Academic Commercialism and the Changing Nature of Academic Cooperation: Indirect Reciprocity, Rewarding, and Abstention *

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ABSTRACT

As the trend of academic commercialism has emphasized for-profit activities in academia, its potential incompatibility with traditional norms of open science seems to undermine cooperative climate in academia. Drawing on the evolutionary game theoretical approach, this study examines how this trend affects academic cooperation, focusing on the practice of the sharing of scientific resources (e.g., research tools and data). In an ideal state of open science, academics are supposed to share scientific resources in a gratis manner, modeled as indirect reciprocity. Extending Donation Game with reputation mechanism, this study shows that the commercialized regime could compromise cooperative climate and gradually increases defectors. Furthermore, as the trend advances, academics could become more demanding of direct reward in exchange for cooperation, and eventually, they become reluctant to participate in cooperation at all. Thus, the current regime could weaken the norms of open science, the foundation of academic science. Further analyses suggest that some interventions (e.g., centralized rewarding, resource repositories) could mitigate these problems.

KEYWORDS

Science Policy, Open science, Indirect reciprocity, Resource sharing, Life Sciences, Scientific Norms, Academic entrepreneurship, Academic Commercialism, Material Transfer, Social Exchange, Evolutionary game theory

CLASSIFICATION CODE

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1. INTRODUCTION

The progress of science is critically underpinned by the norms of open science, where scientific achievement is regarded as the property of science communities but not of individual academics, and thus, academics are expected to cooperate with one another unconditionally (Dasgupta and David, 1994; Merton, 1973). The practice of altruistic cooperation is crucial because individual academics tend to be highly specialized and often need cooperation from strangers (Shibayama and Baba, 2011; Walsh et al., 2007). While the underlying norms of open science seem generally complied with, growing concern has been expressed that they are in jeopardy under the changing regime of contemporary science (Dasgupta and David, 1994; Nelson, 2004).

Over the last decades, science and technology (S&T) policies have emphasized the role of academic science in innovation system and encouraged universities and individual academics to engage in commercial activities and collaboration with industry (Etzkowitz, 1998; Fatas-Villafranca et al., 2009; Grimaldi et al., 2011; Jaffe et al., 2007; Poyago-Theotoky et al., 2002; Toole and Czarnitzki, 2007). In this trend called *academic commercialism*, more academics have been engaging in university start-ups, technology transfer to industry, patent applications, and other for-profit activities, and infrastructure for those activities has been implemented (e.g., technology transfer office) (Etzkowitz, 1998; Grimaldi et al., 2011; AUTM 2007; OECD 2003). While this trend might be facilitating innovation originating from academia and benefit society, it has simultaneously developed self-regarding climate rather than other-regarding, which has spurred debate over its potential conflict with the norms of open science (Dasgupta and David, 1994; Kleinman and Vallas, 2001; Murray and Stern, 2007; Nelson, 2004; Shane and Somaya, 2007). In fact, numerous empirical studies have shown that academics participating in businesses and industry collaboration (*commercial academics*, hereafter) tend to be less cooperative and withhold their knowledge and resources in favor of personal profit (e.g., Campbell et al., 2000; Walsh et al., 2007).

Although most prior literature has focused on non-cooperative behavior of commercial academics, more gravely, the trend of academic commercialism could deter cooperation even among non-commercial academics, who do not engage in any commercial activities, fundamentally compromising the norms of open science (Shibayama et al., 2012). Nevertheless, to my best knowledge, prior literature has not investigated the intertemporal change in cooperation behavior in the emerging regime, perhaps due to limited access to adequate data. To fill in the gap, this study offers a model of academic cooperation drawing on the framework of the evolution of cooperation (Axelrod and Hamilton, 1981; Nowak and Sigmund, 1998; Sigmund, 2010), whereby to predict the broad impact of academic commercialism on the norms and practice of academic cooperation. The model incorporates not only altruistic cooperation but also alternative forms of cooperation. Results suggest that even non-commercial academics become less willing both to offer cooperation and to ask for cooperation under the commercialized regime, and that unconditional cooperation is replaced by reward-based cooperation, where donors demand direct payment from recipients. This study also aims to evaluate the efficacy of some policy interventions as a means to mitigate such side effects of commercialism. In so doing, it attempts to offer implication for future empirical research and policy design.

2. ACADEMIC COOPERATION AS INDIRECT RECIPROCITY

Among various forms of academic cooperation, this study particularly focuses on resource sharing. Particularly in natural sciences, various types of scientific resources (e.g., cell lines, model organisms, chemical substances, reagents, software, and data) are shared. The practice of resource sharing allows academics to avoid redundant efforts, reproduce previous findings, and standardize research methods, substantially contributing to the progress of science (Walsh et al., 2007). It is a highly common practice and the compliance is fairly high; in life sciences, for example, on average, 3-5 requests are made every year, and requests for research tools and data are fulfilled more than 80% of the time (Blumenthal et al., 1997; Campbell et al., 2000; Shibayama and Baba, 2011; Walsh et al., 2007).

In an ideal state of open science, since academics share their resources in a gratis and unconditional manner, donors must bear the cost of giving (e.g., cost of preparing resources, etc.) while recipients, who may be a stranger, can gain substantial benefit (e.g., progress of their research). In general, such an altruistic behavior is vulnerable to free riders. Self-interested players would receive cooperation but refuse to give, presenting a typical situation of social dilemmas. The paradoxical fact that the human society offers numerous examples of altruistic cooperation (e.g., blood contribution, donation) has provoked extensive debate in economics as well as sociology and biology, and several mechanisms behind altruistic cooperation have been proposed (e.g., Blau, 1964; Bowles and Gintis, 2011; Nowak, 2012). Among others, Trivers

(1971) showed that a cooperative strategy (i.e., *tit-for-tat*) can be evolutionarily stable in repeated Prisoner's Dilemma Game. In this setting, the pair of players are fixed during the course of repeated games, so the form of cooperation is called *direct reciprocity*. Going beyond this restrictive player matching, Nowak and Sigmund (1998) developed a pioneering theory on *indirect reciprocity*, which is played by two randomly assigned players. In this setting, no two players are matched more than once. Thus, donors cannot be rewarded directly by their recipients but might be indirectly rewarded by someone else. To sustain this mechanism, indirect reciprocity draws on social information. Simply put, players attach bad reputation to free riders to avoid further cooperation with them. Thus, defection based on bad reputation works as a punishment. Subsequent literature has suggested that more proactive sanctions (e.g., rewarding and punishing) could also sustain altruistic cooperation though such sanctions may need mechanisms to sustain themselves (Fehr and Fischbacher, 2004; Sigmund et al., 2001). Another mechanism is *network reciprocity*, which emphasizes a spatial or network structure between players. Ohtsuki et al. (2006) suggest that a cooperative strategy can be sustained in structured networks, where players' interaction is not completely random.

These theories apply for academic cooperation to different extents. Direct reciprocity is widely observed as bilateral continual collaboration. Network reciprocity is also relevant since real cooperation does not occur randomly. Proactive sanctioning mechanisms may also be at work. For example, funding agencies require their fundees to share their resources for public use after project completion. If academics fail to follow the rule and if such an incident is reported, they could be stripped of their right to future funding. Many academic journals have similar guidelines. Still, the effectiveness of these punishment mechanisms is questioned for the practical difficulty of policing and punishing defectors. Among others, the model of this study is based on indirect reciprocity because altruistic cooperation even with strangers is pivotal in open science (Merton, 1973). In fact, Shibayama et al. (2012) show that only 30% of resource sharing occurs between previous collaborators. The principle of unconditional sharing is clearly articulated in various guidelines (NAS 2003). With this normative basis, non-cooperative behavior is generally despised. My interviewees mentioned that academics who encounter non-cooperative donors sometimes spread a negative word, which can lead not only direct victims of non-cooperative academics but also other academics in the community to avoid supporting them.

3. MODEL

First, this chapter formulates the model of unconditional resource sharing under ordinary circumstances, with which the following chapters analyze how academic commercialism could compromise the sharing practice. It follows a well-studied model of indirect reciprocity based on Donation Game (Nowak and Sigmund, 1998; Sigmund, 2010). From an infinitely large population of players, two players are randomly chosen as a donor and a recipient to engage in a one-shot game. Each player is endowed with a type, based on which a donor decides whether to cooperate with his recipient or defect her (i.e., deny cooperation). If the donor cooperates, he pays a cost, c, and the recipient receives a benefit, b ($> c$). If the donor defects, he pays no cost and the recipient receives no benefit. In reality, recipients gain some benefit by advancing their research thanks to shared resources, while donors have to bear some cost, which consists of direct cost for preparing the resources and indirect cost for foregoing competitive advantage that could have been maintained by denying sharing. In a one-shot Donation Game, indiscriminate defection, where no cooperation takes place, is a rational choice. However, cooperation can emerge in iterated games with the aid of reputation. To explain this, the first model employs three types (Table 1) following prior literature (Nowak and Sigmund, 1998; Sigmund, 2010). One extreme type is *RATL*, who is myopically rational and defects as a donor, representing free riders. The other extreme is *ALLC*, who indiscriminately cooperates as a donor. *RATL* dominates *ALLC* because *RATL* receives full cooperation from *ALLC* but does not bear the cooperation cost. To allow cooperation under the existence of *RATL*, I introduce *DISC*, a discriminate cooperator. A *DISC* donor cooperates with recipients with good reputation but defects those with bad reputation. For simplicity, this study uses dichotomous reputation, zero (*bad*) and one (*good*), and the reputation is formed on the basis of the last game in which a player participated as a donor. This study draws on a reputation rule consistent with the action of *DISC*; cooperation with good players and defection with bad players are regarded as good, while defection with good players and cooperation with bad players are regarded as bad (Table 2).[1]

The evolutionary dynamics of the three types is analyzed as follows. Let x_i denote the frequency of i-th type (1: *ALLC*, 2: *RATL*, 3: *DISC*), where $x_i \geq 0, \sum x_i = 1$. Donation Games are repeated for multiple rounds, where g_n denotes the frequency of good players at the n-th

[1] Ohtsuki and Iwasa (2004) identified several combinations of cooperation action and reputation rule that achieve stability and efficiency, and this study is based on one of them.

round in the whole population and $g_{i,n}$ denotes that among the *i*-th type ($g_n = \sum g_{i,n} x_i$). As an *ALLC* donor always cooperates, his reputation becomes good when encountering a good recipient and becomes bad when encountering a bad recipient; $g_{1,n} = g_{n-1}$. Since an *RATL* donor always defects, his reputation becomes bad when encountering a good recipient and becomes good when encountering a bad recipient; $g_{2,n} = 1 - g_{n-1}$. Since the action of *DISC* agrees with the reputation rule, *DISC* should always be good. However, reputation of other players may not always be available. Following Nowak and Sigmund (1998), this study introduces a parameter, $q \in [0,1]$, the probability that donors know the recipients' reputation. When the reputation is unknown, a *DISC* donor assumes that his recipient is bad.[2] With this setting, $g_{3,n} = 1 - (1-q)g_{n-1}$. The following analysis draws on the equilibrium reputation (Brandt and Sigmund, 2005) by solving these difference equations on the assumption that $g_n = g_{n-1} = g$ and $g_{i,n} = g_{i,n-1} = g_i$. The equilibrium frequency of good players is given by

$$g = \frac{x_2 + x_3}{2x_2 + (2-q)x_3}, g_1 = g, g_2 = 1 - g, \text{ and } g_3 = 1 - (1-q)g \ldots (1).$$

Based on this reputation, the payoff for the *i*-th type, P_i, is computed. As a donor, *ALLC* always bears cooperation cost ($-c$). As a recipient, *ALLC* gains cooperation benefit from an *ALLC* donor (bx_1). She receives cooperation from a *DISC* donor as long as she is good and her reputation is known ($bg_1 q x_3$). She never receives cooperation from an *RATL* donor. All taken together,

$$P_1 = -c + bx_1 + bg_1 q\, x_3 \ldots (2a).$$ [3]

RATL and *DISC* recipients receive cooperation in similar ways, while *RATL* donors never cooperate and *DISC* donors cooperate only with good recipients whose reputation is known (see payoff matrix in Appendix 1). Therefore,

$$P_2 = bx_1 + bg_2 q\, x_3 \ldots \text{(2b)}$$

$$P_3 = -cgq + bx_1 + bg_3 q x_3 \ldots (2c).$$

The evolutionary dynamics of the three types is computed with the continuous replicator dynamics (Hofbauer and Sigmund, 1998):

$$\dot{x}_i = x_i(P_i - \bar{P}) \ \ldots (3),$$

[2] The opposite assumption is plausible, where a *DISC* donor supposes its recipient as good when her reputation is unknown (Sigmund, 2010: Ch.4). Some interviewees suggested that they would not cooperate if no information is available about recipients.

[3] In the following computation, the number of iterated game rounds is ignored as it is irrelevant when the equilibrium reputation is used.

where $\bar{P} = \sum x_i P_i$ (the mean payoff) and $\dot{x_i} = \frac{dx_i}{dt}$. Based on (1) – (3), Figure 1 illustrates a numerical phase plot. It shows two evolutionarily stable equilibria, pure *RATL* and pure *DISC*, and two unstable equilibria, pure *ALLC* and a mix of *RATL* and *DISC*. If the reputation availability is sufficiently high (i.e., $q > \frac{c}{b}$), the phase space is split into two regions; the initial state below the separatrix leads to the pure *RATL* and that above it to the pure *DISC*. Thus, a certain frequency of *DISC* is necessary to eliminate *RATL* and maintain cooperation.

4. RESOURCE SHARING UNDER ACADEMIC COMMERCIALISM

4.1. Decreasing Cooperation

Based on the above model, this section examines the impact of commercialism on the cooperation behavior of non-commercial academics. To model the commercialized environment, this study introduces a player type, *COM*, corresponding to commercial academics with the following assumptions (Table 1). First, they earn certain commercial profit (e.g., licensing income) aside from the cooperation benefit. Second, they do not cooperate because cooperation compromises the commercial profit. They would rather sell their resources on the market than give them away for free. Thus, their behavior is the same as that of *RATL*. This is a simplification of the empirical findings that commercial academics tend to withhold their resources, acting like free riders (Blumenthal et al., 1997; Campbell et al., 2000; Walsh et al., 2007). I further assume that the transition between commercial and non-commercial academics should be less likely or occur more slowly than among non-commercial academics. In reality, starting commercial activities takes various kinds of initial time-consuming effort such as patenting, business planning, and fundraising; once starting a business, they would not abandon it immediately when it turns out unprofitable. Thus, the following analyses exogenously control the frequency of commercial academics and focus our attention on the evolutionary dynamics of non-commercial academics.[4] Hence, *COM* does not contribute to evolution.

First, I analyze the dynamics between *RATL* and *DISC* and see the impact of *COM*, where *ALLC* is neglected for simplicity as *ALLC* is dominated by both *RATL* and *DISC*. A modification of (2b) and (2c) gives the payoff for *i*-th type as follows:

$$P_2 = bg_2q\, x_3 \quad \dots (4a)$$

[4] The transition between non-commercial and commercial academics is not of the primary interest of this study, and it has been studied elsewhere (e.g., Stuart and Ding, 2006).

$$P_3 = -cgq + bg_3qx_3 \ldots (4b).$$

Let $x_0 \in [0,1)$ denote the frequency of *COM* and $z_i \in [0,1]$ the relative frequency of the i-th type among non-commercial players (i.e., $z_i = x_i/(1 - x_0)$). The dynamics of non-commercial types is described by $\dot{z}_i = z_i(P_i - \bar{P})$ where $\bar{P} = \sum z_i P_i$. To examine the impact of *COM*, I illustrate in Figure 2 the reputation, rate of receiving cooperation, payoff, and the phase diagram for *DISC* (blue) and *RATL* (red) with and without *COM* (solid and dashed, respectively). The invasion of *COM* improves the reputation of both types with a greater extent for *RATL* (Figure 2A). *RATL* gains in reputation because it always defects *COM*, which is likely to be bad. While cooperation requests from *DISC* recipients become more likely to be denied because of *COM*, those from *RATL* recipients are less affected thanks to their improved reputation (Figure 2B). This is directly reflected in the payoff for each type (Figure 2C). The intersection of the payoff curves is the unstable interior equilibrium, which corresponds to the z_3-intercept (denoted by z_3^*) in the phase diagram (Figure 2D). With a greater frequency of *DISC* than the equilibrium, *DISC* earns higher payoff than *RATL*, growing its frequency until it dominates the whole population. On the other hand, a smaller *DISC* frequency leads to pure *RATL*. Since the invasion of *COM* causes a rightward shift of the equilibrium, it enlarges the basin of attraction for *RATL*. Figure 2E illustrates the transition of this equilibrium with the whole range of *COM*, suggesting that a greater extent of *COM* creates a more favorable condition (larger basin of attraction) for *RATL*. Formally, $\frac{dz_3^*}{dx_0} > 0$ (the proof shown in Appendix 1A).[5]

In summary, the commercial environment with a greater number of commercial academics is more advantageous for defectors than for cooperators for two reasons. First, prevailing commercial academics, who tend not to share, directly decrease the cooperation benefit for cooperators. Second, commercial academics compromise the reputation mechanism. Academics gain reputation by cooperating with good academics or defecting bad academics. Increasing commercial academics, who tend to be non-cooperative and thus bad, gives defectors a greater chance of gaining in reputation. In other words, altruistic punishers and selfish defectors become less distinguishable once defection by commercial academics becomes

[5] In reality, the composition of each type in the population is unknown. From the fact that indirect reciprocity is widely observed, I assume that the frequency of *DISC* is greater than the unstable equilibrium and the dynamics moves toward the cooperative regime when *COM* does not exist. With this assumption, this mathematical argument implies that a sufficient frequency of *COM* shifts the equilibrium so that the dynamics starts to move to the opposite direction, toward the non-cooperative regime. Even when the frequency of *COM* is low, it can be shown that the shift of the equilibrium slows down the velocity of the dynamics.

common. Therefore, with an increasing number of commercial participants, even non-commercial academics are more inclined toward defection.

Proposition 1: With a greater prevalence of academic commercialism, academics become less willing to engage in unconditional cooperation.

4.2. Private Rewarding

In the face of malfunctioning indirect reciprocity, recipients who need others' resources have a few alternatives. For one, they can privately offer donors some kind of reward such as coauthorship or acknowledgments in their publications, a promise of future support, and the payment of money (Shibayama and Baba, 2011). This is acceptable for rational donors in that the risk of non-reciprocity is mitigated through negotiation. As long as the reward is larger than the cooperation cost, reward-based cooperation is more profitable than defection. Rewarding is known as one mechanism to sustain cooperation along with punishment (Rand et al., 2009; Sigmund et al., 2001). To incorporate this possibility, I extend the Donation Game with the option of private rewarding, where a recipient who receives cooperation may return a part of her benefit to the donor. For this, I introduce a type, *PAY*, that favors reward-based cooperation (Table 1).[6] *PAY* is also rational; *PAY* donors cooperate only for their own benefit (i.e., when reward is expected and it exceeds the cooperation cost), and *PAY* recipients give reward only when necessary (i.e., when reward is demanded and it is smaller than the cooperation benefit). Let β and γ denote the values of reward for donors and recipients. Reward-based cooperation yields payoff of $\beta - c$ and $b - \gamma$ for donors and recipients, respectively. I assume $\beta \in [c, b]$ and $\gamma \in [0, \beta]$ so that both sides do not make a loss from this transaction, and that rewarding of itself does not decrease the total payoff.

While indirect reciprocity has the limitation of incomplete reputation, reward-based cooperation has its own limitation. In resource sharing in academia, unlike economic transaction, money is almost never used and a universal currency is not available (Shibayama and Baba, 2011). Thus, as in barter exchange, two players have to simultaneously find each other's resources valuable, but this may be difficult in academia, where individuals specialize in a

[6] This setting is similar to Trust Game (Berg et al., 1995) but is peculiar in that donors can know whether recipients are willing to reward or not through negotiation.

narrow expertise and recipients may possess nothing valuable for donors. Coauthorship in expected publications might function as a currency, where a recipient gives away to her donor a certain credit in her publication. Nevertheless, donors may not appreciate coauthorship (e.g., due to an expected low quality of publication) and may doubt that recipients could really publish. To incorporate this limitation, I introduce a parameter, $p \in [0,1]$, the matching rate at which a donor finds possible rewards from his recipient valuable. For simplicity, I assume that the contract of private rewarding is binding,[7] and thus, *PAY* is immune to the risk of non-reciprocity.

With this setting, I analyze how indirect reciprocity competes with reward-based cooperation under the commercialized regime. That is, the evolutionary dynamics of *DISC* and *PAY* with the existence of *COM* is analyzed.[8] The payoffs for both types are given by

$$P_3 = -cgq + bg_3qx_3 \ldots (5a)$$

$$P_4 = p(\beta - c)(x_0 + x_4) + bg_4qx_3 + p(b - \gamma)x_4 \ldots (5b),$$

where x_4 denotes the frequency of *PAY*. Figure 3 illustrates how the invasion of *COM* affects the dynamics. *COM* does not largely change the reputation of *DISC* while it improves that of *PAY*. Second, it reduces the successful transaction for *DISC* to a greater extent than it does for *PAY*. Taken together, the payoff for *DISC* decreases more, especially when the frequency of *DISC* is high. The phase diagram shows that the unstable equilibrium shifts rightwards. Therefore, the invasion of *COM* creates a more favorable condition for *PAY* than for *DISC* (see mathematical details in Appendix 1B).

This analysis suggests that the increase in commercial academics weakens the reputation mechanism and undermines their potential benefit from indirect reciprocity, which forces academics to depend on safer transactions conditioned on private rewarding. This bilateral transaction resembles an economic exchange, where the immediate payment offers an incentive for donors. However, the academic context allows only incomplete economic exchange due to the lack of universal currency and the limitation of barter exchange (modeled as low *p*). Consequently, the shift toward reward-based cooperation results in a socially undesirable state

[7] In the case of coauthorship, our interviewees suggested that the promise of coauthorship is usually kept. Of course, recipients may fail to publish a paper, which is understood as a discount of the reward.
[8] *ALLC* and *RATL* are neglected because the former is dominated by *DISC* and *PAY* and the latter is dominated by *PAY*.

with fewer transactions (the gray lines in Figure 3B).[9] Even so, academics would resort to such a suboptimal option to avoid being exploited by free riders.

Proposition 2: With a greater prevalence of academic commercialism, academics become more likely to demand private reward in exchange for cooperation.

4.3. Abstention from Cooperation

The above argument assumes compulsory participation in cooperation games, where recipient players must request cooperation. However, in reality, academics have the option of not making a request. If academics engage in no cooperation and work alone, their payoff from cooperation is zero, but this could be better than being exploited by defectors in the commercialized regime. In addition, making a request itself can incur some cost; for example, academics may have to reveal their research plan to donors (which could compromise their scientific lead), and they have to negotiate the conditions under which the resources are used. Such cost could become a burden when cooperation requests are likely to be denied. Thus, the malfunction of indirect reciprocity can affect academics' willingness to participate in cooperation.

To examine this possibility, I further extend the Donation Game by adding a type, *ABST* (Table 1), which abstains from participating in the game (Batali and Kitcher, 1995). *ABST* players do not engage in Donation Games at all, but instead, concentrate on their independent work. While foregoing potential benefit from cooperation, *ABST* earns a constant benefit, σ. I assume σ is sufficiently small so that participation in Donation Game makes at least some sense.[10] First, I analyze the dynamics between *DISC* and *ABST* with the existence of *COM* (Figure 4A). The payoffs for *DISC* and *ABST* are given by

$$P_3 = -cg_{-5}q(1 - x_5) + bg_3qx_3 \ldots (6a)$$

$$P_5 = \sigma \ldots (6b),$$

where g_{-5} denotes the mean reputation of non-*ABST* players. Figure 4A shows that the invasion of *COM* decreases the payoff for *DISC*. Under the commercialized regime, indirect reciprocity

[9] The rate of receiving cooperation is $\frac{1(1-x_0)(1+qx_0)}{2-q(1-x_0)}$ at the pure *DISC* equilibrium and $p(1 - x_0)$ at the pure *PAY* equilibrium. The former is larger (i.e., reward-based cooperation is less socially desirable) when $p < \frac{q}{2-q}$ $(x_0 = 0)$. For example, $p < 0.67$ if $q = 0.8$.

[10] i.e., $0 < \sigma < \frac{q(b-c)}{2-q}$. The right-hand side is the maximum payoff for *DISC*, which is achieved in a pure *DISC* population.

becomes vulnerable to loners, who secure the minimum payoff by avoiding cooperation (see the proof in Appendix 1C).

Next, I examine how *ABST* competes with *PAY*. The payoff for *PAY* is given by

$$P_4 = p(\beta - c)(x_0 + x_4) + p(b - \gamma)x_4 \dots (6c).$$

Similarly, Figure 4B shows that the invasion of *COM* creates a more favorable condition for *ABST* than for *PAY*. The reward-based cooperation could sustain itself if the matching rate, p, or the reward value, β, is sufficiently high. Put differently, with the limited efficiency of rewarding, cooperation based on private rewarding is likely to be invaded by loners (see the proof in Appendix 1D).

In summary, the commercialized environment, where indirect reciprocity is likely denied and private reward is demanded, discourages academics from making cooperation requests, and abstention from cooperation becomes a viable option.

Proposition 3: With a greater prevalence of academic commercialism, academics become less willing to engage in cooperation and more likely to refrain from making requests.

4.4. Integrated Model

For a holistic view, I examine the dynamics of *DISC*, *PAY*, and *ABST* with the invasion of *COM* (detail in Appendix 2A). Figure 5A shows numerical phase plots with and without *COM*. They indicate that the phase space is divided into three regions that converge into each of the three types (Blue: *DISC*, green: *PAY*, Orange: *ABST*). Figure 5B illustrates the area percentage of each region with increasing *COM*, suggesting that the basin of attraction for *ABST* consistently increases at the sacrifice of *DISC*, and that *PAY* is compromised with a high prevalence of *COM*. I also examine the sensitivity to parameter settings (Appendix 2B). The basin of attraction for *DISC* consistently shrinks with greater frequencies of *COM*, and that *DISC* is especially vulnerable with a low availability of reputation, q. The balance between *PAY* and *ABST* depends on parameters. A higher matching rate, p, and higher value of reward, β, gives an advantage to *PAY*, and a higher opportunity cost of cooperation, σ, to *ABST* (see also Appendix 1D).

5. INTERVENTION

With the above prediction for possible disruption of indirect reciprocity under commercialism, what policy interventions are feasible? A simplistic approach may be to reverse the trend of commercialism. Though completely abandoning the emerging regime is unrealistic, reducing the incentive of commercial participation may be feasible (e.g., universities extract a greater portion of commercial profit from their employees). For example, some science communities have been trying to discourage academics from excessively patenting research tools if they are used mainly inside academia (Lei et al., 2009). This type of interventions must be implemented swiftly. For, once the norm of unconditional sharing deteriorates to a certain extent, recovering from a non-cooperative equilibrium might be impossible. Such irreversibility has been observed in reality, where the introduction of economic incentives has rationalized people and destroyed social norms (Frey and Jegen, 2001; Gneezy and Rustichini, 2000).

5.1. Centralized Rewarding

A more proactive incentive system may be feasible. Literature suggests that centralized rewarding and punishing contribute to sustaining cooperation (Baldassarri and Grossman, 2011) (Ostrom, 1990). Mechanisms to officially punish defectors do exist in academia though their effect has been questioned (NAS 2003). Alternatively, the central authority could offer cooperators some rewards such as awards and research funds. In addition, science communities have recently been calling for rewarding mechanisms for cooperators, such as mandating acknowledgments (Schofield et al., 2009; NAS 2003). Since this is imposed by the central authority and recipients bear practically no cost, it is different from the private rewarding (Ch.4.2) and is theoretically closer to centralized rewarding.

First, I investigate the effect of centralized rewarding on the evolutionary dynamics between *RATL* and *DISC* with the existence of *COM* (see details in Appendix 3). Let $r \in (0, b)$ denote the value of reward given by the central authority. I assume that the central authority rewards all cooperation (i.e., it cannot distinguish between cooperation with good recipients and that with bad recipients), and that this fact is publicly known. If $r < c$, *RATL* donors keep defecting. However, if $r > c$, they cooperate as if they were *ALLC* since cooperation is more beneficial than defection. Further, I assume that *DISC*'s action is not affected by centralized rewarding because cooperating with bad recipients is still against the norms of open science. Figure 6 (upper row) illustrates the evolutionary dynamics with different levels of *COM* with low and high rewarding (left: $r < c$ and right: $r > c$). The solid and dashed curves respectively show unstable equilibria with and without rewarding. When $r < c$, the rewarding increases the basin of attraction for *DISC* (the blue region corresponds to the increased part of the basin). Thus, even after the invasion of *COM* created a favorable condition for *RATL*, *DISC* could regain its advantage with the support of centralized rewarding. However, when $r > c$, the effect of rewarding could become limited because *RATL* also takes advantage of the rewarding. The rewarding could even facilitate *RATL* to dominate *DISC* (indicated by the red region). If $r > c$ and *RATL* prevails, the average cooperation level is high. Though this might appear socially acceptable, it instantly collapses when the rewarding ceases because cooperation is not motivated by the norms of open science but by personal profit. Therefore, the central authority should choose an adequate (not too large) size of rewarding to support the advocates of indirect reciprocity. The situation is similar for the competition between *DISC* vs. *PAY*. I additionally assume that the rewarding is given only for gratis cooperation. When $r <$ c, *PAY*'s action is not affected by the rewarding. When $r > c$, *PAY* acts like *ALLC* to exploit the centralized rewarding. Figure 6 (bottom row) shows the shift of dynamics. The effect of rewarding is rather limited compared to the case with *RATL*. Likewise, excessive reward could be counterproductive.

Appendix 3D examines the effect of centralized rewarding different sizes of reward. For *DISC* vs. *RATL*, the rewarding is effective when the reward size is close to the cooperation cost. The rewarding is effective even when the frequency of *COM* is very high. The choice of an adequate size of rewarding is rather difficult when the reputation availability is low, where a reward size slightly above the cooperation cost could be counterproductive. When private rewarding is allowed, centralized rewarding becomes even more difficult to implement in that reward size below the cooperation cost becomes less effective.

In sum, though rewarding could contribute to indirect reciprocity, the choice of reward size may be difficult, and an inadequate size of rewarding could have no effect or even a negative effect. Thus, if the central authority provides awards or funds to cooperation, the choice of proper reward size is critical. Though acknowledgments in publication could work as a reward, its impact may be limited since academics are usually evaluated on the basis of publication record but not of acknowledgments. With this regard, mandating citation (i.e., a recipient must cite the donor's paper related to the received resources) may have a greater effect.

5.2. Charging Cooperation Cost

Another option to sustain cooperation is to transfer the donors' cooperation cost to recipients. In resource sharing, the cooperation cost for donors consists of the direct cost for preparing resources and the indirect cost for foregoing potential scientific lead. Though the latter may be difficult to address, the former can be mitigated by charging recipients minimum fees for resource preparation. However, this rarely happens in reality for some reasons: the cost for collecting fees is not negligible. Fair pricing is difficult, and money payment is sometimes prohibited. To address this issue, universities or the central authority may act as an agent for academics in collecting fees and supplying resources. Theoretically, this has a similar effect to the rewarding.[11] Thus, as long as an adequate fee level is chosen, it could protect *DISC* against *RATL*, but it is less effective against *PAY*.

5.3. Central Repositories

Finally, I examine the effect of central repositories. Many repositories, such as the Jackson Laboratory, American Type Culture Collection, and NIH data repositories, are already in operation (Furman and Stern, 2011). Donor academics store their resources in repositories, and recipients use the resources at cost from the repositories. Though this system has been recommended by various quarters (Schofield et al., 2009), it is not playing the main role in resource sharing, and the vast majority of resource sharing still depends on bilateral transactions between individual academics (Shibayama and Baba, 2011). This section investigates how central repositories could stabilize indirect reciprocity in a population of *DISC* and *PAY*, where *DISC* pools part of their resources in repositories to facilitate sharing (see details in Appendix 4).

The model incorporates additional four parameters. *DISC* players store a fraction $\theta \in (0,1)$ of their resources in repositories. In so doing, they can save the cost for supplying resources, but they need to bear the cost for preparing resources for storage. As repositories usually require some standardization for stored resources, the preparation cost for storage could be higher than that for bilateral transaction. Still, it is a one-time cost and can be discounted through repeated sharing. These factors taken together, the storage cost is given by δc ($\delta > 0$). Recipients find necessary resources stochastically either in the hands of other players or in repositories. Because resource information in repositories is better disseminated (Furman and

[11] For donors, the cooperation fee paid by recipients is the same as the reward given in the centralized rewarding. For recipients, fee payment can be understood as the reduction of cooperation benefit.

Stern, 2011), a resource in repositories is more likely to be requested than a resource in someone's hands. The ratio of these probabilities is denoted by $\alpha > 1$. If a resource is found in a repository, recipients pay some fees to the repository and receive the resource. Otherwise, a bilateral transaction occurs. Finally, I assume that when a resource is supplied from repositories, its original owner earns some benefit, $\pi \in (0, \beta)$,[12] through acknowledgments, citations, and so forth. Furman and Stern (2011) suggest that original owners of repository resources have their papers cited more often.

Appendices 5B and 5C examine the effect of central repositories with some parameter settings. Quite straightforwardly, the result suggests that higher repository registration (θ), higher visibility of repository resources (α), lower storage cost (δ), and greater benefit for the owner of repository resources (π) contribute to sustaining indirect reciprocity. It shows that low repository registration and low visibility substantially compromises the effect of repositories, that storage cost needs to be sufficiently low, and that sufficient benefit has to be given to owners of repository resources. Thus, in order to successfully run repositories, the authority should not only build a physical infrastructure but also educate academics to pool their resources in it, support their storage financially and technically, disseminate resource information, and make rules about the acknowledgments, etc. With all these efforts, repositories could contain self-regarding players. Central repositories also have some limitations. Among others, most resources are of special and infrequent use, and thus, the storage cost might not be sufficiently small. In addition, since the maintenance of repositories is costly, repositories need to be selective in the resources that they store.

6. DISCUSSION AND CONCLUSIONS

Although academic science heavily depends on the norms of open science (Dasgupta and David, 1994; Merton, 1973), the current regime of academic commercialism has been emphasizing the for-profit activities inside academia, and their conflict seems to affect the practices in science (Dasgupta and David, 1994; Kleinman and Vallas, 2001; Nelson, 2004). One noticeable example is observed in resource sharing, where commercial academics tend to be reluctant to give their resources for the sake of commercial profit (Blumenthal et al., 1997; Campbell et al., 2000; Walsh et al., 2007). While few prior studies have investigated a broad

[12] With $\pi < \beta$, I assume that *PAY* prefers to keep its resources in hands rather than pooling in repositories.

impact of commercialism, the current study predicts that the commercialized regime could rationalize not only commercial academics but also non-commercial academics and substantially undermine the norms of open science.

This study models the academic cooperation in the ideal state of open science as indirect reciprocity (Nowak and Sigmund, 1998) and predicts the impact of the invasion of commercial academics. The analyses suggest that the growing commercialism could lead to the following three behavioral change in cooperation. First, even non-commercial academics could become unwilling to share their resources because increasing commercial academics, who tend to be defectors, decrease the expected benefit from indirect reciprocity, and because they compromise the reputation mechanism underpinning indirect reciprocity. Second, the compromised indirect reciprocity could force academics to rely on private rewarding (e.g., coauthorship). That is, the sharing becomes more dependent on short-term personal profit. However, this is not always feasible for the limitation of barter exchange, leading to a suboptimal situation. Third, consequently, academics could be discouraged from participating in sharing and would rather work alone (or collaborate with certain fixed partners). These predictions suggest that the commercial regime could undermine the climate of open science, which underpins the progress of science. Thus, although the policy intention of academic commercialism was to facilitate the practical use of achievement from academia, it could damage the very source of academic achievement.

This study also examines whether such unintended consequences could be mitigated with some interventions. Centralized rewarding may be effective to suppress defection by rational academics. However, the effect seems limited against rational cooperators who participate in sharing with private rewarding. Charging recipients some fees could have a similar effect. Central repositories could contribute to indirect reciprocity, but arranging a series of conditions (e.g., dissemination of resource information) is required.

This study offers some implications for future empirical research. First of all, behavior of non-commercial academics and the general impact of commercialism is of practical relevance. Since most prior empirical studies have focused on non-cooperative behavior of commercial academics, future research should investigate behavior of ordinary academics in diverse contexts (e.g., different fields, countries). Certainly, it is desirable to follow inter-temporal transition in the practice of cooperation. Cooperation based on private rewarding is also of both theoretical and practical concern because gratis cooperation is supposed to be the norm in academia (Dasgupta and David, 1994; Merton, 1973). Future research should inquire into detailed conditions of cooperation and identify what kinds of direct and indirect incentive are at work in the choice of cooperation forms. Abstention from cooperation also needs studying. Future research should investigate more about recipients (rather than donors) to elucidate the antecedents of the willingness to ask for cooperation. In addition, the parameters employed in this study need empirical investigation. Some of them offer important information in designing interventions. For example, the role of reputation is of theoretical and practical interest, and it should be studied to what extent academics share the social information about their peers (availability of reputation, q). The efficiency of private rewarding (the matching rate, p) and the value of rewarding (β, γ, and r), private or centralized, should be investigated, such as coauthorship, acknowledgements, citation, and future support. The cost structure of cooperation also needs more empirical basis: i.e., the breakdown of the cooperation cost, c, into the direct cost for preparing resources and the perceived indirect cost for foregoing scientific leads. Finally, the weakening norms of open science could cause even broader effect on the practice of science. Thus, different types of self-regarding behavior (e.g., secrecy, misconduct) should be investigated in connection with the regime shift.

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Table 1 List of Types

ID	**Type**	**Description**
1	*ALLC*	Indiscriminate cooperators who always cooperate.
2	*RATL*	Rational players.
3	*DISC*	Discriminate cooperators who cooperate with good recipients but defect bad recipients.
4	*PAY*	Rational players with the option of private rewarding who cooperate if rewarded and pay reward if demanded.
5	*ABST*	Loners who never participate in cooperation games.
0	*COM*	Rational players who defect in favor of commercial profit. They do not contribute to evolution.

Table 2 Reputation Rule

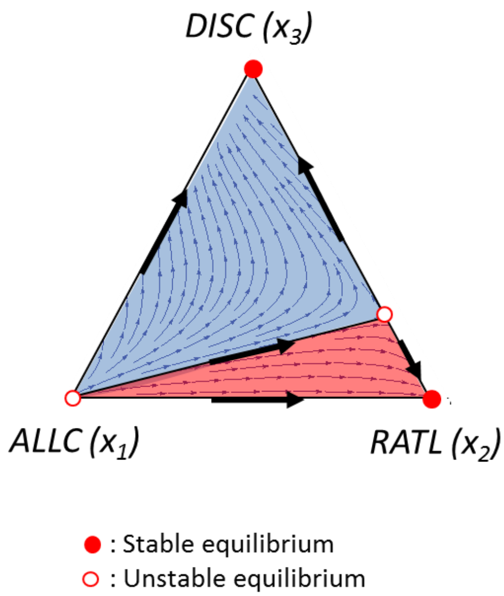
Recipient's reputation	**Donor's action**	**Donor's evaluation**
Good	Cooperate	Good
Good	Defect	Bad
Bad	Cooperate	Bad
Bad	Defect	Good

Table 3 Payoff Matrix [a]

Donor \ Recipient	*1: ALLC*	*2: RATL*	*3: DISC*	*4: PAY*	*5: ABST*	*0: COM*
1: ALLC	$-c, b$	$-c, b$	$-c, b$	$-c, b$	$0, \sigma$	$-c, b$
2: RATL	$0, 0$	$0, 0$	$0, 0$	$0, 0$	$0, \sigma$	$0, 0$
3: DISC	$-cqg_1, bqg_1$	$-cqg_2, bqg_2$	$-cqg_3, bqg_3$	$-cqg_4, bqg_4$	$0, \sigma$	$-cqg_0, bqg_0$
4: PAY	$0, 0$	$p(\beta - c), p(b - \gamma)$	$0, 0$	$p(\beta - c), p(b - \gamma)$	$0, \sigma$	$p(\beta - c), p(b - \gamma)$
5: ABST	$0, 0$	$0, 0$	$0, 0$	$0, 0$	$0, \sigma$	$0, 0$
0: COM	$0, 0$	$0, 0$	$0, 0$	$0, 0$	$0, \sigma$	$0, 0$

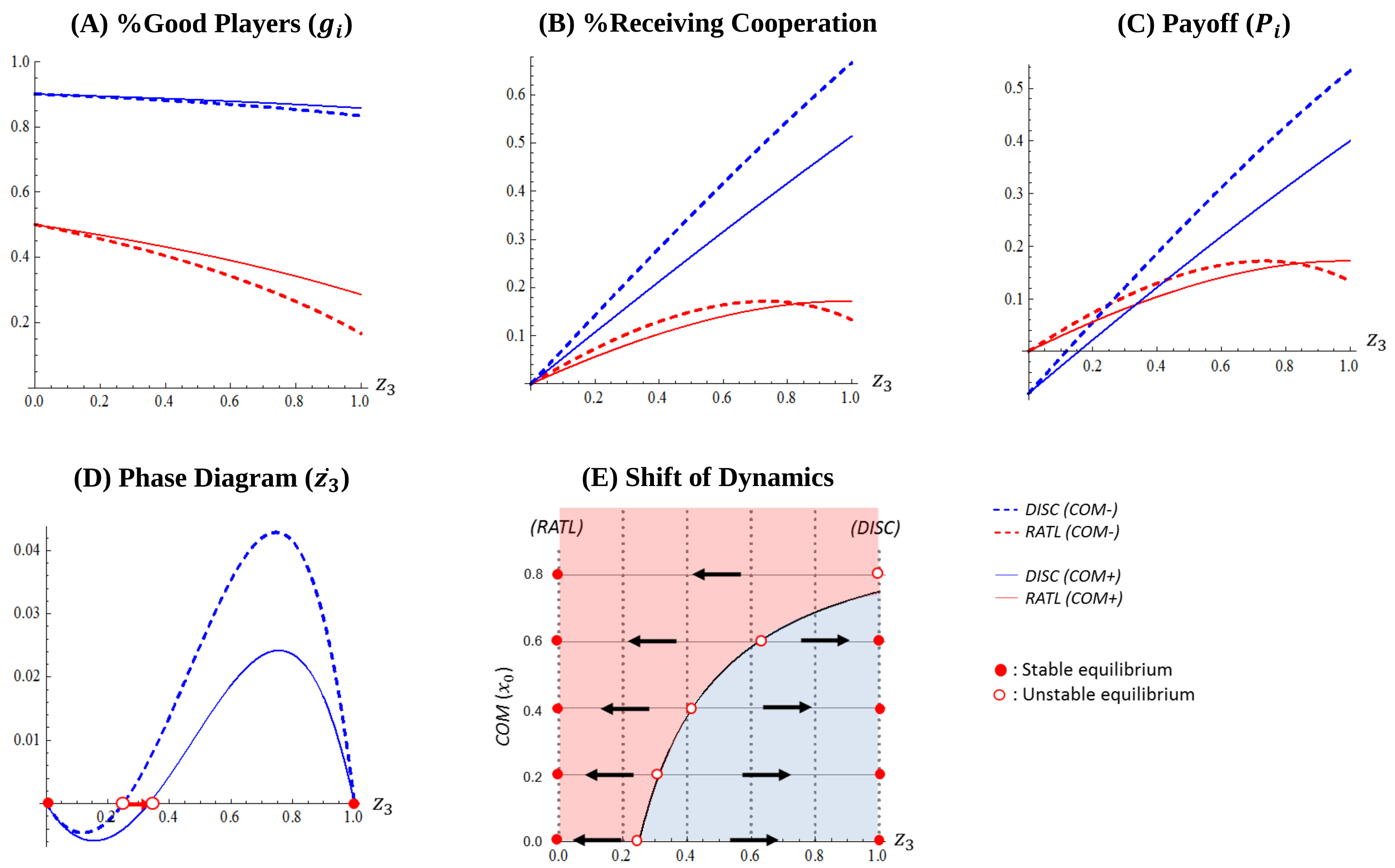
[a] The left-hand number in each cell is the payoff for the donor and the right-hand number is that for the recipient.

Figure 1 Numerical Phase Plot of *ALLC*, *RATL*, and *DISC* [a]



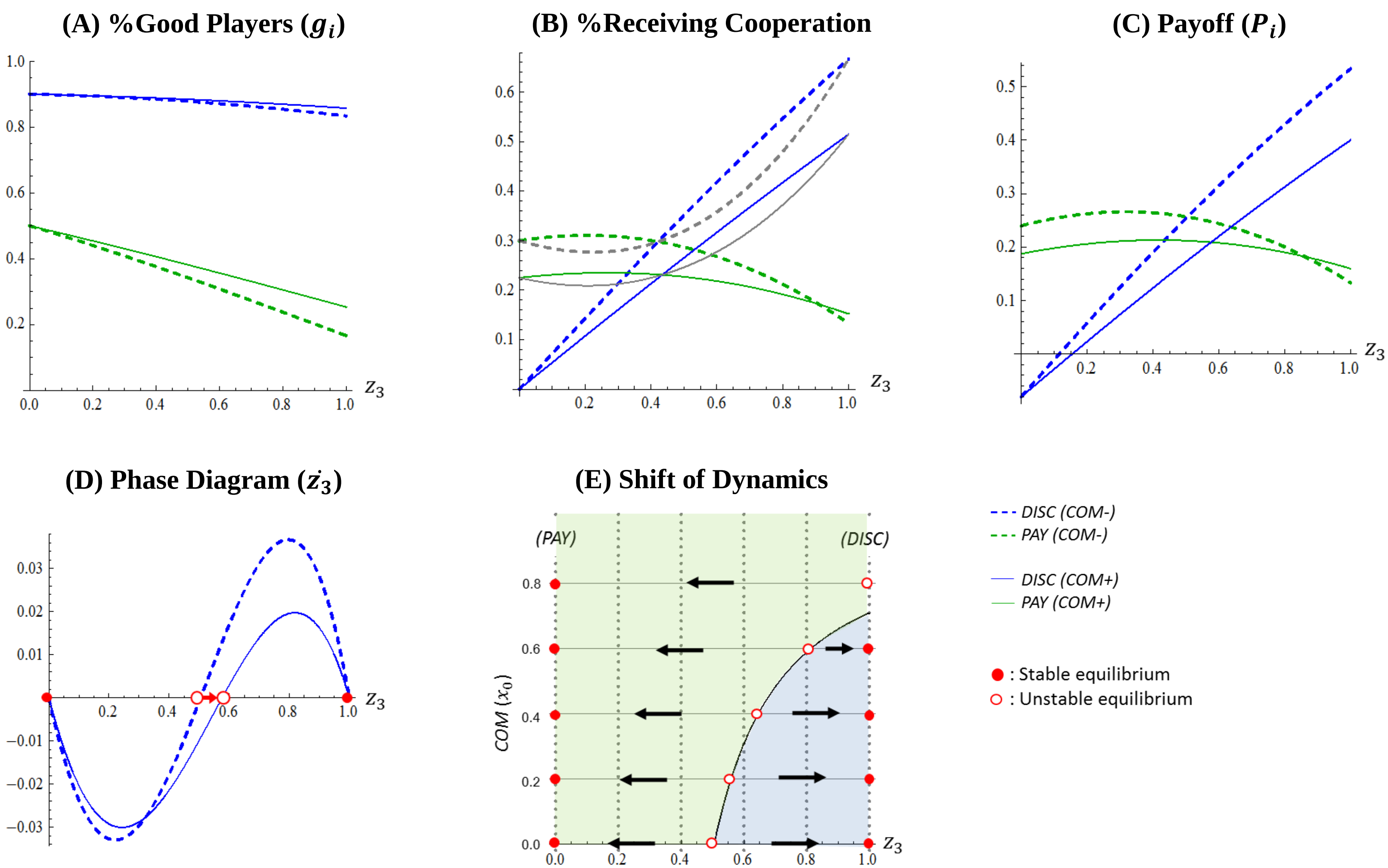
[a] The pure *RATL*, (0,1,0), and the pure *DISC*, (0,0,1), are stable equilibria. *A* mix of *RATL* and *DISC*, $\left(0,1-\frac{c}{qb},\frac{c}{qb}\right)$, and the pure *ALLC*, (1,0,0), are unstable equilibria. The phase space is split into one region converging to *DISC* (Blue) and the other converging to *RATL* (Red). $b = 1.0$. $c = 0.2$. $q = 0.8$.

Figure 2 *RATL* vs. *DISC* [a]



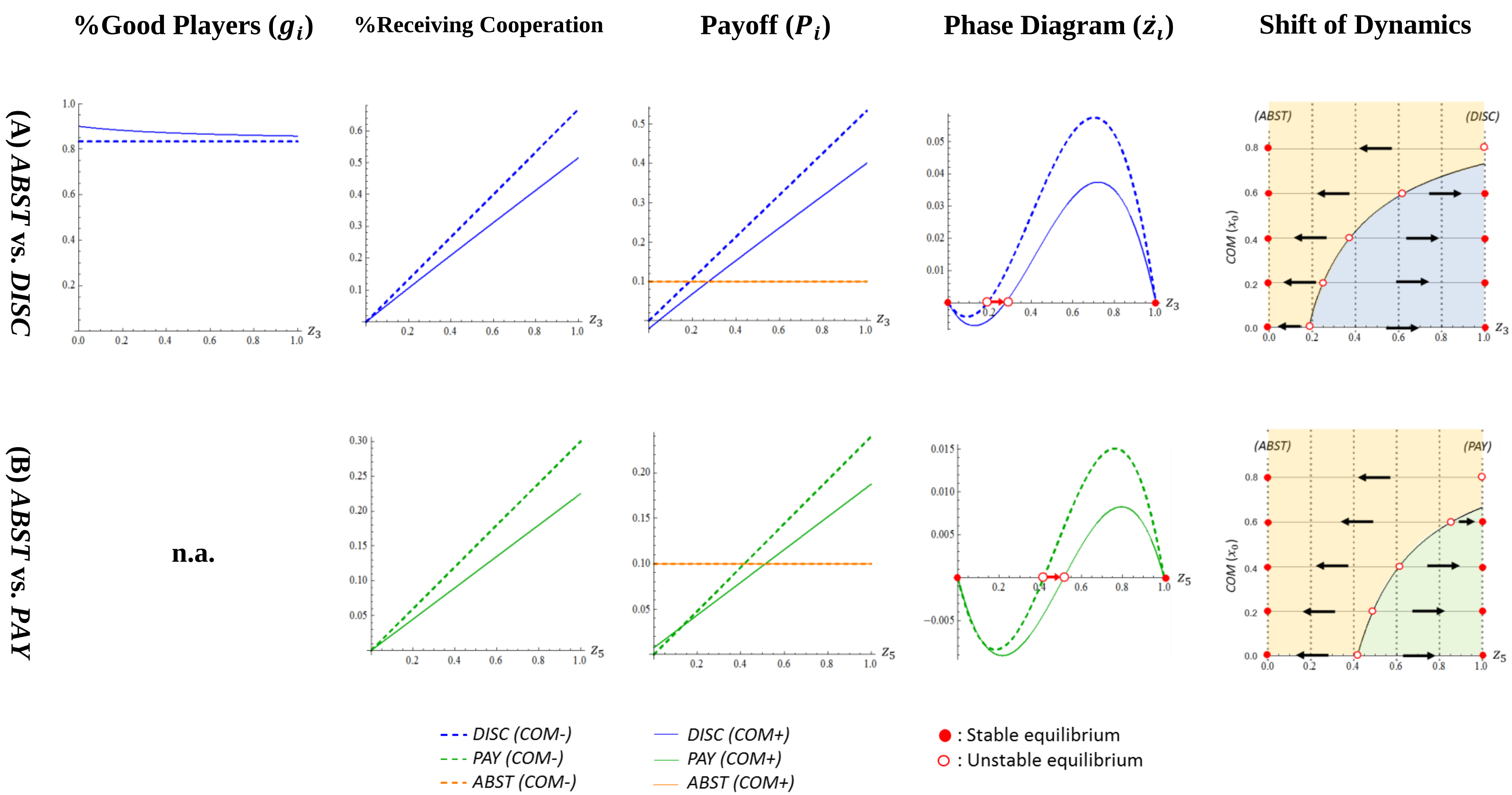
[a] Blue: *DISC*, Red: *RATL*. Solid line: $x_0 = 0.25$ (with *COM*), Dashed line: $x_0 = 0$ (without *COM*). In (D) and (E), to the right of unstable equilibria, the dynamics moves rightwards (greater frequency of *DISC*), while, to the left, it moves leftwards (greater frequency of *RATL*). In (E), the solid curve indicates the transition of the unstable equilibrium. $b = 1.0$. $c = 0.2$. $q = 0.8$.

Figure 3 ***PAY* vs. *DISC*** [a]



[a] Blue: *DISC*, Green: *PAY*. Gray: Total in (B). Solid line: $x_0 = 0.25$ (with *COM*), Dashed line: $x_0 = 0$ (without *COM*). $b = 1.0$. $c = 0.2$. $\beta = \gamma = 0.3$. $q = 0.8$. $p = 0.3$.

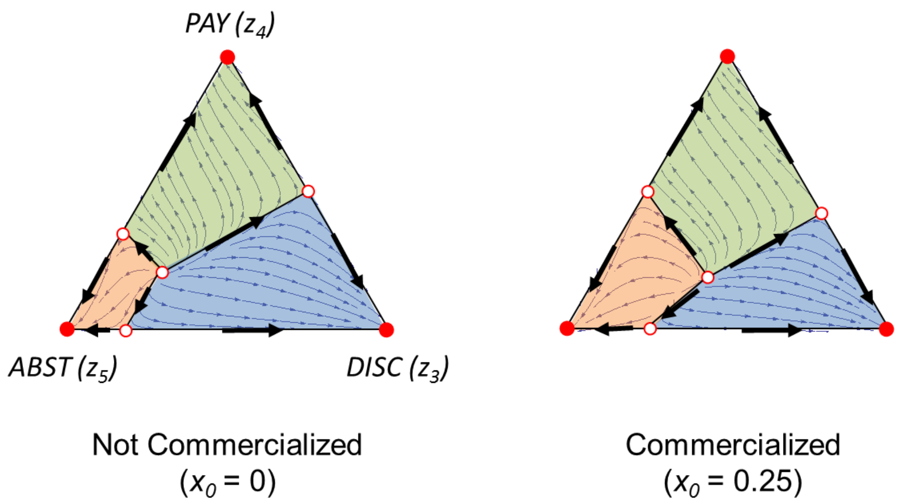
Figure 4 *ABST* vs. *DISC* and *PAY* [a]



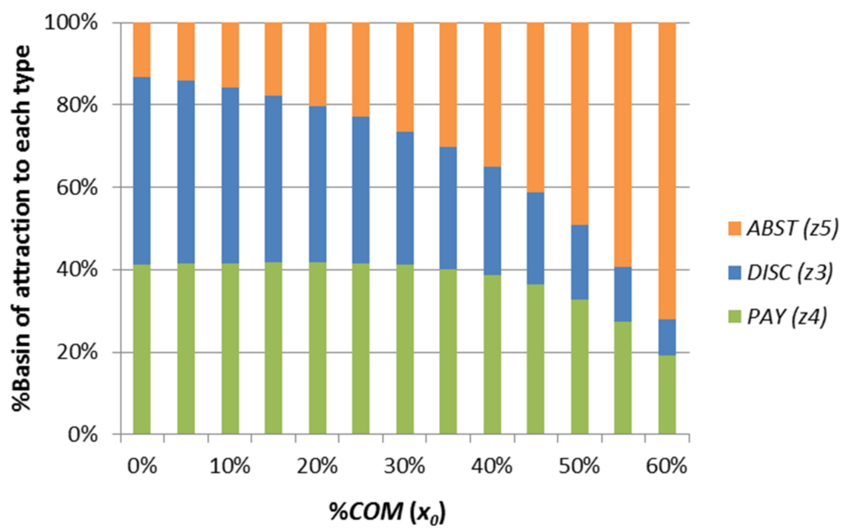
[a] Blue: *DISC*, Green: *PAY*, Orange: *ABST*. Solid line: $x_0 = 0.25$ (with *COM*), Dashed line: $x_0 = 0$ (without *COM*). $b = 1.0$. $c = 0.2$. $\beta = \gamma = 0.3$. $\sigma = 0.1$. $q = 0.8$. $p = 0.3$.

Figure 5 ***DISC*, *PAY*, vs. *ABST*** [a]

(A) Numerical Phase Plot

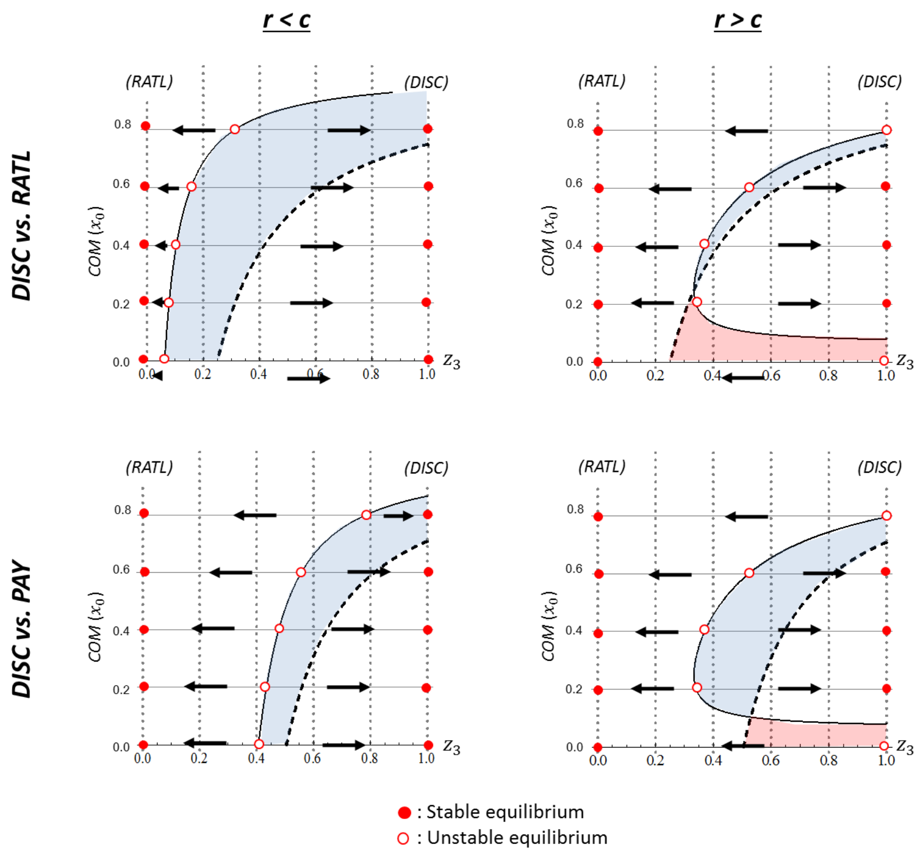


(B) Basin of Attraction [b]



[a] The mathematical detail is given in Appendix 2A. b = 1.0. c = 0.2. $\beta = \gamma$ = 0.3. σ = 0.1. p = 0.3. q = 0.8.
[b] The area percentage of the basin of attraction for each type is numerically computed. For each lattice point in the phase space with the interval of 0.02 (1,326 points) as the initial state, the coordinate (z_3, z_4, z_5) at t = 10,000 is computed with $\dot{z}_3 = z_3(P_3 - \bar{P})$ and $\dot{z}_4 = z_4(P_4 - \bar{P})$. If it is within the distance of 0.01 from one of the three pure types, it is regarded as a convergence to the type. The percentage of the cases converging to each type is used as the area percentage of basin of attraction.

Figure 6 Centralized Rewarding [a]



[a] Solid curves represent unstable equilibria when central rewarding is implemented, and dashed curves are those without the rewarding. The frequency of *DISC* is shrinking ($\dot{z}_3 < 0$) to the left of the equilibria and increasing ($\dot{z}_3 > 0$) to the right. Thus, the centralized rewarding expands the basin of attraction for *DISC* in blue regions and shrinks it in red regions. Details are given in Appendix 3. $b = 1.0$. $c = 0.2$. $\beta = \gamma = 0.3$. $p = 0.3$. $q = 0.8$. $r = 0.15$ for $r < c$ and $r = 0.3$ for $r > c$.

Appendix 1 Mathematical Details for Propositions

(A) Proposition 1

The equilibrium reputation satisfies $g_2 = g_0 = 1 - g$, $g_3 = 1 - (1-q)g$, and $g = x_2 g_2 + x_3 g_3 + x_0 g_0$. Since $z_i = x_i/(1-x_0)$, $g = \frac{1}{2 - qz_3(1-x_0)}$. With (4a) and (4b), $P_3 - P_2 = \frac{q\{qbz_3(1-x_0) - c\}}{2 - qz_3(1-x_0)}$. The solution of $P_3 - P_2 = 0$ for z_3 gives $z_3^* = \frac{c}{qb(1-x_0)}$.[a] $\frac{dz_3^*}{dx_0} = \frac{c}{qb(1-x_0)^2} > 0$. ■

(B) Proposition 2

A *PAY* donor, upon request, examines if his recipient has a valuable reward, and if so, he cooperates with her only if she is willing to give the reward. I assume that recipients of rational types (i.e., *PAY* and *COM*) accept paying private rewards, but that *DISC* does not because it violates the norms of open science. Thus, *PAY* donors cooperate with *PAY* and *COM* recipients with the probability of p but never cooperate with *DISC*. With this setting, the equilibrium reputation of *PAY* is given by $g_4 = (1-g_3)x_3 + \{pg_4 + (1-p)(1-g_4)\}x_4 + \{pg_0 + (1-p)(1-g_0)\}x_0$, where $g_0 = 1 - g, g_3 = 1 - (1-q)g$ and $g = x_3 g_3 + x_4 g_4 + x_0 g_0$. From (5a) and (5b), $P_3 - P_4 = b(g_3 - g_4)qx_3 - p(\beta - c)x_0 - p(b - \gamma + \beta - c)x_4 - cgq$. Formally, Proposition 2 states $\frac{dz_3^*}{dx_0} > 0$, where z_3^* is the solution of $P_3 - P_4 = 0$ for z_3. With $f(z_3, x_0)$ and $g(z_3, x_0)$ being polynomials of z_3 and x_0, $P_3 - P_4 = \frac{f(z_3,x_0)}{g(z_3,x_0)}$, where $g(z_3, x_0) > 0$ and $f(z_3, x_0) = f_0(x_0) + f_1(x_0)z_3 + f_2(x_0)z_3^2 + f_3(x_0)z_3^3$ with $f_0(x_0) < 0$ and $f_3(x_0) > 0$. Since analytically deriving $\frac{dz_3^*}{dx_0} > 0$ is not possible, I indirectly show this by simulation. From the whole parameter regions, $c \in [0,1], q \in [c, 1], p \in \left[0, \frac{q}{2-q}\right]$[b]$, \beta \in [c, 1], \gamma \in [0, \beta]$, and $x_0 \in [0,1)$ with b fixed at 1 without losing generality, I randomly choose a set of parameters, with which $f(z_3, x_0) = 0$ is numerically solved for z_3. If a solution is found in (0,1), the same equation is solved again with the same set of parameters except that x_0 is replaced by $x_0 + \varepsilon$, where $\varepsilon = \frac{1}{10000}$. The first solution is denoted by z_3^* and the second by z_3^{**}. This computation is repeated 100,000 times. Approximately 70% of the time, no solution was found in (0,1). For the rest, a single solution was found

[a] $x_0 < 1 - \frac{c}{qb}$. Otherwise, the interior equilibrium disappears and the pure *RATL* becomes the only stable equilibrium.

[b] The region of p is restricted so that *DISC* can be socially more desirable than *PAY* at least when *COM* does not exist. See fn.9.

in (0,1).[a] In these cases, it always holds that $z_3^{**} > z_3^*$, which implies $\frac{dz_3^*}{dx_0} > 0$. ■

(C) Proposition 3 (*DISC* vs. *ABST*)

The game involving *ABST* is played as follows. Two players are randomly chosen from a population of *DISC*, *ABST*, and *COM*. When *ABST* is chosen as a donor, it always defects, so payoffs for both sides are zero. When *ABST* is chosen as a recipient, it does not ask for cooperation, where the payoff for *ABST* is σ while that for a donor is zero. Here, as the donor neither defects nor cooperates, its reputation does not change. Because the reputations of *DISC* and *COM* are unaffected by games with *ABST* recipients, reputation is computed only within non-*ABST* players: i.e., $g_3 = 1 - (1-q)g_{-5}$ and $g_0 = 1 - g_{-5}$, where $g_{-5} = \frac{x_3 g_3 + x_0 g_0}{x_3 + x_0}$. For mathematical tractability, denote $y = \frac{x_0}{1-x_0}$. Proposition 3 implies that $\frac{dz_3^*}{dx_0} > 0$, where z_3^* is the solution of $P_3 - P_5 = 0$ for z_3. Instead of $\frac{dz_3^*}{dx_0}$, $\frac{dz_3^*}{dy}$ is evaluated on the basis that $\frac{dx_0}{dy} = \frac{1}{(1+y)^2} > 0$. From (6a) and (6b), $P_3 - P_5 = \frac{q[b\{z_3^2 + (1+q)yz_3\} - c(z_3+y)^2]}{\{(2-q)z_3 + 2y\}(1+y)} - \sigma$. Let $h(z_3, y) = P_3 - P_5$. Since $h(z_3^*, y) = 0$, $\frac{dz_3^*}{dy} = -\frac{\partial h}{\partial y} / \frac{\partial h}{\partial z_3}$. Because $\frac{\partial h}{\partial z_3} = \frac{\{2(1+q)b - (2+q)c\}y^2 + 4(b-c)yz_3 + (2-q)(b-c)z_3^2}{(1+y)(2y + (2-q)z_3)^2} > 0$, it suffices to show that $\frac{\partial h}{\partial y} < 0$. However, $\frac{\partial h}{\partial y} = \frac{(qb-2c)(1-q)z_3^2 - (2-q)(b-c)z_3^3 - 4(b-c)yz_3^2 - \{2(1+q)b - (2+q)c\}y^2 z_3 - 2(2-q)cyz_3 - 2cy^2}{(1+y)^2(2y + (2-q)z_3)^2}$ is not necessarily negative. The numerator of $\frac{\partial h}{\partial y}$ is a decreasing function of y. Thus, if $\frac{\partial h}{\partial y}(z_3, 0) < 0$, $\frac{\partial h}{\partial y} < 0\ \forall y \geq 0$. $\frac{\partial h}{\partial y}(z_3, 0) < 0 \Leftrightarrow z_3 > \frac{(qb-2c)(1-q)}{(2-q)(b-c)}$. Thus, if $z_3^*|_{y=0} > \frac{(qb-2c)(1-q)}{(2-q)(b-c)}$, it follows that $\frac{\partial h}{\partial y} < 0\ \forall y \geq 0$. This condition is satisfied if $c > \frac{qb}{2}$ or $\sigma > \frac{q(1-q)(qb-2c)}{(2-q)^2}$. Otherwise, $\frac{\partial h}{\partial y} < 0\ (y > y^*)$ and $\frac{\partial h}{\partial y} > 0\ (0 \leq y < y^*)$, where y^* is the solution of $\frac{\partial h}{\partial y}(z_3, y) = h(z_3, y) = 0$ for y.[b] In sum, If c or σ is sufficiently large, the invasion of *COM* offers a favorable condition for *ABST* regardless of *COM*'s frequency. Otherwise, with a minimal frequency of *COM*, *ABST* starts to gain advantage over *DISC*. ■

[a] Since $f(0, x_0) = f_0(x_0) < 0$ and $f_3(x_0) > 0$, if a single solution is found in (0,1), the solution, z_3^*, is the unstable equilibrium. No incident was found where two or three solutions were in (0,1).

[b] This threshold y^* is very small. I ran Monte-Carlo simulation to estimate its maximum over the feasible parameter range, and the maximum of 10,000 runs was $y^* = 0.012$, i.e., $x_0 = 1.2\%$.

(D) Proposition 3 (*PAY* vs. *ABST*)

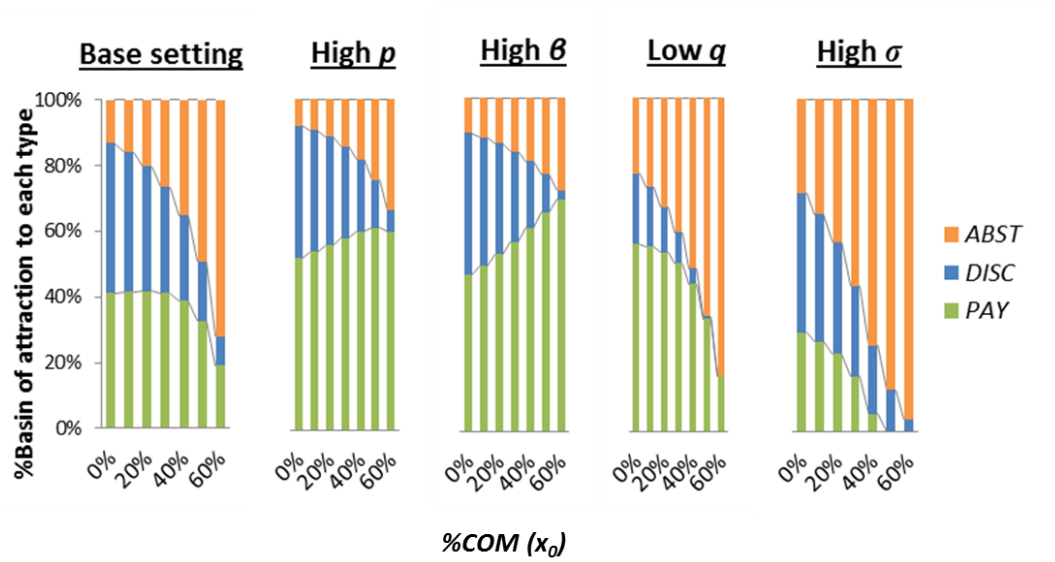
Since *DISC* is not present, reputation does not play a role. From (6b) and (6c), $P_4 - P_5 = p(\beta - c)(x_4 + x_0) + p(b - \gamma)x_4 - \sigma$. Solving $P_4 - P_5 = 0$ for z_4, $z_4^* = \frac{\sigma - p(\beta - c)x_0}{p(b-\gamma+\beta-c)(1-x_0)}$. $\frac{dz_4^*}{dx_0} = \frac{\sigma - p(\beta - c)}{p(b-\gamma+\beta-c)(1-x_0)^2}$. $\frac{dz_4^*}{dx_0} > 0$ if $\sigma > p(\beta - c)$. Thus, the invasion of *COM* is favorable for *ABST* when the matching rate, *p*, or the value of return payment, β, is sufficiently small. ■

Appendix 2 Integrated Model

(A) Payoff and Reputation Equations

For the reputation, the same argument applies as in Appendix 1C. $g_3 = 1 - (1-q)g_{-5}$ and $g_0 = 1 - g_{-5}$, where $g_{-5} = \frac{x_3 g_3 + x_4 g_4 + x_0 g_0}{x_3 + x_4 + x_0}$. The reputation of *PAY* is given by $g_4 = \frac{(1-g_3)x_3 + \{pg_4 + (1-p)(1-g_4)\}x_4 + \{pg_0 + (1-p)(1-g_0)\}x_0}{x_3 + x_4 + x_0}$. The payoffs for *DISC*, *PAY*, and *ABST* follow (6a), (5b), and (6b), respectively.

(B) Sensitivity to Parameter Setting [a]



[a] High p = 0.5. High β = 0.5. Low q = 0.5. High σ = 0.15.

Appendix 3 Centralized Rewarding Model

(A) Model Description

Under centralized rewarding, *RATL* behaves like *ALLC* if $r > c$ since it is more profitable to earn the reward by cooperation than to defect. As for the action of *PAY*, I assume that the reward is given only for gratis cooperation (i.e., if *PAY* receives private reward, it is not additionally rewarded by central authority). With this setting, *PAY* also behaves like *ALLC* if $r > c$. This is the case even if $c < r < \beta$. This is because recipients would decline the payment of private reward knowing that *PAY* donors would cooperate for the reward anyway. *COM* does not cooperate to protect commercial profit even with the existence of the rewarding. In the population of *RATL* and *DISC*, the reputation equation of *RATL* is given by $g_2 = \begin{cases} 1-g & (r<c) \\ g & (r>c) \end{cases}$, and the payoff equation is given by $P_2 = \begin{cases} bg_2qx_3 & (r<c) \\ r-c+bx_2+bg_2qx_3 & (r>c) \end{cases}$ and $P_3 = \begin{cases} (r-c)qg+bg_3qx_3. & (r<c) \\ (r-c)qg+bx_2+bg_3qx_3 & (r>c) \end{cases}$.

Likewise, for *PAY* and *DISC*, the reputation equation of *PAY* is given by $g_4 = \begin{cases} (1-g_3)x_3+\{pg_4+(1-p)(1-g_4)\}x_4+\{pg_p+(1-p)(1-g_p)\}x_0 & (r<c) \\ g & (r>c) \end{cases}$, and the payoff equation is given by $P_3 = \begin{cases} (r-c)qg+bg_3qx_3 & (r<c) \\ (r-c)qg+bg_3qx_3+bx_4 & (r>c) \end{cases}$ and

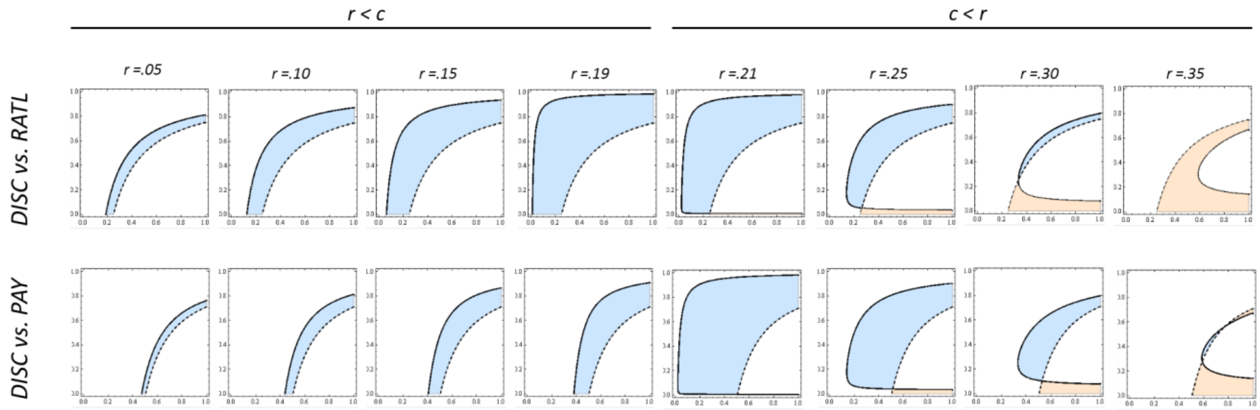
$$P_4 = \begin{cases} p(\beta-c)(x_0+x_4)+bg_4qx_3+p(b-\gamma)x_4 & (r<c) \\ (r-c)+bg_4qx_3+bx_4 & (r>c) \end{cases}.$$

(B) Payoff matrix [a]

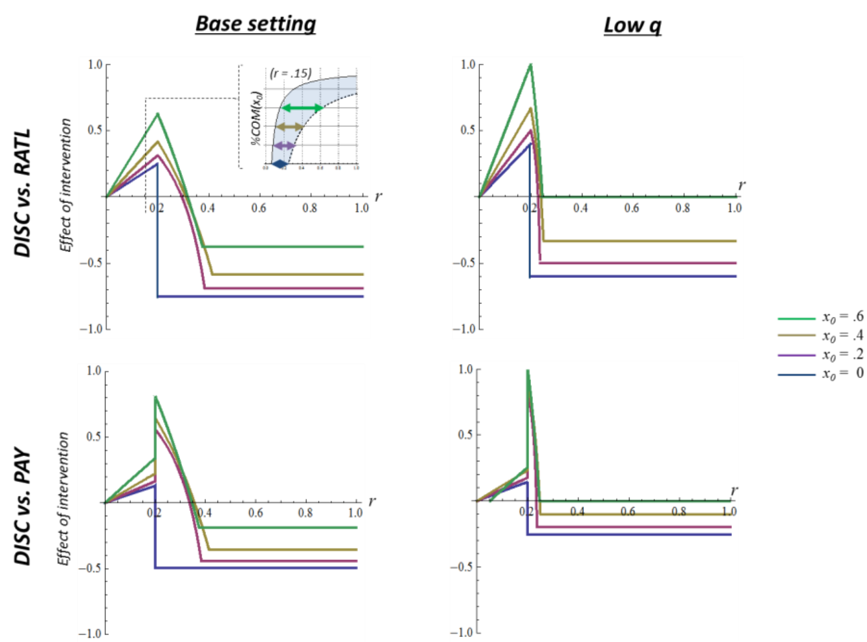
Donor \ Recipient		*2: RATL*	*3: DISC*	*4: PAY*	*0: COM*
2: RATL	$r<c$	$0, 0$	$0, 0$	$0, 0$	$0, 0$
	$r>c$	$r-c, b$	$r-c, b$	$r-c, b$	$r-c, b$
3: DISC		$(r-c)qg_2, bqg_2$	$(r-c)qg_3, bqg_3$	$(r-c)qg_4, bqg_4$	$(r-c)qg_0, bqg_0$
4: PAY	$r<c$	$p(\beta-c), p(b-\gamma)$	$0, 0$	$p(\beta-c), p(b-\gamma)$	$p(\beta-c), p(b-\gamma)$
	$r>c$	$r-c, b$	$r-c, b$	$r-c, b$	$r-c, b$
0: COM		$0, 0$	$0, 0$	$0, 0$	$0, 0$

[a] The left-hand number in each cell is the payoff for the donor and the right-hand number is that for the recipient.

(C) Shift of Dynamics [a]



(D) Effect of Intervention [b]



[a] The rewarding increases the basin of attraction for *DISC* in blue-shaded regions and shrinks it in red-shaded regions. b = 1.0. c = 0.2. $\beta = \gamma = 0.3$. p = 0.3. q = 0.8.

[b] The effect is measured by the expanded part of the basin of attraction for *DISC* (indicated by the sub-graph in the upper left panel). b = 1.0. c = 0.2. $\beta = \gamma = 0.3$. p = 0.3. q = 0.8 in the base setting and q = 0.5 in the low-q setting.

Appendix 4 Central Repository Model

(A) Model Description

The probabilities of a recipient finding necessary resources in the hands of *DISC*, *PAY*, and *COM*, and in repositories are given by $\frac{(1-\theta)x_3}{A}$, $\frac{x_4}{A}$, $\frac{x_0}{A}$, and $\frac{\alpha\theta x_3}{A}$, respectively, where $A = (1-\theta+\alpha\theta)x_3 + x_4 + x_0$. The frequency of a *PAY* donor being asked for cooperation is $\frac{1}{A}$, among which the frequency of a *PAY* donor being asked for cooperation by *DISC*, *PAY*, and *COM* recipients, respectively, are $\frac{x_3}{A}$, $\frac{x_4}{A}$, and $\frac{x_0}{A}$. The frequency of a *DISC* donor being asked for cooperation is, on the other hand, $\frac{1-\theta}{A}$. The frequency of a *DISC* donor's resources in repositories being requested is $\frac{\alpha\theta}{A}$. The payoff for *DISC* is the summation of the cost for cooperating not through repositories ($-cgq$); the benefit from cooperation by *DISC* donors (bg_3q); the benefit from using repository resources ($b-c$); the cost for storing their resources in repositories ($-\delta c$); and the benefit from their repository resources being used by someone (π). The payoff for *PAY* is the summation of the benefit from cooperating with private reward ($p(\beta-c)$); the benefit from cooperation by *DISC* donors (bg_4q); the benefit from cooperation by *PAY* donors ($p(b-\gamma)$); and the benefit from using repository resources ($b-\tau$), where τ is the fee paid to repositories.[a] The payoff for each type is given by:

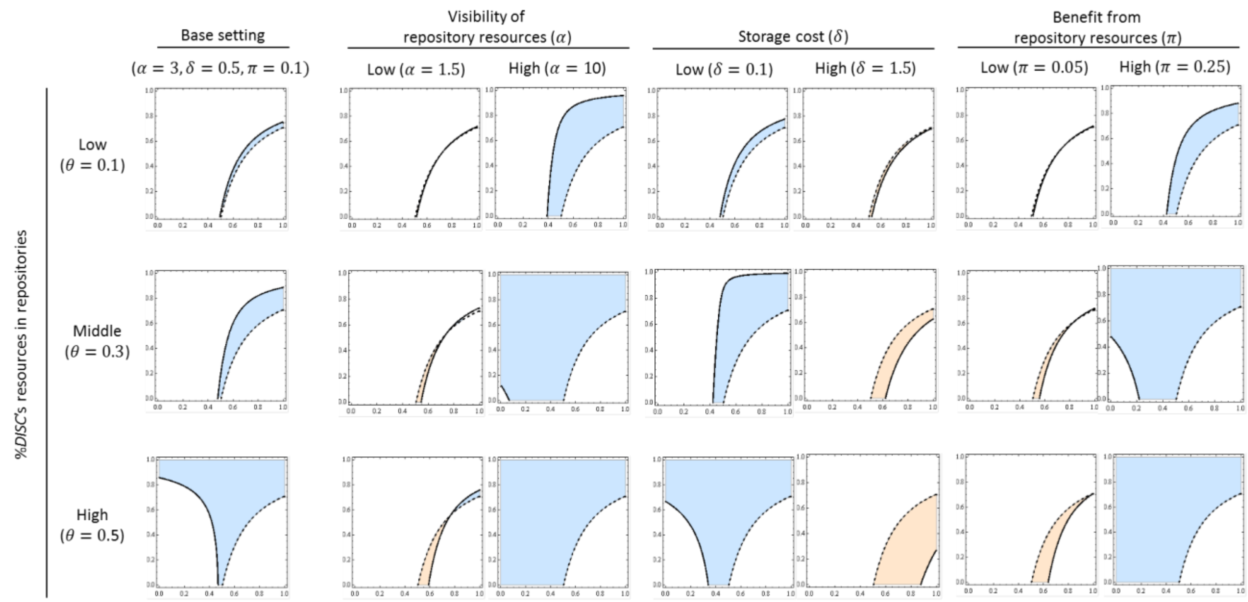
$$P_3 = -cgq\frac{1-\theta}{A} + bg_3q\frac{(1-\theta)x_3}{A} + (b-\tau)\frac{\alpha\theta x_3}{A} - \delta c\theta + \pi\frac{\alpha\theta}{A}, \text{ and}$$

$$P_4 = p(\beta-c)\frac{x_4+x_0}{A} + bg_4q\frac{(1-\theta)x_3}{A} + p(b-\gamma)\frac{x_4}{A} + (b-\tau)\frac{\alpha\theta x_3}{A}.$$

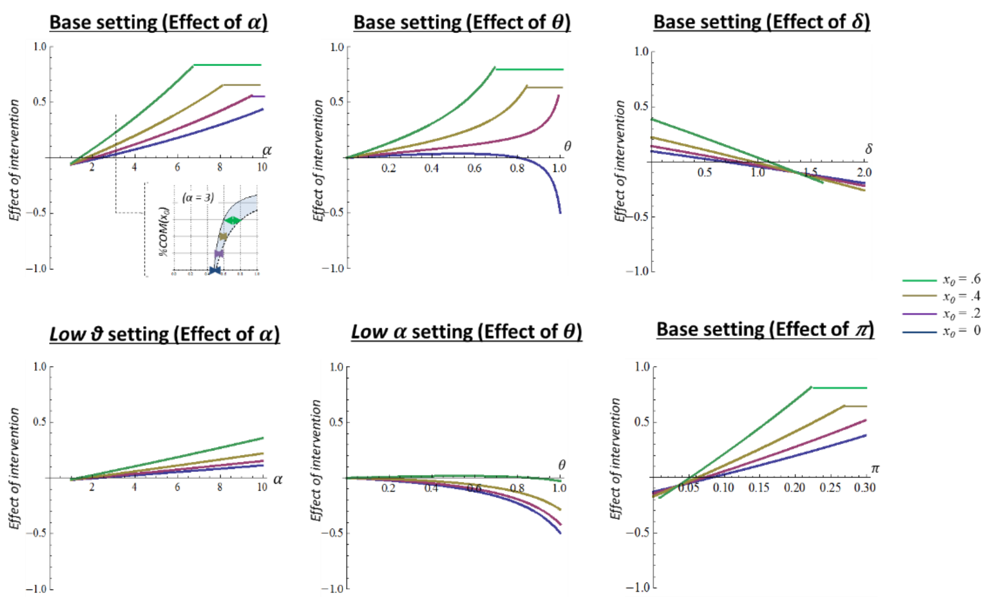
Repositories do not affect the equilibrium reputation because the probability of a certain type becoming a donor for each type is not affected (i.e., proportional to its frequency). Thus, the reputations of *DISC*, *PAY*, and *COM* follow the same argument as in Appendix 2B.

[a] The size of τ does not matter since it contributes to the payoff of *DISC* and *PAY* identically.

(B) Shift of Dynamics [a]



(C) Effect of Intervention [b]



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[a] Central repositories increase the basin of attraction for *DISC* in blue-shaded regions and shrink it in red-shaded regions. $b = 1.0$. $c = 0.2$. $\beta = \gamma = 0.3$. $p = 0.3$. $q = 0.8$.

[b] The effect is measured by the expanded part of the basin of attraction for *DISC* (indicated by the sub-graph in the top left panel). In the basic setting, $b = 1.0$, $c = 0.2$, $\beta = \gamma = 0.3$, $p = 0.3$, $q = 0.8$, $\alpha = 3$, $\theta = 0.3$, $\delta = 0.5$, $\pi = 0.1$. In low-θ setting, $\theta = 0.1$. In low-α setting, $\alpha = 1.5$.