Academic Entrepreneurship and the Changing Nature of Academic Cooperation: Indirect Reciprocity, Rewarding, and Abstention [*]

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ABSTRACT

As the trend of academic entrepreneurship has emphasized proprietary rights in academia, its 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 the Donation Game with reputation mechanism, this study shows the entrepreneurial regime could transform cooperators into defectors. Furthermore, when the options of bilateral transaction and abstention from cooperation are allowed, the growing trend makes academics demanding of direct return in exchange for cooperation, and then, hesitant to participate in cooperation. Thus, the current regime could weaken the norms of open science, which calls for policy interventions to sustain the cooperative climate. Further analyses suggest that some mechanisms (e.g., rewarding, central resource repositories) could mitigate these problems.

KEYWORDS

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

CLASSIFICATION CODE

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1. INTRODUCTION

The progress of science is critically based on the norms of open science, where scientific achievement is regarded as the property of the science community but not of individual academics, and thus, academics are expected to share their knowledge and resources with one another unconditionally (Merton, 1973). Particularly in natural sciences, various types of scientific resources (e.g., cell lines, model organisms, chemical substances, reagents, software, and data) are frequently shared, which eliminates the need for redundant efforts to reproduce research tools (Blumenthal et al., 1997; Campbell et al., 2002; Shibayama and Baba, 2011; Walsh et al., 2007). This practice of resource sharing is supposed to be altruistic (i.e., without charge and without condition), which is crucial because individual academics tend to specialize in a narrow research area and often need the resources of academics whom they may not personally know. While the underlying norms of open science seem generally complied with, growing concern has been expressed that the norms are in jeopardy under the changing regime of contemporary science (Dasgupta and David, 1994; Nelson, 2004; Shibayama et al., 2012).

Over the last decades, in the trend called academic entrepreneurship, science policies have emphasized more direct contribution of academic organizations to society and encouraged their engagement in commercial activities and collaboration with businesses (Etzkowitz, 1998; Geuna and Rossi, 2011; Nagaoka et al., 2009; OECD 2003; Slaughter and Leslie, 1997; Slaughter and Rhoades, 1996). As intended, infrastructure for entrepreneurial activities (e.g., technology transfer office) have been implemented, and an increasing number of academics are engaged in university start-ups, patent applications, technology transfer to industry, and other entrepreneurial activities (Etzkowitz, 1998; e.g., Grimaldi et al., 2011; AUTM 2007; Nagaoka et al., 2009; OECD 2003; Slaughter and Leslie, 1997). Although this trend might facilitate innovation originating from academia and benefit society, it has simultaneously developed the atmosphere emphasizing proprietary rights, which could be fundamentally inconsistent with the norms of open science (Dasgupta and David, 1994; Kleinman and Vallas, 2001; Nelson, 2004).[1] In fact, numerous empirical studies have shown that commercial academics (e.g., those participating in commercial activities) tend to withhold their research tools and information in favor of commercial profit (Blumenthal et al., 1997; Blumenthal et al., 2006; Walsh et al., 2007).

[1] Some literature argues that academic science and entrepreneurship can be compatible, (e.g., Murray, 2002; Thursby and Thursby, 2011; Zucker et al., 1998).

Importantly, this emerging regime may be undermining the norms of open science, affecting not only commercial academics but also other academics who do not engage in any commercial activities. In fact, Walsh et al. (2007) reported that the overall compliance rate of resource sharing in American life sciences has significantly declined in recent years. Shibayama et al. (2012) also show that prevailing entrepreneurship discourages unconditional sharing even among non-commercial academics in Japanese life and material sciences. Furthermore, Shibayama et al. (2012) suggest that high levels of entrepreneurship are associated with less reliance on the gratis form of sharing but with a greater emphasis on reward-based sharing, where donors demand direct benefit (e.g., coauthorship) from recipients, as well as a lower overall frequency of sharing. Similarly, using German and British biologist data, Haeussler (2011) suggests that the likelihood of sharing research information is related to community-level scientific norm, and that information sharing is facilitated by the expectation of reciprocity.

Despite these prior findings, empirical evidence for the weakening norms of open science is still lacking, and more importantly, a theoretical mechanism behind the possible disruption of cooperation has been understudied. Thus, this study aims to predict the potential influence of weakening norms under the regime of academic entrepreneurship and to evaluate the efficacy of possible policy interventions, drawing on the framework of the evolution of cooperation (Axelrod and Hamilton, 1981; Nowak and Sigmund, 1998; Sigmund, 2010). In so doing, this study offers implications for future empirical studies and policy design.

2. THEORETICAL BACKGROUND

2.1. Resource Sharing as Indirect Reciprocity

Resource sharing in natural sciences is a highly common practice; for example, on average, 3-5 requests are made every year in life sciences (Blumenthal et al., 1997; Campbell et al., 2002; Shibayama and Baba, 2011; Walsh et al., 2007). Furthermore, the compliance is fairly high; requests for research materials and data in life sciences are fulfilled more than 80% of the time (Blumenthal et al., 1997; Campbell et al., 2002; Walsh et al., 2007). In an ideal state of open science, where academics share their resources in a gratis and unconditional manner, each academic must bear the cost of giving (e.g., cost of preparing resources, etc.) for recipients, who may be a stranger. In general, such altruistic behavior is vulnerable to free riders. That is, self-interested players would receive cooperation but refuse to give. Anticipating this, rational players also avoid giving in the first place. Nevertheless, the human society offers many examples of altruistic cooperation such as blood contribution, donation, and peer review of academic papers (e.g., Blau, 1964; Ekeh, 1974). This paradox has provoked extensive debate in economics as well as sociology and biology, and a few mechanisms behind altruistic cooperation have been proposed (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 cooperative strategy is called direct reciprocity. Going beyond the restriction in this player assignment, 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 supposed to be matched more than once. Thus, donors cannot be rewarded directly by their recipients but can be indirectly by someone else. To sustain this mechanism, indirect reciprocity draws on social information. Simply put, players attach bad reputation to free riders to avoid cooperating with them. Thus, defection based on bad reputation works as a punishment. Further studies have suggested that more proactive sanctions (e.g., rewarding and punishing) could also sustain altruistic cooperation though such sanctions may need mechanisms to sustain themselves (Boyd et al., 2003; Fehr and Fischbacher, 2003; Sigmund et al., 2001). Network reciprocity is another mechanism that 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 resource sharing in academia 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 the 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 questionable for the practical difficulty of policing and punishing defectors. Among others, this study focuses 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 stingy donors sometimes spread the word about such uncooperative behavior, which can lead not only direct victims of stingy academics but also other academics in the community to avoid supporting them.

2.2. Basic Model of Indirect Reciprocity

Before discussing how academic entrepreneurship could compromise open science, this section illustrates how unconditional resource sharing can be sustained under ordinary circumstances. Following prior literature (Nowak and Sigmund, 1998; Sigmund, 2010), this study models indirect reciprocity with the Donation Game. 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 has 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 owing to shared resources, while donors have to bear some cost, which consists of the direct cost for preparing the resources and the indirect cost for foregoing competitive advantage that could have been maintained by rejecting 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). 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. For sustainable cooperation, DISC, a discriminate cooperator, is introduced. A DISC donor cooperates with recipients with good reputation but defects those with bad reputation.[2] For simplicity, this study uses dichotomous reputation, 0 (bad) and 1 (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. That is, 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).[3]

[2] This cooperation behavior is known as CO-strategy (Brandt and Sigmund, 2004).
[3] (Ohtsuki and Iwasa, 2004) identified several combinations of cooperation action and reputation rule that achieve stability and efficiency, and this study uses one of them.

The evolutionary dynamics of the three types is examined 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 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 after meeting a good recipient and becomes bad after meeting a bad recipient; $g_{1,n} = g_{n-1}$. Since an RATL donor always defects, his reputation becomes bad after meeting a good recipient and becomes good after meeting 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, the 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.[4] With this setting, $g_{3,n} = 1 - (1-q) g_{n-1}$. The following analysis draws on equilibrium reputation (Brandt and Sigmund, 2005) by solving these difference equations based on $g_n = g_{n-1}$.[5] The equilibrium frequency of good players in the whole population, g, and that among the i-th type, g_i, are 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,

$$P_1 = -c + bx_1 + bg_1 q\, x_3 \ldots (2a).$$ [6]

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 Appendix 1). Therefore,

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

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

[4] Some of the interviewees suggested that they would not cooperate with complete strangers. Of course, the opposite assumption is plausible, where a DISC donor may suppose its recipient as good when reputation is unknown. Prior literature suggests that this does not make a substantial difference.

[5] This is not only for mathematical tractability. Proper solution of the difference equations depend on arbitrarily given initial reputation. This is avoided by taking the equilibrium reputation.

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

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

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

where $\bar{P} = \sum x_i P_i$ (the average payoff) and $\dot{x}_i = \frac{dx_i}{dt}$. This equation describes the learning process, or shift from lower-payoff types to higher-payoff types. 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 F_{23} (a mix of RATL and DISC).[7] The phase space is split into two regions, and 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.

3. RESOURCE SHARING UNDER ACADEMIC ENTREPRENEURSHIP

3.1. Decreasing Cooperation

Based on the above model, this section examines the impact of academic entrepreneurship on the cooperation behavior of non-commercial academics. To model the entrepreneurial environment, this study introduces players corresponding to commercial academics, COM, with the following assumptions. 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 cooperation action 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; Blumenthal et al., 2006; 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 financing. Once they start a business, academics would not abandon it immediately when it turns out unprofitable. Thus, the following analyses exogenously control the frequency of commercial

[7] Solving $P_2 = P_3$ and $x_1 = 0$, F_{23} has coordinates $x_2 = 1 - \frac{c}{qb}$ and $x_3 = \frac{c}{qb}$ when $q > \frac{c}{b}$. If $q \leq \frac{c}{b}$, i.e., reputation availability is lower than the cost-benefit ratio, the whole space converges to the pure RATL. For a given $q > \frac{c}{b}$, as the cost-benefit ratio increases, the separatrix shifts upward and RATL prevails more easily.

academics and focus our attention on the evolutionary dynamics of non-commercial academics.[8] 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, since it is dominated by RATL and DISC. A modification of (2b) and (2c) gives the payoff for i-th type as follows:

$$P_2 = bg_2q\, x_3 \ldots (4a)$$

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

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 introduction of COM does not significantly affect the reputation of DISC but clearly improves that of RATL (Figure 2A). This is because RATL always defects bad COM players, which is evaluated as good. 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 $z_{3,F_{23}}$) 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. Thus, the rightward shift of the equilibrium implies that the invasion of COM enlarges the basin of attraction for RATL. Figure 2E illustrates the shift of the equilibrium within the whole range of COM, suggesting that a greater extent of COM creates a more favorable condition for RATL. Formally, $\frac{dz_{3,F_{23}}}{dx_0} > 0$. The proof is given in Appendix 2A.[9]

In summary, the entrepreneurial 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

[8] 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).

[9]

for cooperators. Second, commercial academics compromise the reputation mechanism. Academics gain reputation by cooperating with good academics or defecting bad academics. The prevalence of 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 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 entrepreneurship, academics become less willing to engage in unconditional cooperation.

3.2. Bilateral Transaction

In the face of malfunctioning indirect reciprocity, academics who need others' resources have a few options. 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 et al., 2012). This can be acceptable for rational donors because the risk of non-reciprocity is mitigated through negotiation. As long as the reward size is greater than the cooperation cost, reward-based cooperation is more profitable than defection. 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).[10] PAY is also rational; PAY donors cooperate only for profit (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 respectively. Reward-based cooperation yields payoff of β – c and b – γ for donors and recipients, respectively. I assume $c < \beta$ and $\gamma < b$ so that both sides benefit from this transaction.

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. Thus, as in a barter exchange,

[10] This setting is similar to Trust Game (Sigmund et al., 2001) but is different in that donors can know whether recipients are willing to reward or not through negotiation.

two players have to simultaneously find each other's resources valuable, but this is not very likely in academia, where individuals specialize in a narrow scientific area and recipients may possess nothing beneficial to donors. Coauthorship in expected publications might function as a currency, but donors may not value it (e.g., due to its perceived low quality) or may be skeptical if recipients can really publish. To incorporate this limitation, I introduce a parameter, $p \in [0,1]$, the matching rate at which a donor finds his recipient's reward valuable. To be specific, the following analysis models the case of coauthorship-based sharing, where a recipient gives away a certain credit in her publication to her donor. Upon request, a PAY donor evaluates whether coauthorship with his recipient is beneficial and cooperates only if it is. I assume that the contract of coauthorship is binding.[11] Thus, PAY is immune to the risk of non-reciprocity. I further assume that the value of this reward is equal for both sides ($\beta = \gamma$).

The evolutionary dynamics of DISC and PAY is analyzed with the existence of COM.[12] The payoffs for both types are given by

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

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

where x_4 denotes the frequency of PAY. Figure 3 illustrates how the invasion of COM affects the balance between DISC and PAY. 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 DISC occupies a large frequency. The phase diagram shows that the unstable equilibrium shifts rightwards. Formally, $\frac{dz_{3,F_{34}}}{dx_0} > 0$, where $z_{3,F_{34}}$ denotes the z_3-coordinate of the unstable equilibrium. Therefore, the invasion of COM creates a more favorable condition for PAY than for DISC (mathematical details in Appendix 2B).

These analyses suggest 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. In practice, plausible rewards include coauthorship and so forth. This one-to-one direct exchange resembles an economic transaction, where the immediate payment offers an incentive for the transaction.

[11] Our interviews suggest that the promise of coauthorship is usually kept. Of course, recipients may fail to publish a paper, which is understood as a smaller value of return payment.
[12] I focus on these two strategies because indirect reciprocity (DISC) is of primary interest in this study. ALLC is dominated by DISC and PAY, and RATL is dominated by PAY.

However, the academic context allows only an incomplete economic transaction 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 with fewer transactions (the gray lines in Figure 3B).[13] Even so, academics would resort to such suboptimal behavior to avoid being exploited by free riders.

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

3.3. 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 entrepreneurial 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 usually 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. Then, 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, direct their efforts to 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 Games makes at least some sense.[14] 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

$$P_3 = -cg_{-5}q(x_0 + x_3) + bg_3qx_3 \dots (6a)$$

[13] 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 $q = 0.8$.

[14] 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.

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

where g_{-5} denotes the average reputation of non-ABST players. Figure 4A shows that the invasion of COM decreases the payoff for DISC. Under the entrepreneurial regime, indirect reciprocity becomes vulnerable to loners, who secure the minimum payoff by avoiding cooperation.

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

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

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 (mathematical details in Appendix 2C).

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

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

3.4. Integrated Model

For a holistic view, I further examine the dynamics of multiple types. I examine the dynamics of DISC, PAY, and ABST under varying levels of COM invasion, omitting ALLC and RATL, which are dominated by some of the other types. Mathematical details are given in Appendix 3. Figure 5A shows 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 affected by a high prevalence of COM. Additionally, I examine the sensitivity to parameter settings. Figure 5C shows that the basin of attraction for DISC consistently shrinks with greater frequencies of COM, and that DISC with low availability of reputation, q, is especially vulnerable. 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 2C).

4. INTERVENTION

With prior empirical findings (Shibayama et al., 2012; Walsh et al., 2007) and the above mathematical predictions for possible disruption of cooperation, what policy interventions are feasible? A simplistic option may be to reverse the trend of entrepreneurship. Though completely abandoning entrepreneurial effort is unrealistic, it may be plausible to reduce the incentive of commercial participation (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 the tools are used mainly in 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 regime might be impossible. Such irreversibility has been observed in reality, where the introduction of economic incentives has rationalized people and destroyed social norms (Bowles, 2008; Gneezy and Rustichini, 2000).

4.1. Rewarding

A more proactive incentive system may be feasible. Literature suggests that rewarding and punishing contribute to sustaining cooperation (Baldassarri and Grossman, 2011; Rand et al., 2009). Mechanisms to officially punish defectors do exist in academia though their effect has been questioned (NAS 2003). More recently, science communities have been calling for rewarding mechanisms for cooperators, such as mandating acknowledgments (Schofield et al., 2009; NAS 2003). Since this is mandated by the central authority and imposes practically no cost on recipients, it is different from the private rewarding in bilateral transaction (Ch.3.2) and is theoretically closer to centralized rewarding. This section examines how rewarding could stabilize cooperation under the entrepreneurial environment.

First, I investigate the effect of rewarding on the evolutionary dynamics between RATL and DISC with the existence of COM (detail in Appendix 4). 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. Then, if $r < c$, they keep defecting. However, if $r > c$, defection is not optimal for RATL donors, but instead, they cooperate as if they were ALLC. Further, I assume that DISC is not affected by rewarding because cooperating with bad recipients is still against the norms of open science. Figure 6A (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). Thus, even if the invasion of COM created a favorable condition for RATL, DISC could regain its advantage with the support of rewarding. However, when $r > c$, the effect of rewarding could become limited because RATL also takes advantage of the rewarding. Especially, in the red region, the rewarding allows RATL to dominate DISC, which should be otherwise evolutionarily stable. If $r > c$ and RATL dominates, the average cooperation level would be very 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 short-term profit. Therefore, the central authority must choose an optimal (not too large) size of rewarding to sustain 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 behavior is not affected by the rewarding. When $r > c$, PAY acts like ALLC to exploit the (centralized) rewarding. Figure 6A (bottom row) shows the shift of dynamics. The effect of rewarding is rather limited compared to the case with RATL. Likewise, excessive centralized rewarding could be counterproductive.

Figure 6B illustrates the effect of rewarding as a function of the reward size. For the competition of DISC vs. RATL (upper row), the rewarding is effective when the reward size is around the cooperation cost ($c = 0.2$ in this example). The rewarding is even more effective when the frequency of COM is higher. The choice of an adequate size of rewarding is rather difficult when the reputation availability, q, is low (upper right), where a reward size only slightly above the cooperation cost could make a negative impact. When private rewarding is allowed (bottom row), the situation is aggravated in that (centralized) rewarding smaller than cooperation cost becomes even 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.

As actual interventions, the central authority might be able to literally offer cooperators some rewards such as awards and research funds. In such cases, the choice of reward size is critical as above discussed. Another possibility is acknowledgments, as is recommended by science communities (NAS2003). However, as academics are usually evaluated by publication record, the impact of acknowledgments, which are not counted as publication, is unclear. 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.

4.2. Transfer of 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. This is probably because the cost for collecting fees is not negligible, or because fair pricing is difficult and money payment is sometimes prohibited. To overcome these issues, it may be possible that universities or the central authority act as an agent for academics in collecting fees and supplying resources. Mathematically, this has a similar effect to the rewarding.[15] That is, as long as an adequate fee level is chosen, it could protect DISC against RATL, but it is less effective against PAY.

4.3. 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. 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 has not played a main role in resource sharing thus far, and the vast majority of resource sharing still depends on bilateral transactions between individual academics. This section investigates how central repositories could stabilize indirect reciprocity in a population of DISC

[15] For donors, cooperation cost covered by charging is the same as centralized rewarding. For recipients, fee payment can be understood as the reduction of cooperation benefit from b to b - r.

and PAY with the existence of COM, where DISC pools part of their resources in repositories to facilitate sharing (details in Appendix 5).

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 could be higher than cooperation cost for bilateral sharing. Still, this is a one-time cost and can be discounted by repeated sharing. These factors taken together, the storage cost is given by δc ($\delta > 0$; $0 < \delta < 1$ suggests a discount). 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 Stern, 2011), a resource in repositories is more likely to be requested than a resource not in repositories. The ratio of these probabilities is denoted by $\alpha \geq 1$. 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 through repositories, its original owner earns benefit, $\pi \in (0, \beta)$,[16] through acknowledgments, citations, and so forth. Furman and Stern (2011) suggest that original owners of repository resources have their papers cited more often.

Figure 7 illustrates the effect of central repositories with some parameter settings (details in Appendix 5B). 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 (top-right panel) and low visibility (middle right) substantially compromises the effect of repositories, that storage cost needs to be suppressed (bottom left), and that minimum benefit needs to be given to the owners of repository resources (bottom right). 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 effort financially or technically, disseminate resource information, and make rules about the acknowledgments, etc. With all these efforts, repositories can contribute to sustaining open science. Note that repositories essentially offer the mechanisms of rewarding and cost transfer. Central repositories have some limitations. Among others, most resources are of special and infrequent

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

use, and thus, donors would possibly be discouraged by the storage cost. As the maintenance of repositories is costly, repositories would need to be selective in the resources that they store.

5. DISCUSSION AND CONCLUSIONS

Although academic science heavily depends on the norms of open science (Merton, 1973), the recent regime of academic entrepreneurship has been emphasizing the private rights to the achievements from academic science (Etzkowitz, 1998), and the conflict in these two notions seem to affect the practice of science (Dasgupta and David, 1994; Kleinman and Vallas, 2001; Nelson, 2004). The slowdown of open science has been noticeably observed in resource sharing; commercial academics tend to be reluctant to give their resources for the sake of commercial profit (Blumenthal et al., 1997; Campbell et al., 2002; Shibayama and Baba, 2011; Walsh et al., 2007). Importantly, a few recent empirical studies imply that the regime shift could rationalize not only commercial academics but also non-commercial academics (Shibayama et al., 2012). The current study aims to explicate the mechanism behind these observations and to predict possible consequences under the current regime.

This study models the resource sharing in the ideal state of open science as indirect reciprocity (Nowak and Sigmund, 1998) and simulates the impact due to the invasion of commercial academics. The mathematical analyses suggest that the growing entrepreneurship 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 benefit, but this is not always feasible for the limitation of barter exchange. 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 entrepreneurial regime could undermine the climate of open science, which underpins the progress of science. Thus, although the goal of academic entrepreneurship is to facilitate the practical use of achievement from academia, it could damage the very source of academic achievement. Subsequently, this study investigates whether such unintended consequences could be mitigated with some interventions. Rewarding is 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 sustain indirect reciprocity, but arranging a series of conditions (e.g., dissemination of resource information) is necessary.

This study offers some implications for future empirical research. First, non-cooperative behavior of academics in general is of a practical interest. Though it is implied by Shibayama et al. (2012), empirical evidence in more diverse contexts (e.g., fields, countries) is needed. In addition, inter-temporal change in the practice of cooperation needs stronger empirical basis. Cooperation based on private rewarding is also of theoretical concern in that gratis cooperation is supposed to be the norm in academia (Merton, 1973). Future empirical research should inquire into detailed conditions of cooperation and identify what kinds of direct and indirect incentive structure are at work. Abstention from cooperation is also interesting. Future research should investigate more about recipients (rather than donors) to elucidate the antecedents of the willingness to ask for cooperation. Second, the parameters employed in this study need empirical investigation. 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 feasibility of bilateral transaction (the matching rate, p) should also be examined. The value of rewarding, private or centralized, for academics (β, γ, and r) should be investigated, such as coauthorship, acknowledgements, citation, and future support. This is important information in designing policy interventions. In addition, the cost structure of cooperation 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 advantage. Third, the weakening norms of open science could cause a more general effect on the practice of science. Thus, different types of egoistic behavior (e.g., secrecy, misconduct) should be investigated in connection with the regime shift.

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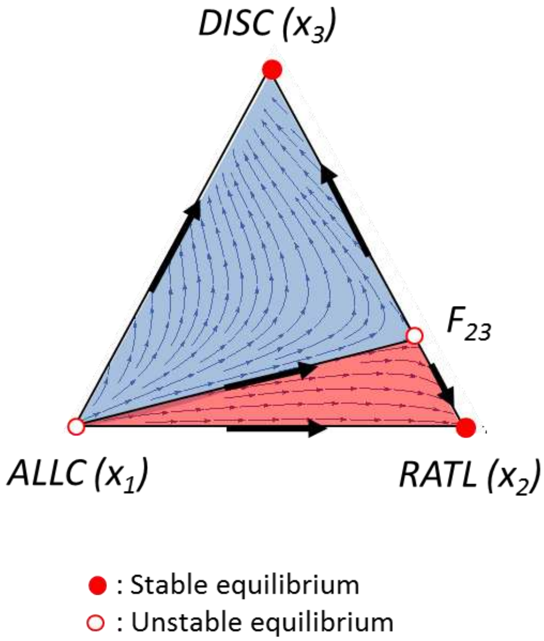
Table 1 List of Types

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 for 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

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



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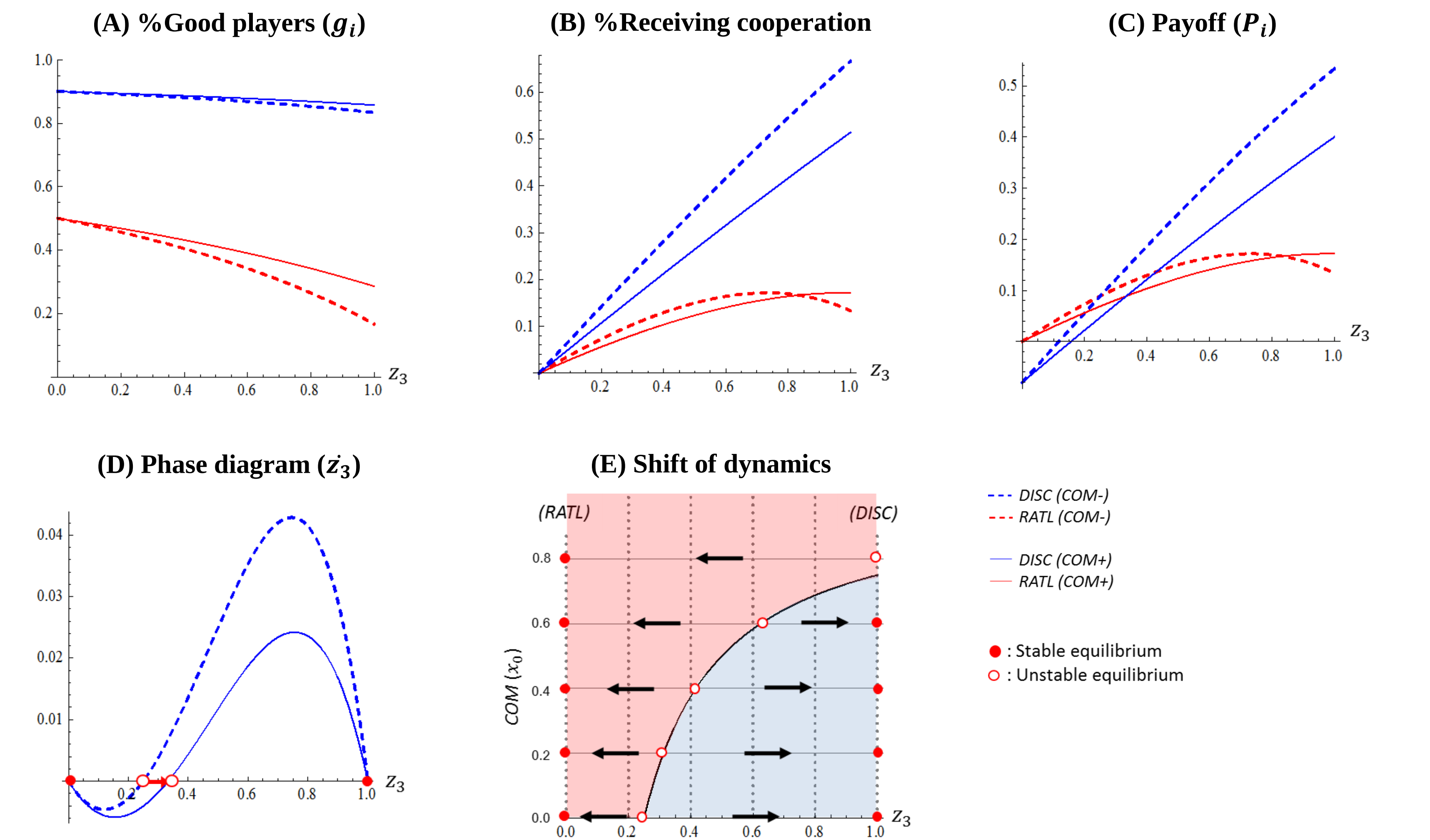
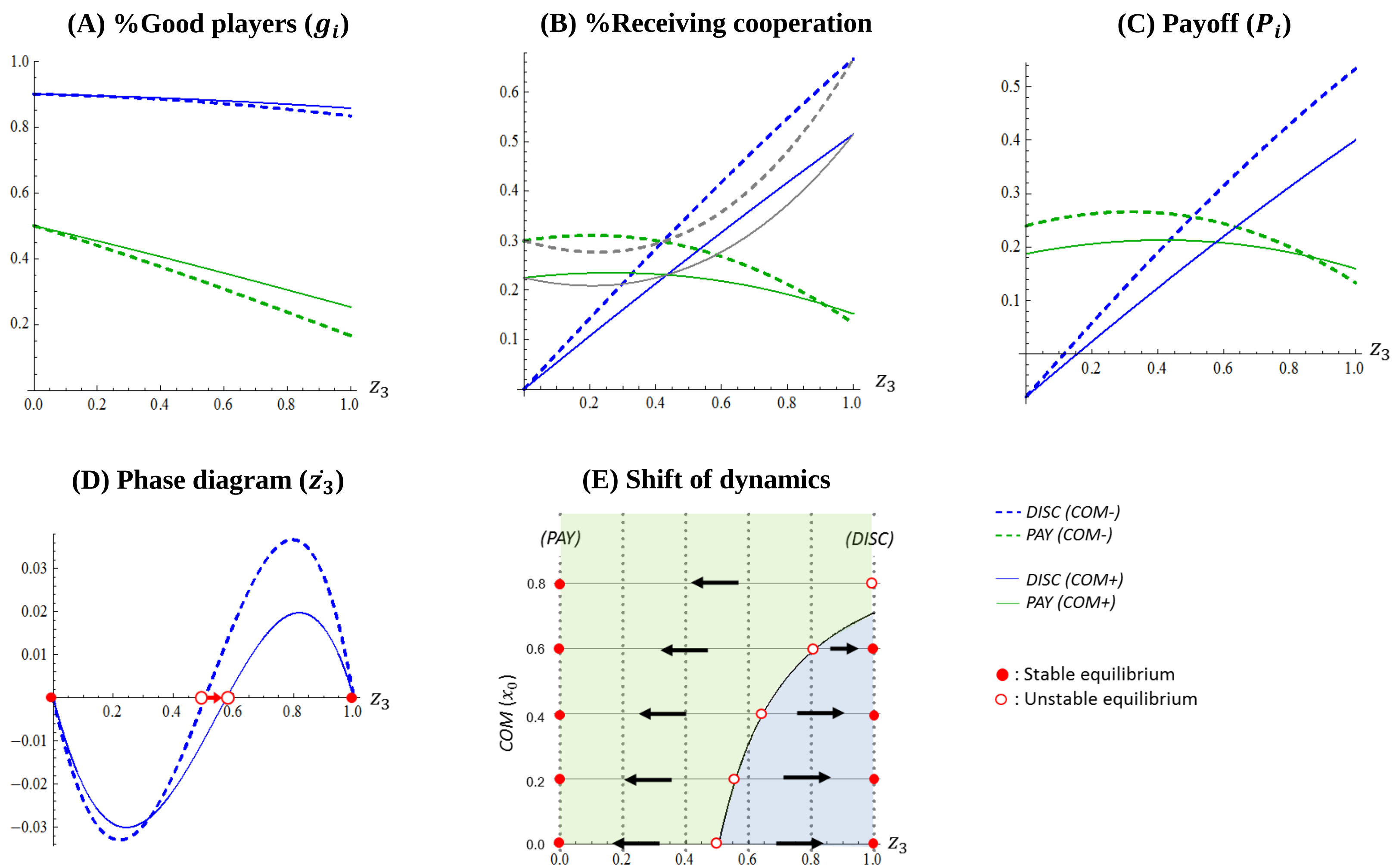
[a] The pure RATL (0,1,0) and the pure DISC (0,0,1) are stable equilibria. No interior equilibrium, where $P_1 = P_2 = P_3$, is found. $F_{23}\left(0,1-\frac{c}{qb},\frac{c}{qb}\right)$ and the pure ALLC (1,0,0) are unstable equilibria. The phase space is separated into one area converging to DISC (Blue) and the other converging to RATL (Red). b = 1.0. c = 0.2. q = 0.8.

Figure 2 RATL vs. DISC with COM [a]



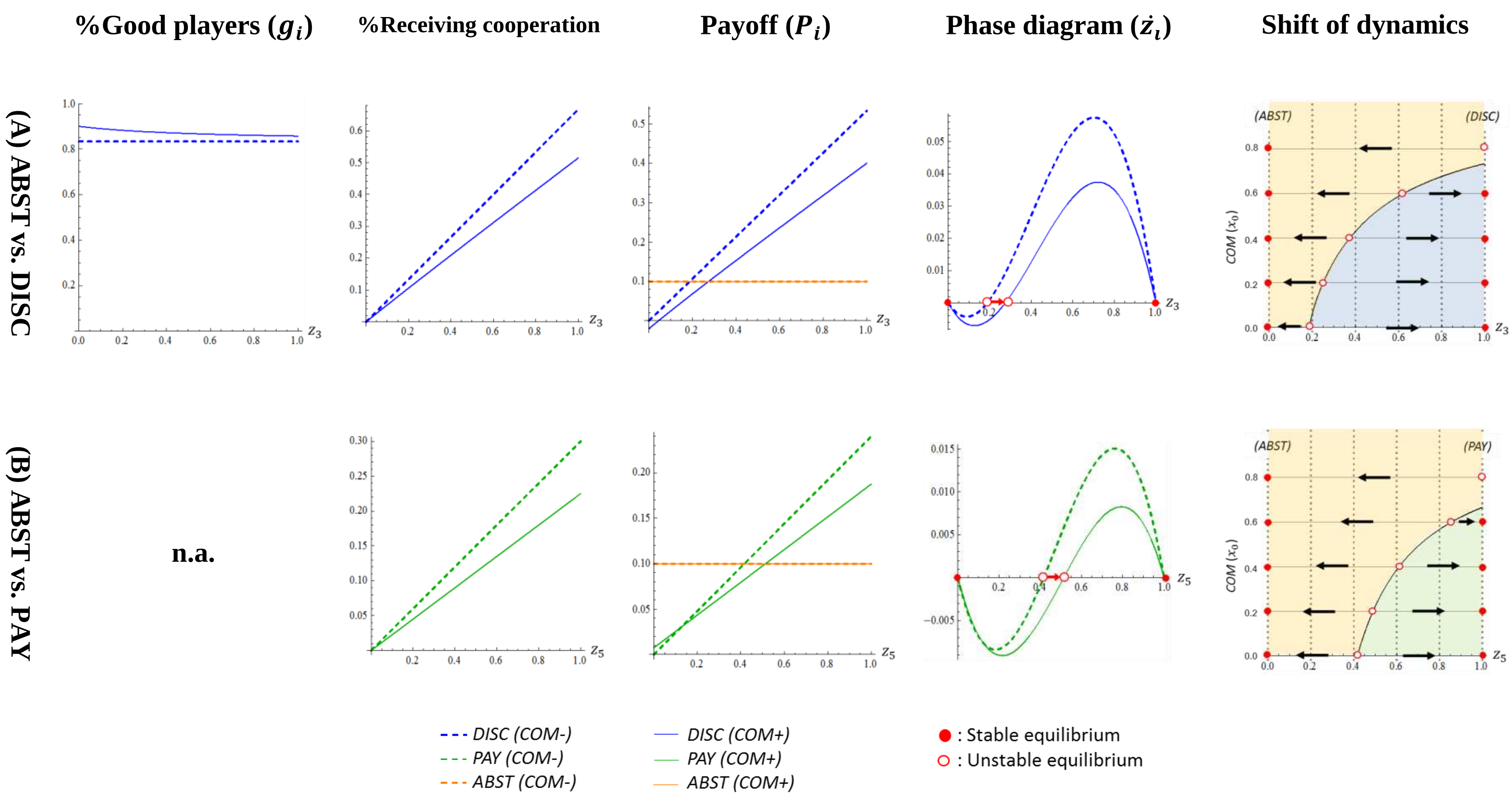
[a] Blue: DISC, Red: RATL. Solid line: with COM (x_0 = 0), Dashed line: without COM (x_0 = 0.25). In (D) and (E), red circles are stable equilibria and red outlined circles are unstable equilibria. To the right of the equilibrium, the dynamics moves rightwards (greater frequency of DISC). To the left of the equilibrium, the dynamics moves leftwards (greater frequency of RATL). b = 1.0. c = 0.2. q =0.8.

Figure 3 PAY vs. DISC with COM [a]



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

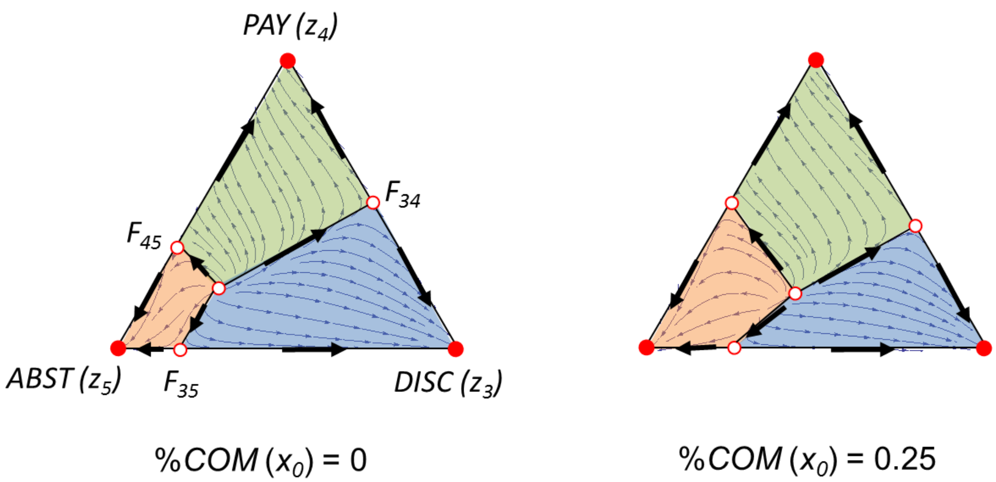
Figure 4 ABST vs. DISC and PAY with COM [a]



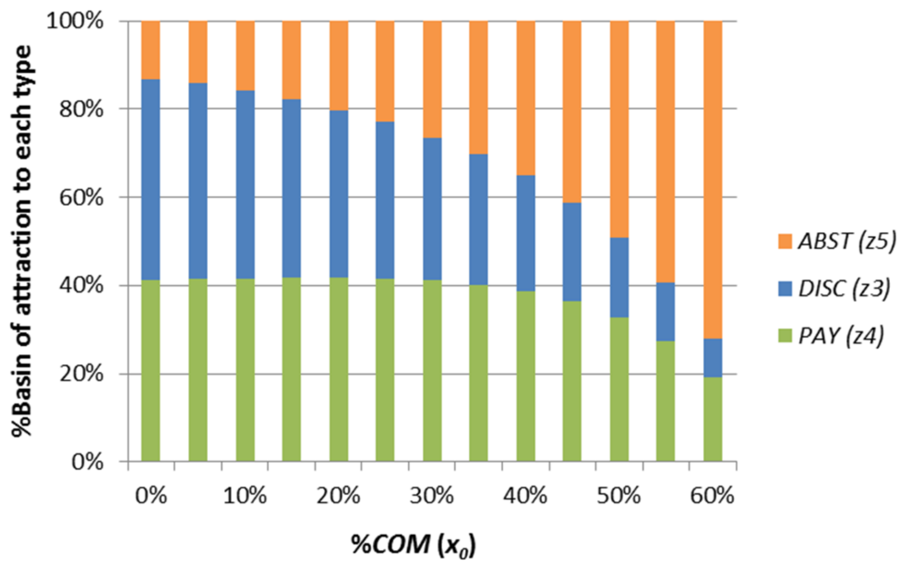
[a] Blue: DISC, Green: PAY, Orange: ABST. Solid line: with COM ($x_0 = 0$), Dashed line: without COM ($x_0 = 0.25$). b = 1.0. c = 0.2. $\beta = 0.3$. $\sigma = 0.1$. q = 0.8. p = 0.3.

Figure 5 DISC, PAY, vs. ABST with COM [a]

(A) Numerical Phase Plot

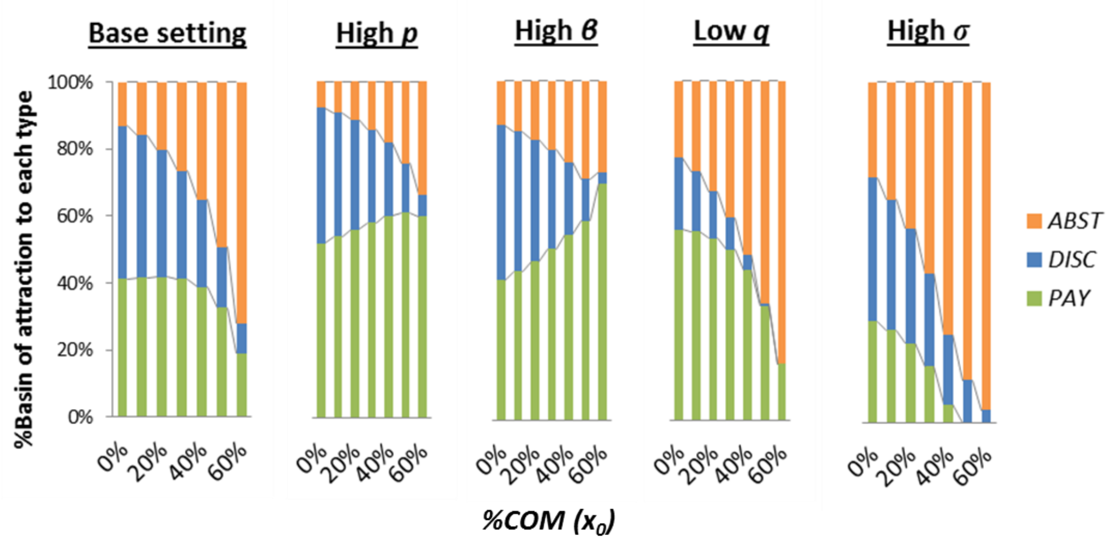


(B) Basin of Attraction



[a] b = 1.0. c = 0.2. β = 0.3. σ = 0.1. p = 0.3. q = 0.8. For the computation of area percentage (B and C), see Appendix 2D.2.

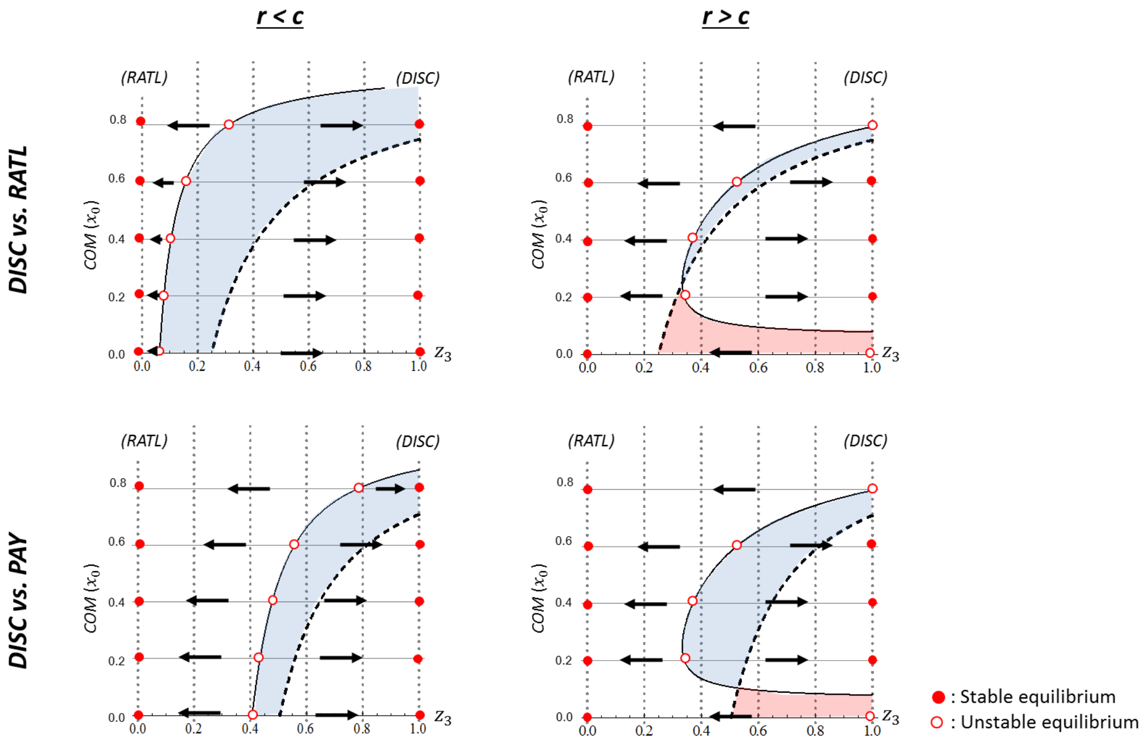
(C) Sensitivity to parameter setting [a]



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

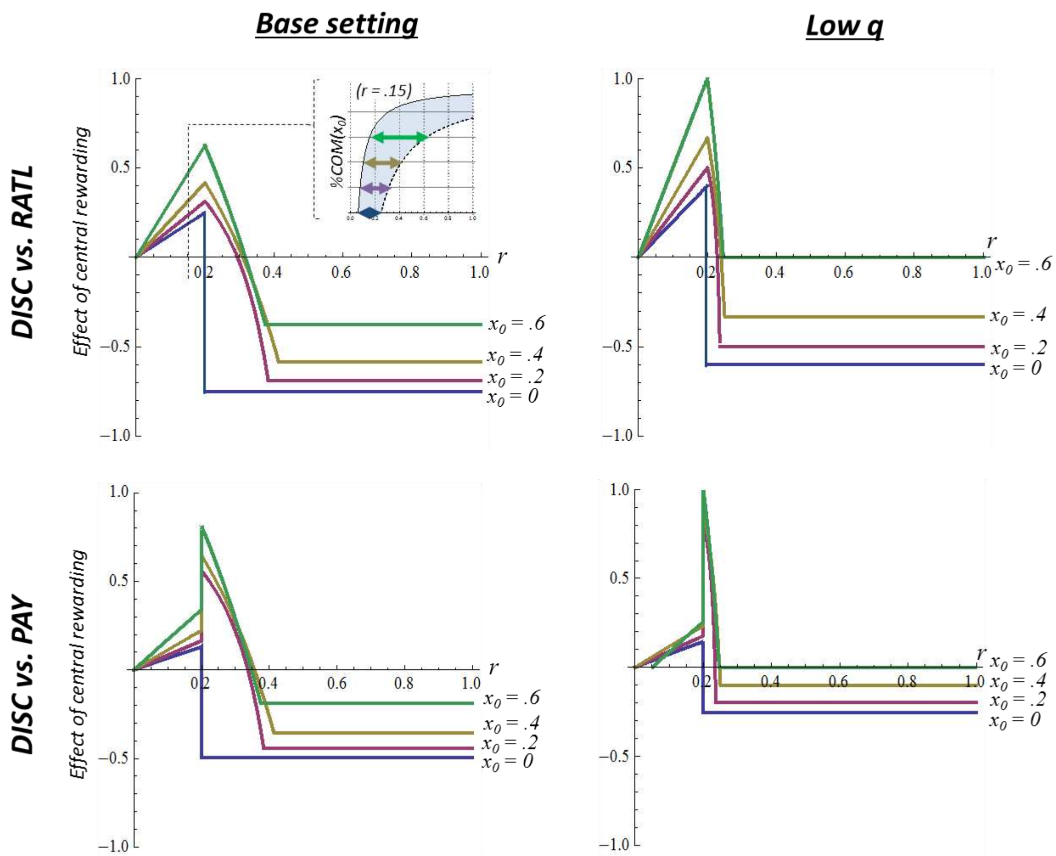
Figure 6 Central Rewarding

(A) Shift of dynamics [a]



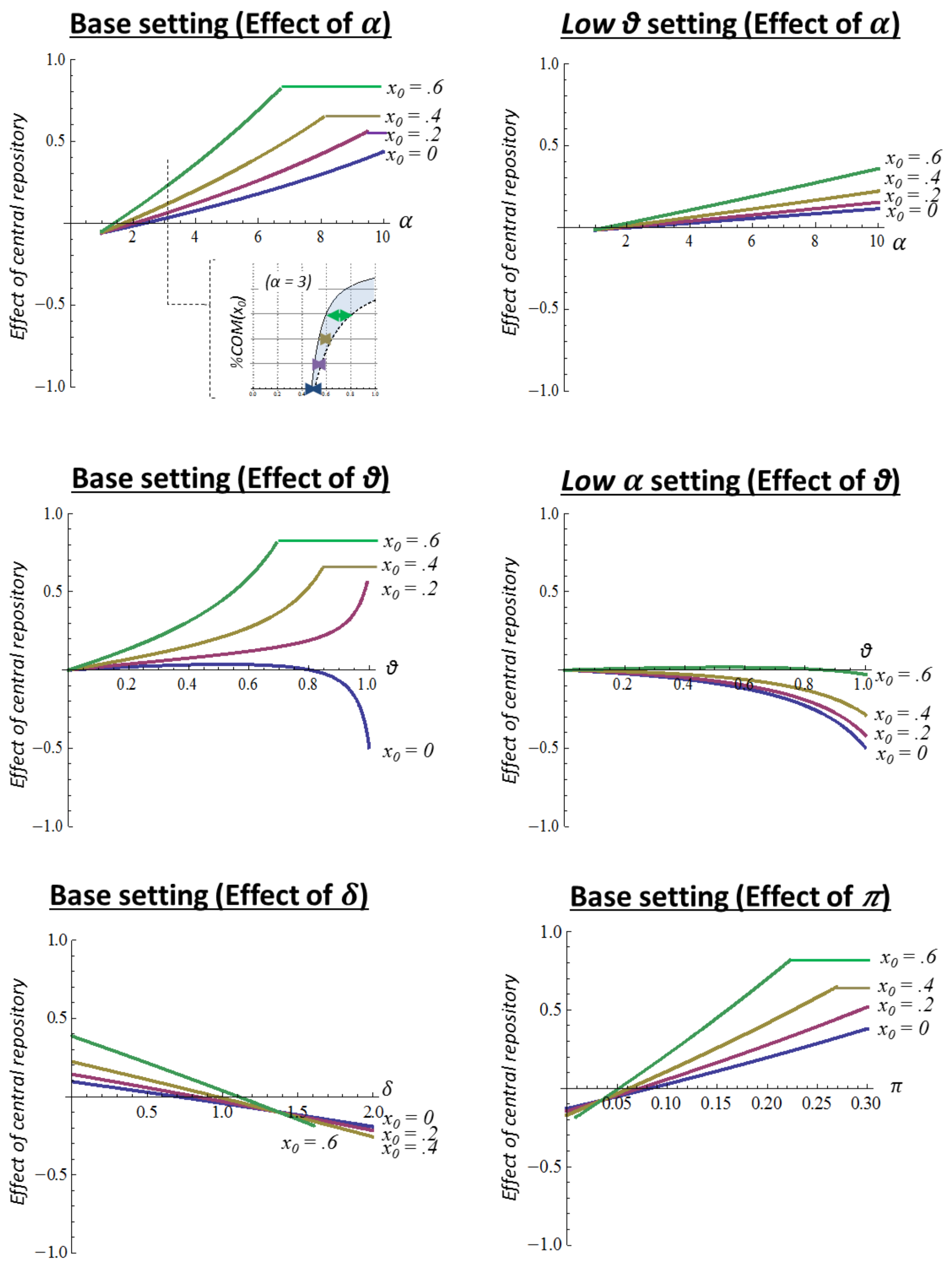
[a] Solid curves are unstable equilibria when central rewarding is implemented, and dashed curves are those without it. DISC is shrinking ($\dot{z}_3 < 0$) to the left of the equilibria and increasing ($\dot{z}_3 > 0$) to the right. Thus, the central rewarding expands the basin of attraction for DISC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

(B) Effect of Central Rewarding [a]



[a] 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. β = 0.3. p = 0.3. q = 0.8 in the base setting and q = 0.5 in the low-q setting.

Figure 7 Effect of Central Repository [a]



[a] 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, β = 0.3, p = 0.3, q = 0.8, α = 3, θ = 0.3, δ = 0.5, π = 0.1. In low-θ setting, θ = 0.1. In low-α setting, α = 1.5.

Appendix 1 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	$0, 0$	$p(\beta - c), p(b - \beta)$	$0, 0$	$p(\beta - c), p(b - \beta)$	$0, \sigma$	$p(\beta - c), p(b - \beta)$
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.

Appendix 2 Mathematical Details for Propositions

A. Proposition 1

The equilibrium reputation satisfies $g_2 = g_0 = 1 - g$, $g_3 = 1 - (1-q)g$, and $g = x_2 g_2 + x_3 g_3 + x_0 g_0$. Thus, $g = \frac{1}{2 - q z_3 (1 - x_0)}$. From (4a) and (4b), $P_3 - P_2 = \frac{q\{qbz_3(1-x_0) - c\}}{2 - q z_3 (1 - x_0)}$. The solution of $P_3 - P_2 = 0$ for z_3 gives $z_{3,F_{23}} = \frac{c}{qb(1-x_0)}$.[a] $\frac{dz_{3,F_{23}}}{dy} = \frac{c}{qb(1-x_0)^2} > 0$. ■

B. Proposition 2

A PAY donor, upon request, first examines if his recipient has a profitable reward, and if so, he negotiates with the recipient and cooperates with her only if she is willing to give the reward. I assume that recipients of rational types (i.e., PAY and COM) agree with this condition but that DISC does not agree with it because it violates the norms of open science (see Appendix 1). 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 $g_4 = (1 - g_3)x_3 + \{pg_4 + (1-p)(1-g_4)\}x_4 + \{pg_0 + (1-p)(1-g_0)\}x_0$. With $g_0 = 1 - g, g_3 = 1 - (1-q)g$ and $g = x_3 g_3 + x_4 g_4 + x_0 g_0$, it is obtained $g = \frac{1 + p(1-x_0)(1-z_3)\{1 + (1-x_0)z_3\}}{2 - 2p(1-x_0)(1-z_3)\{1 + (1-q)(1-x_0)z_3\} - q(1-x_0)z_3}$. From (5a) and (5b), $P_3 - P_4 = b(g_3 - g_4)qx_3 - p(\beta - c)x_0 - p(b-c)x_4 - cgq$. The right-hand side is rearranged as $\frac{f(z_3, x_0)}{g(z_3, x_0)}$, where $g(z_3, x_0) > 0$ and $f(z_3, x_0)$ is a cubic function of z_3. Thus, $z_{3,F_{34}}$ is the solution of $f(z_3, x_0) = 0$ for z_3, but this is analytically unsolvable. Thus, I attempt to indirectly show $\frac{dz_{3,F_{34}}}{dx_0} > 0$ drawing on simulation. From the whole parameter regions ($c \in [0,1], \beta \in [c,1], p \in [0,1], q \in [c,1]$, 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 $[0,1)$,[b] it is denoted by z_3^*. Then, the same equation is solved again with the same set of parameters with x_0 being replaced by $x_0 + \varepsilon$, where $\varepsilon = \frac{1}{10000}$. This solution is denoted by z_3^{**}. If $z_3^{**} > z_3^*$, it implies that $\frac{dz_{3,F_{34}}}{dx_0} > 0$ at this parameter setting. I repeated this process 10,000 times and found no incident against the proposition. ■

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

[b] No incident was found where three solutions are in the [0,1).

C. Proposition 3

C.1. 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 $y = \frac{x_0}{1-x_0}$, the ratio of commercial players to non-commercial players ($y \geq 0$).

I evaluate $\frac{dz_{3,F_{35}}}{dy}$ instead of $\frac{dz_{3,F_{35}}}{dx_0}$ on the basis that $\frac{dx_0}{dy} = \frac{1}{(1+y)^2} > 0$. From (6a) and (6b), $P_3 - P_5 = \frac{q\left[b\{z_3^2+(1+q)yz_3\}-c(z_3+y)^2\right]}{\{(2-q)z_3+2y\}(1+y)} - \sigma$. Let $f(z_3, y) = P_3 - P_5$. Since $f\left(z_{3,F_{35}}(y), y\right) = 0$, $\frac{dz_{3,F_{35}}}{dy} = -\frac{\partial f}{\partial y} \Big/ \frac{\partial f}{\partial z_3}$. Because $\frac{\partial f}{\partial z_3} = \frac{\{2(1+q)b-(2+q)c\}y^2+4(b-c)yz_3+(2-q)(b-c)z_3^2}{(1+y)(2y+(2-q)z_3)^2} > 0$, it suffices to show that $\frac{\partial f}{\partial y} < 0$ to prove $\frac{dz_{3,F_{35}}}{dy} > 0$. However, $\frac{\partial f}{\partial y} = \frac{(qb-2c)(1-q)z_3^2-(2-q)(b-c)z_3^3-4(b-c)yz_3^2-\{2(1+q)b-(2+q)c\}y^2z_3-2(2-q)cyz_3-2cy^2}{(1+y)^2(2y+(2-q)z_3)^2}$ is not necessarily negative. The numerator of $\frac{\partial f}{\partial y}$ is a decreasing function of y. Thus, if $\frac{\partial f}{\partial y}(z_3, 0) < 0$, $\frac{\partial f}{\partial y} < 0 \ \forall y \geq 0$. Solving $\frac{\partial f}{\partial y}(z_3, 0) < 0$, I obtain $z_3 > z_3^*$, where $z_3^* = \frac{(qb-2c)(1-q)}{(2-q)(b-c)}$. Thus, if $z_{3,F_{35}}(0) > z_3^*$, it follows that $\frac{\partial f}{\partial y} < 0 \ \forall y \geq 0$. This condition is satisfied if $c > \frac{qb}{2}$ or $\sigma > \frac{q(1-q)(qb-2c)}{(2-q)^2}$.[a] Otherwise, $\frac{\partial f}{\partial y} < 0 \ (y > y^*)$ and $\frac{\partial f}{\partial y} > 0 \ (0 \leq y < y^*)$, where y^* is the solution of $\frac{\partial f}{\partial y}(z_3, y^*) = f(z_3, y^*) = 0$.[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. Even if not, with minimal frequency of COM, ABST starts to gain advantage over DISC. ■

C.2. PAY vs. ABST

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[a] This threshold of σ takes the maximum of approximately 0.09b when $q = 3 - \sqrt{5}$ and c = 0.

[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 $x_0 = 1.2\%$.

Since DISC is not present, reputation is irrelevant. From (6b) and (6c), $P_4 - P_5 = p(\beta - c)(x_4 + x_0) + p(b - \beta)x_4 - \sigma$. Solving $P_4 - P_5 = 0$ for z_4, $z_{4,F_{45}} = \frac{\sigma - p(\beta - c)x_0}{p(b-c)(1-x_0)}$. $\frac{dz_{4,F_{45}}}{dx_0} = \frac{\sigma - p(\beta - c)}{p(b-c)(1-x_0)^2}$. $\frac{dz_{4,F_{45}}}{dx_0} > 0$ 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 3 Integrated Model

A. Payoff and reputation equations

For the reputation, the same argument applies as in Appendix 2.C.1. $g_3 = 1 - (1-q)g_{-5}$ 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 $g_4 = \frac{(1-g_3)x_3 + \{p g_4 + (1-p)(1-g_4)\}x_4 + \{p g_0 + (1-p)(1-g_0)\}x_0}{x_3 + x_4 + x_0}$. The payoffs for DISC and ABST follow (6a) and (6b) respectively, and that of PAY is $P_4 = p(\beta - c)(x_0 + x_4) + b g_4 q x_3 + p(b - \beta)x_4$.

B. Computation of the areas percentage of basin of attraction

The area percentage of the basin of attraction for each type (Figures 5B and 5C) is computed as follows. The initial coordinate (z_3, z_4, z_5) is chosen to cover all the lattice points in the phase space with the interval of 0.02 (1,326 points). For each initial coordinate, the simultaneous differential equations, $\dot{z_3} = z_3(P_3 - \bar{P})$ and $\dot{z_4} = z_4(P_4 - \bar{P})$, are numerically solved. If the coordinate at t = 10,000 is within the distance of 0.01 from one of the three pure types, it is regarded as a convergence to the type. Then, the percentage of cases converging to each type is used as the areas percentage of basin of attraction.

Appendix 4 Rewarding Model

A. Model description

Under 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 < β. 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 and payoff equations are given as:

$$g_2 = \begin{cases} 1-g & (r<c) \\ g & (r>c) \end{cases},$$

$$g_3 = 1-(1-q)g,$$

$$g_0 = 1-g,$$

$$P_2 = \begin{cases} bg_2qx_3 & (r<c) \\ r-c+bx_2+bg_2qx_3 & (r>c) \end{cases}, \text{ and}$$

$$P_3 = \begin{cases} (r-c)qg + bg_3qx_3. & (r<c) \\ (r-c)qg+bx_2+bg_3qx_3 & (r>c) \end{cases}.$$

Likewise, for PAY and DISC, the reputation and payoff equations are given as:

$$g_3 = 1-(1-q)g,$$

$$g_4 = \begin{cases} (1-g_3)x_3 + \{pg_4+(1-p)(1-g_4)\}x_4 + \{pg_p+(1-p)(1-g_p)\}x_0 & (r<c) \\ g & (r>c) \end{cases},$$

$$g_0 = 1-g,$$

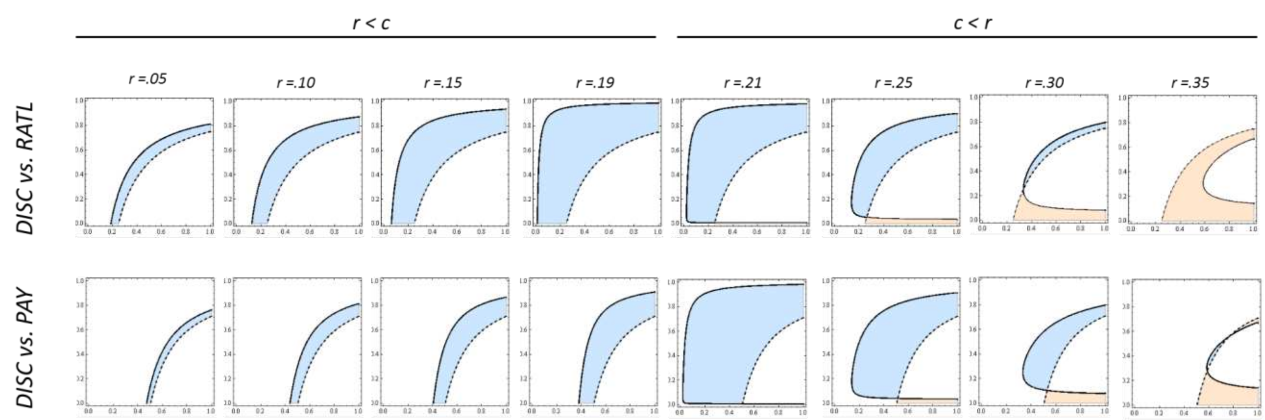
$$P_3 = \begin{cases} (r-c)qg + bg_3qx_3 & (r<c) \\ (r-c)qg + bg_3qx_3+bx_4 & (r>c) \end{cases}, \text{ and}$$

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

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	$r < c$	$p(\beta - c), p(b - \beta)$	$0, 0$	$p(\beta - c), p(b - \beta)$	$p(\beta - c), p(b - \beta)$
	$r > c$	$r - c, b$	$r - c, b$	$r - c, b$	$r - c, b$
0: COM		$0, 0$	$0, 0$	$0, 0$	$0, 0$

C. Shift of dynamics [b]



[a] The left-hand number in each cell is the payoff for the donor and the right-hand number is that for the recipient.
[b] 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. β = 0.3. p = 0.3. q = 0.8.

Appendix 5 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 ($p(b - \beta)$); and the benefit from using repository resources ($b - \omega$), where ω is the fee paid to repositories.[a] The payoff for each type is given by:

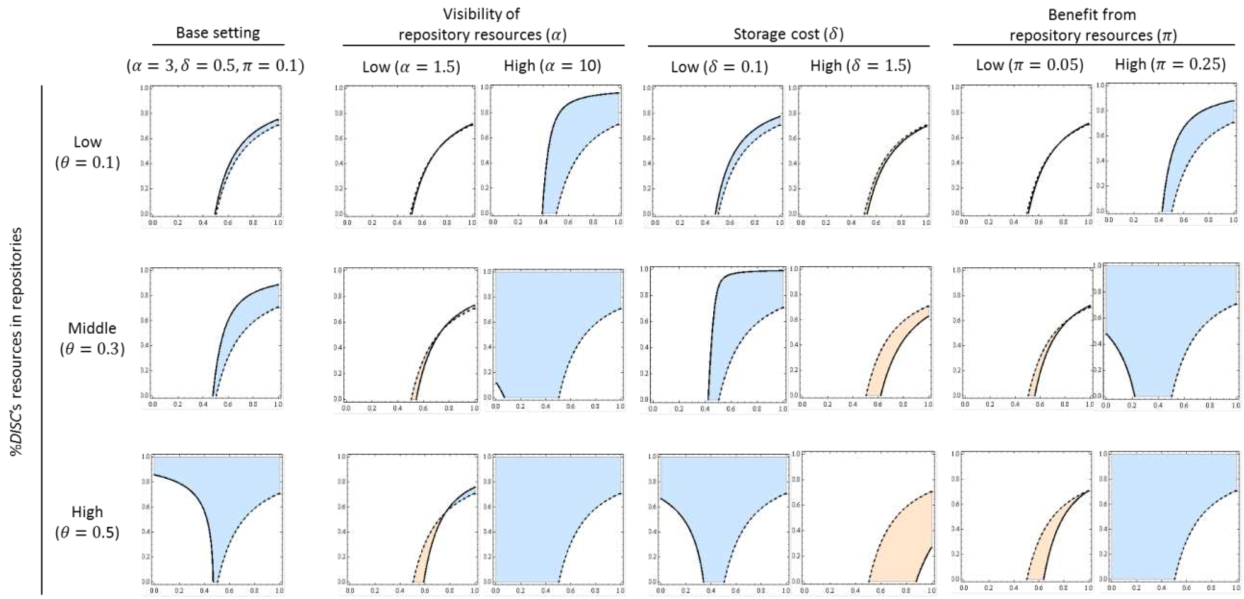
$$P_3 = -cgq\frac{1-\theta}{A} + bg_3q\frac{(1-\theta)x_3}{A} + (b-\omega)\frac{\alpha\theta x_3}{A} - \delta c\theta + \pi\frac{\alpha\theta}{A}, \text{ and}$$

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

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 ω does not affect the dynamics.

B. Shift of dynamics [a]



[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. β = 0.3. p = 0.3. q = 0.8.