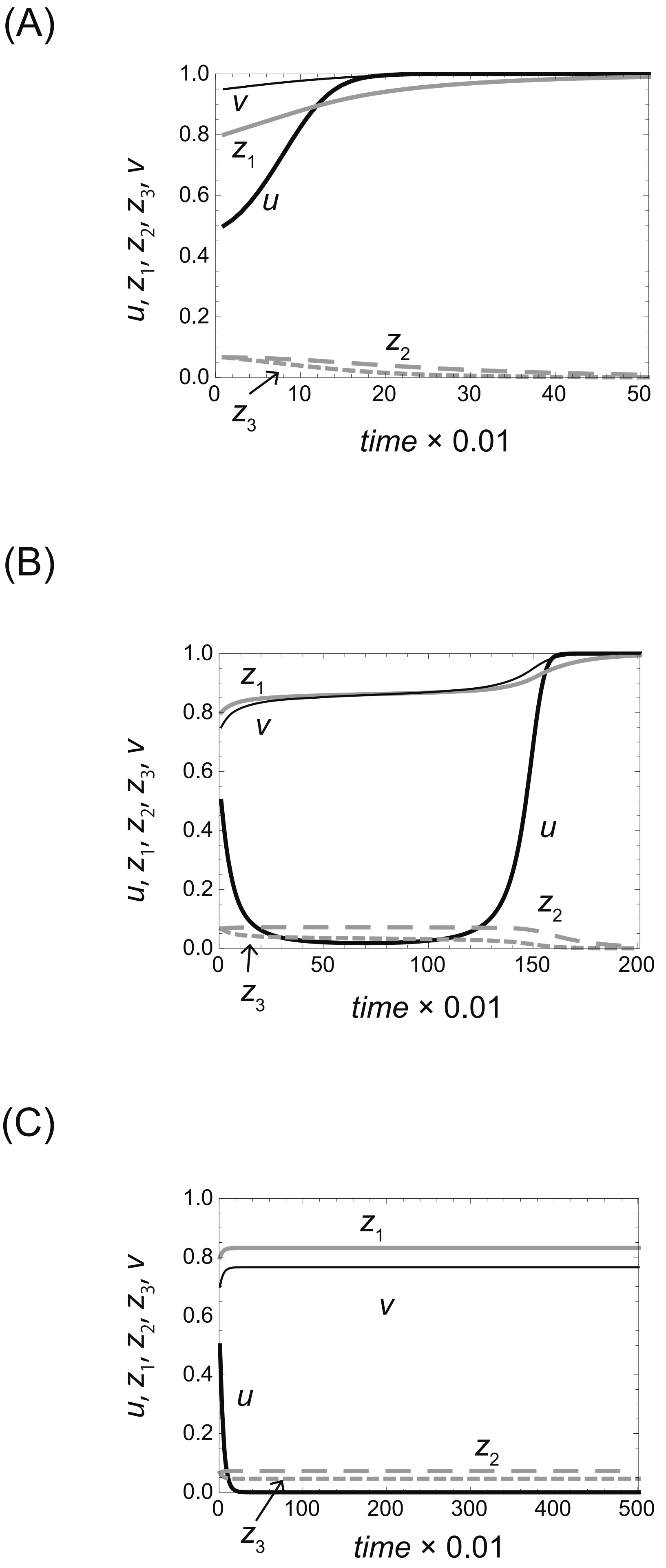

1.0
0.8
0.6
0.4
0.2
0.0
initial v
0.0
0.2
0.4
0.6
0.8
1.0
initial z1

Figure 3


(A)
1.0
0.8
0.6
0.4
0.2
0.0
u, z_1, z_2, z_3, v
v
z_1
u
z_2
z_3
0
10
20
30
40
50
time × 0.01
(B)
1.0
0.8
0.6
0.4
0.2
0.0
u, z_1, z_2, z_3, v
z_1
v
u
z_2
z_3
0
50
100
150
200
time × 0.01
(C)
1.0
0.8
0.6
0.4
0.2
0.0
u, z_1, z_2, z_3, v
z_1
v
u
z_2
z_3
0
100
200
300
400
500
time × 0.01

5. Tables

Table 1 Parameters in the three systems in the three-role model

The leftmost column presents the parameters in the model, and the middle column presents the explanations. The rightmost column indicates the estimated values based on Kitakaji and Ohnuma (2014) when the industrial waste is 100 tons (see the result section for more information).

b	the generator's benefit from production	65s
x_1	the commission cost of the g-cooperator	45s
c_{mid}	the intermediate treatment cost of the C-C or C-D player	10s
x_2	the commission cost paid by the C-C player	20s
x_2'	the commission cost paid by the D-C player	40s
c_t	the treatment cost of an ls-cooperator when the ITF has treated the waste	10s
c_t'	the treatment cost of an ls-cooperator when the ITF has not treated the waste	20s
g_0	the amount of industrial waste when a g-defector or a D-D player dumps the waste or a ls-defector dumps the waste from a D-C player	100 tons
g_1	the amount of industrial waste when a C-D player dumps the waste or when a ls-defector dumps the waste from a C-C player	50 tons
r	the environmental restoration expense or damage per unit of waste dumped illegally	0.1
s	the generator group is forced to pay for the environmental restoration expense s times more than the ITF and LS group	4
f	the fine in the actor responsibility system model	30s
d	the probability of being detected by the local government in the actor responsibility system model	0.0065
f_1	the fine in the producer responsibility system model	100s/50s
p_2	the probability that the g-defector does not hand the manifest to the local government in the producer responsibility system model	
	$1-p_2$, the probability that the g-defector hands the fictitious manifest	
p_3	the probability that the C-D or D-D player does not hand the manifest back to the generator in the producer responsibility system model	
	$1-p_3$, the probability that the C-D or D-D player hands the fictitious manifest	
p_4	the probability that the ls-defector does not hand the manifest back to the ITF in the producer responsibility system model	
	$1-p_4$, the probability that the ls-defector hands the fictitious manifest	
q_3	the probability that the C-C or D-C player does not hand the manifest back to the generator in the producer responsibility system model (very low q_3)	
q_4	the probability that the ls-cooperator does not hand the manifest back to the ITF in the producer responsibility system model (very low q_4)	

Table 2

The local stability of seven equilibrium points in each of three systems of the three-role model.

C in the left-most column denotes cooperation; D, defection. The right-most column shows the interpretation of each equilibrium point. “stable/unstable” means that some parameters cause the equilibrium point to be locally stable and others make it unstable. “Unstable” means that the equilibrium point is always locally unstable.

Equilibrium points (u_1, z_1, z_2, z_3, v) = (G, ITF, LS)	Baseline system	Actor responsibility system	Producer responsibility system	Interpretation
(1, 1, 0, 0, 1) = (C, C-C, C)	stable/unstable	stable/unstable	stable/unstable	cooperation in the division of labor
(1, 0, 0, 1, 1) = (C, D-C, C)	stable/unstable	stable/unstable	stable/unstable	
(0, *, *, *, *) = (D, *, *)	stable/unstable	stable/unstable	stable/unstable	illegal dumping of G
(1, 0, 1, 0, *) = (C, C-D, *)	stable/unstable	stable/unstable	stable/unstable	illegal dumping of ITF
(1, 0, 0, 0, *) = (C, D-D, *)	unstable	stable/unstable	stable/unstable	
(1, 0, 0, 1, 0) = (C, D-C, D)	unstable	stable/unstable	unstable	illegal dumping of LS
(1, 1, 0, 0, 0) = (C, C-C, D)	unstable	stable/unstable	unstable	

Table C1 The local stability conditions of (1, 1, 0, 0, 1) = (C, C-C, C) in each of three systems.

Baseline model	Actor responsibility system	Producer responsibility system
$x_1 < srg_0$	$x_1 - df < srg_0$	$x_1 + f_1(q_3 - p_2 + q_4(1 - q_3)) < srg_0$
$c_{mid} + x_2 - x_2' < 0$	$c_{mid} + x_2 - x_2' < 0$	$c_{mid} + x_2 - x_2' < 0$
$c_{mid} + x_2 - rg_0 < 0$	$c_{mid} + x_2 - rg_0 - df < 0$	$c_{mid} + x_2 - rg_0 < 0$
$x_2 - rg_1 < 0$	$x_2 - rg_1 - df < 0$	$x_2 - rg_1 < 0$
$c_t - rg_1 < 0$	$c_t - rg_1 - df < 0$	$c_t - rg_1 < 0$

Table C2 The local stability conditions of (1, 0, 0, 1, 1) = (C, D-C, C) in each of three systems.

Baseline model	Actor responsibility system	Producer responsibility system
$x_1 < srg_0$	$x_1 - df < srg_0$	$x_1 + f_1(q_3 - p_2 + q_4(1 - q_3)) < srg_0$
$c_{mid} + x_2 - x_2' > 0$	$c_{mid} + x_2 - x_2' > 0$	$c_{mid} + x_2 - x_2' > 0$
$c_{mid} - x_2' + rg_1 > 0$	$c_{mid} - x_2' + rg_1 + df > 0$	$c_{mid} - x_2' - rg_1 > 0$
$x_2' - rg_0 < 0$	$x_2' - rg_0 - df < 0$	$x_2' - rg_0 < 0$
$c_t' - rg_0 < 0$	$c_t' - rg_0 - df < 0$	$c_t' - rg_0 < 0$

Table C3 The local stability conditions of (0, *, *, *, *) = (D, *, *) in each of three systems.

Baseline model	Actor responsibility system	Producer responsibility system
$sr(g_0 - g_1)(z_1^*+z_2^*) + v^*sr(g_1z_1^* + g_0z_3^*) - x_1 < 0$	$sr(g_0 - g_1)(z_1^*+z_2^*) + v^*sr(g_1z_1^* + g_0z_3^*) - x_1 + df < 0$	$sr(g_0 - g_1)(z_1^*+z_2^*) + v^*sr(g_1z_1^* + g_0z_3^*) - x_1 - f_1(z_1^*+z_3^*)\{p_4 + (1 - p_4)q_3 - p_3 + v^*(q_4 - p_4)(1 - q_3)\} - f_1(p_3 - p_2) < 0$

Table C4 The local stability conditions of (1, 0, 1, 0, *) = (C, C-D, *) in each of three systems.

Baseline model	Actor responsibility system	Producer responsibility system
$x_1 - sr(g_0 - g_1) < 0$	$x_1 - sr(g_0 - g_1) - df < 0$	$x_1 - sr(g_0 - g_1) + f_1(p_3 - p_2) < 0$
$r(g_0 - g_1) > c_{mid}$	$r(g_0 - g_1) > c_{mid}$	$r(g_0 - g_1) > c_{mid}$
$c_{mid} + r(g_1 - g_0) + rg_0v^* - x_2' < 0$	$c_{mid} + r(g_1 - g_0) + rg_0v^* - x_2' + df < 0$	$c_{mid} + r(g_1 - g_0) + rg_0v^* - x_2' < 0$
$- x_2 + rg_1 v^* < 0$	$- x_2 + rg_1 v^* + df < 0$	$- x_2 + rg_1 v^* < 0$

Table C5 The local stability conditions of (1, 0, 0, 0, *) = (C, D-D, *) in each of three systems.

Baseline model	Actor responsibility system	Producer responsibility system
$x_1 < 0$	$x_1 - df < 0$	$x_1 + f_1(p_3 - p_2) < 0$
$r(g_0 - g_1) < c_{mid}$	$r(g_0 - g_1) < c_{mid}$	$r(g_0 - g_1) < c_{mid}$
$c_{mid} + x_2 + r(g_1 - g_0) - rg_1v^* > 0$	$c_{mid} + x_2 + r(g_1 - g_0) - rg_1v^* - df > 0$	$c_{mid} + x_2 + r(g_1 - g_0) - rg_1v^* > 0$
$- x_2' + rg_0 v^* < 0$	$- x_2' + rg_0 v^* + df < 0$	$- x_2' + rg_0 v^* < 0$

Table C6 The local stability conditions of (1, 0, 0, 1, 0) = (C, D-C, D) in each of three systems.

Baseline model	Actor responsibility system	Producer responsibility system
$x_1 < 0$	$x_1 - df < 0$	$x_1 - f_1\{-p_2 + p_4 + (1 - p_4)q_3\} < 0$
$x_2' < 0$	$x_2' - df < 0$	$x_2' < 0$
$x_2' - c_{mid} + r(g_0 - g_1) - x_2 < 0$	$x_2' - c_{mid} + r(g_0 - g_1) - x_2 < 0$	$x_2' - c_{mid} + r(g_0 - g_1) - x_2 < 0$
$x_2' - c_{mid} + r(g_0 - g_1) < 0$	$x_2' - c_{mid} + r(g_0 - g_1) - df < 0$	$x_2' - c_{mid} + r(g_0 - g_1) < 0$
$- c_t' + rg_0 < 0$	$- c_t' + rg_0 + df < 0$	$- c_t' + rg_0 < 0$

Table C7 The local stability conditions of (1, 1, 0, 0, 0) = (C, C-C, D) in each of three systems.

Baseline model	Actor responsibility system	Producer responsibility system
$x_1 - sr(g_0 - g_1) < 0$	$x_1 - sr(g_0 - g_1) - df < 0$	$x_1 - sr(g_0 - g_1) + f_1\{-p_2 + p_4 + (1 - p_4)q_3\} < 0$
$c_{mid} + x_2 - r(g_0 - g_1) < 0$	$c_{mid} + x_2 - r(g_0 - g_1) - df < 0$	$c_{mid} + x_2 - r(g_0 - g_1) < 0$
$x_2 < 0$	$x_2 - df < 0$	$x_2 < 0$
$c_{mid} - r(g_0 - g_1) + x_2 - x_2' < 0$	$c_{mid} - r(g_0 - g_1) + x_2 - x_2' < 0$	$c_{mid} - r(g_0 - g_1) + x_2 - x_2' < 0$
$- c_t' + rg_1 < 0$	$- c_t' + rg_1 + df < 0$	$- c_t' + rg_1 < 0$