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REGULAR ARTICLE

Academic commercialization and changing nature of academic cooperation

Sotaro Shibayama

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Abstract Recent economic policies emphasize the role of academic science in technological innovation and economic growth and encourage universities and individual academics to engage in commercial activities. In this trend of academic commercialization, a growing concern has been expressed that its potential incompatibility with the traditional norms of open science could undermine the cooperative climate in academia. Drawing on the framework of evolution of the cooperation, this study examines the changing nature of academic cooperation under the current policy trend. In an ideal state of open science, academics are supposed to cooperate gratis and unconditionally. However, results predict that the commercialized regime could compromise underlying mechanisms of cooperation and allow defectors to prevail. As the trend further grows, academics would become more demanding of direct reward in exchange for cooperation, and they would refrain from engaging in cooperation but would prefer to work independently. Some interventions (e.g., centralized rewarding) could mitigate the problem but require delicate system design.

Keywords Indirect reciprocity · Evolution of cooperation · Social norms · Open science · Academic commercialization · Academic Entrepreneurship · Evolutionary game theory

JEL Classification I23 · L26 · O33 · C73 · O38

1 Introduction

Recent economic policies emphasize the role of universities and academic science in economic growth and encourage direct interaction between industry and academia (Argyres and Liebeskind 1998; Jensen and Thursby 2001; Etzkowitz 1998; Grimaldi

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S. Shibayama (✉)
Research Center for Advanced Science and Technology, the University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan
e-mail: shibayama@00.alumni.u-tokyo.ac.jp

et al. 2011; Poyago-Theotoky et al. Hauert et al. 2002). Consequently, in the trend called *academic entrepreneurship* or *commercialization*, universities and individual academics have increasingly been engaging in industry collaboration, technology transfer, and other commercial activities (AUTM 2007; OECD 2003). While this might increase the social contribution of academic science, a growing concern has been voiced that the commercialized regime could develop a self-regarding climate and compromise the basis of academic science (Dasgupta and David 1994; Nelson 2004). Behind this is a notion that the progress of science is critically underpinned by the norms of open science, and potential conflict between open science and the emerging regime has spurred intense debate (Murray and Stern 2007; Thursby and Thursby 2011; David 1998; Nelson 2004).

Under the norms of open science, scientific achievement is regarded as the property of the scientific community, not of individuals, and thus academics are expected to share their knowledge and resources with one another gratis and unconditionally (Merton 1973; Dasgupta and David 1994). This altruistic practice is crucial in academia, where individuals are highly specialized and often need cooperation, even from strangers (Walsh et al. 2007; Shibayama and Baba 2011). While the underlying norms seem reasonably respected, empirical studies have shown that academics engaging in commercial activities, industry collaboration, and other for-profit activities (*commercial academics*, hereafter) tend to deviate from the norms; i.e., they are non-cooperative and unwilling to share their knowledge and resources so that they can earn personal profit (e.g., Campbell et al. 2000; Walsh et al. 2007).

While non-cooperative behavior of commercial academics has been repeatedly reported, little attention has been paid to a graver consequence that commercialization could deteriorate cooperation even among ordinary academics who do not engage in any commercial activities, and fundamentally compromise the norms of open science (Shibayama et al. 2012). To fill this gap, the current study offers a model of academic cooperation drawing on the framework of the evolution of cooperation (Nowak and Sigmund 1998; Sigmund 2010). Evolutionary games allow rich predictions to various economic issues (e.g., Friedman 1998; Arce 1996). Exploiting the feature, this study aims to predict a broader impact of academic commercialization on the norms and practices of academic cooperation. In so doing, this study provides implications for science and technology policies and future empirical research. Results suggest that, under the commercialized regime, ordinary academics would become unwilling to cooperate gratis, become more demanding of direct reward in exchange for cooperation, and be hesitant to participate in cooperation. This study also evaluates the efficacy of some policy interventions to mitigate these issues.

2 Academic cooperation as indirect reciprocity

Academic science relies on various forms of cooperation. Some are continuous, such as collaboration between a pair of laboratories, while others are temporary, such as material transfer. In general, a mechanism behind continuous cooperation between a fixed pair of players and that behind one-time cooperation between a random pair are considerably different (Sigmund 2010). The focus of this study is the latter, where one academic needs expertise or resources that he does not have and has to receive cooperation from another academic. This is pivotal in open science characterized by extreme specialization and active interaction (Merton 1973). Particularly in natural sciences, academics frequently share various types of resources such as cells, chemicals, reagents, software, and data (Walsh et al. 2007; Campbell et al. 2000), and importantly, the majority of such transactions occur between strangers, not between fixed collaborators (Shibayama and Baba 2011). This practice sustains the progress of science by allowing academics to avoid redundant efforts, reproduce previous findings, and standardize research methods (Walsh et al. 2007).

In the ideal state of open science, academics are supposed to cooperate gratis and unconditionally. Thus, donors bear the cost of cooperation while recipients benefit by advancing their research. In general, such altruistic behavior is vulnerable to free riders, who receive cooperation but refuse to give. However, the reality is that the compliance is fairly high; for example, in life sciences, average academics make 3–5 requests for research tools and data every year, and greater than 80 % of the requests are fulfilled (Walsh et al. 2007; Campbell et al. 2000).

The paradoxical fact that altruistic cooperation is very common in the human society (e.g., blood contribution, donation), despite the temptation to free-ride, 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 iterated Prisoner's Dilemma Games. This form of cooperation is called *direct reciprocity,* since a fixed pair of players cooperate with each other. Going beyond this restricted player matching, Nowak and Sigmund (1998) developed a pioneering theory on *indirect reciprocity*. In this model, a player encounters a different opponent in each round of repeated games, so donors cannot be rewarded directly by their recipients. Instead, they are indirectly rewarded by someone else, where social information plays a key role. Simply put, players are assigned reputation based on their history of cooperation so that free riders are denied cooperation. Hence, defection based on bad reputation functions as a punishment. This model has offered a foundation for subsequent theories on the evolution of cooperation (Seinen and Schram 2006; Nowak 2012).[1] Another mechanism to sustain cooperation is *network reciprocity,* which relies on a spatial structure or network between players. Ohtsuki et al. (2006) suggest that a cooperative strategy can be sustained in structured network, where players' interaction is not completely random. Further, a line of literature emphasizes the role of explicit forms of punishment and reward in sustaining cooperation (Fehr and Gachter 2000; Fehr and Fischbacher 2004; Sefton et al. 2007).

These theories explain academic cooperation to some extent. Direct reciprocity is widely observed as bilateral continual collaboration. Network reciprocity is also relevant, since real cooperation is influenced by social networks. There are some official sanction mechanisms; for example, funding agencies require their recipients to share their resources for open use after project completion. If academics do not comply with the rule and such an incident is reported, they could be stripped of their right to future

[1] Some literature criticizes this approach because knowing the reputation of other players is practically difficult (e.g., Leimar and Hammerstein 2001).

funding. Many scientific journals have similar guidelines. Still, the effectiveness of these mechanisms may be questionable for the practical difficulty of policing and punishing defectors. Among others, I draw on indirect reciprocity to model the focal form of cooperation in this study. The principle of gratis cooperation is clearly articulated in various guidelines (National Academy of Sciences 2003), and non-cooperative behavior is generally despised. Academics who encounter non-cooperative donors sometimes spread a negative word, whereby not only direct victims of non-cooperation but also other academics in the community could eliminate free riders (Shibayama et al. 2012). Thus, a reputation mechanism appears to be at work in academic cooperation.

3 Model

This section formulates a model of unconditional cooperation under ordinary circumstances, and the following sections analyze how it is affected by academic commercialization. This study draws on a well-established model of indirect reciprocity based on the Donation Game (Sigmund 2010; Nowak and Sigmund 1998). 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 to defect (i.e., deny cooperation). If the donor cooperates, he pays a cost (c) for preparing and providing the resources, and the recipient receives a benefit (b) by advancing his research. I assume $b>c$ so that cooperation is collectively beneficial. If the donor defects, he pays no cost and the recipient receives no benefit. Apparently, defection is dominant in a one-shot game, but cooperation can emerge in iterated games with the aid of reputation. To illustrate this, the first model involves three types (Table 1) following the convention of prior literature (Sigmund 2010; Nowak and Sigmund 1998). One extreme type is *ALLD*, who is myopically self-regarding and always defects as a donor, representing free riders. The other extreme is *ALLC*, who indiscriminately cooperates as a donor. *ALLD* dominates *ALLC* because *ALLD* receives full cooperation from *ALLC* but does not bear the cooperation cost. The third type, *DISC*, is a discriminate cooperator. A *DISC* donor cooperates with recipients with good reputation but refuses to help those with bad reputation. Thus, *DISC* can avoid being exploited by *ALLD*. For simplicity, I use dichotomous reputation, zero (*bad*) and one (*good*). Reputation is evaluated 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 cooperation behavior of *DISC*; i.e., 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).[2] Although the literature on indirect reciprocity offers a great variety of model settings, I follow as simple and established a model as possible because the goal of this study is not to study indirect reciprocity of itself.

The evolutionary dynamics are analyzed as follows. Let x_i denote the frequency of i-th type (1: *ALLC*, 2: *ALLD*, 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

[2] The variation of cooperation behavior and reputation rules is comprehensively studied by Ohtsuki and Iwasa (2004), and this study draws on one of the most stable and efficient.

Table 1 List of player types

ID	Type	Description
1	*ALLC*	Altruistic players who always cooperate.
2	*ALLD*	Myopically self-regarding players who always defect.
3	*DISC*	Discriminately altruistic players who cooperate with good recipients but refuses to cooperate with bad recipients.
4	*PAY*	Myopically self-regarding players who cooperate if rewarded and pay reward if demanded.
5	*ABST*	Loners who abstains from participating in cooperation games.
0	*COM*	A variant of *ALLD* who always defects in favor of commercial profit. This type does not contribute to evolution.

the whole population and $g_{i,n}$ denotes that among the i-th type ($g_n=\sum x_i g_{i,n}$). As an *ALLC* donor always cooperates, his reputation becomes good when encountering a good recipient and becomes bad when encountering a bad recipient; $g_{1,n}=g_{n-1}$. To the contrary, since an *ALLD* 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, 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.[3] With this setting, $g_{3,n}=1-(1-q)g_{n-1}$. Further for simplicity, the following analysis draws on the equilibrium reputation (Brandt and Sigmund 2005). That is, the above difference equations are solved with the assumption that $g_n=g_{n-1}=g$ and $g_{i,n}=g_{i,n-1}=g_i$.[4] The equilibrium frequencies of good players are given by

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

Based on this reputation and the payoff of a single game (Table 3), the average 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) but never receives cooperation from an *ALLD* donor. An *ALLC* recipient, only if his reputation is good and known, receives cooperation from a *DISC* donor (bg_1qx_3). All taken together,[5]

[3] This setting is chosen mainly for mathematical tractability. I found from interviews that some academics in fact avoid cooperation if no information is available about recipients. However, the opposite assumption is plausible, where a *DISC* donor takes its recipient as good when his reputation is unknown. A more realistic assumption may be that *DISC* donors guess recipients' reputation based on the frequency of good players. All these settings give qualitatively similar results, though the magnitude of the commercialization effect may differ.

[4] The dynamics without this assumption are analyzed by Nowak and Sigmund (1998). I suppose that this assumption is justifiable due to rather frequent resource sharing in academia (e.g., Walsh et al. 2007).

[5] In this and the following computation, the number of iterated game rounds is ignored since it is irrelevant when the equilibrium reputation is used.

Table 2 Reputation rule

Recipient's reputation	Donor's action	Evaluation of donors
Good	Cooperate	Good
Good	Defect	Bad
Bad	Cooperate	Bad
Bad	Defect	Good

$$P_1 = -c + bx_1 + bg_1 q\, x_3. \tag{2a}$$

ALLD and *DISC* recipients receive cooperation in similar ways, while *ALLD* donors never cooperate and *DISC* donors cooperate only with good recipients whose reputation is known. Thus,

$$P_2 = bx_1 + bg_2 q\, x_3, \tag{2b}$$

$$P_3 = -cgq + bx_1 + bg_3 q x_3. \tag{2c}$$

The evolutionary dynamics are computed with the continuous replicator dynamics (Hofbauer and Sigmund 1998):

$$\dot{x_i} = x_i\left(P_i - \overline{P}\right), \tag{3}$$

where $\overline{P} = \sum x_i P_i$ (the mean payoff) and $\dot{x_i} = dx_i/dt$. Based on (1) – (3), Figure 1 illustrates a numerical phase plot. It shows two evolutionarily stable equilibria, pure *ALLD* and pure *DISC*, and two unstable equilibria, pure *ALLC* and a mix of *ALLD* and *DISC*. If the reputation availability is sufficiently high (i.e., $q>c/b$), the phase space is split into two parts; the initial state in the shaded part leads to a non-cooperative regime (*ALLD*) and the other to a cooperative regime (*DISC*). Thus, a certain frequency of *DISC* is necessary to maintain cooperation.

Table 3 Payoff matrix[a]

Recipient Donor	*1: ALLC*	*2: ALLD*	*3: DISC*	*4: PAY*	*5: ABST*	*0: COM*
1: ALLC	$-c$, b	$-c$, b	$-c$, b	$-c$, b	0,σ	$-c$, b
2: ALLD	0, 0	0, 0	0, 0	0, 0	0,σ	0, 0
3: DISC	$-cqg_1$,bqg_1	$-cqg_2$,bqg_2	$-cqg_3$,bqg_3	$-cqg_4$,bqg_4	0,σ	$-cqg_0$, bqg_0
4: PAY	0, 0	$p(\beta-c)$,$p(b-\gamma)$	0, 0	$p(\beta-c)$,$p(b-\gamma)$	0,σ	$p(\beta-c)$,$p(b-\gamma)$
5: ABST	0, 0	0, 0	0, 0	0, 0	0,σ	0, 0
0: COM	0, 0	0, 0	0, 0	0, 0	0,σ	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. Since this matrix includes g_i, which is a function of frequencies of involved types, it specifies a non-linear game in a normal form

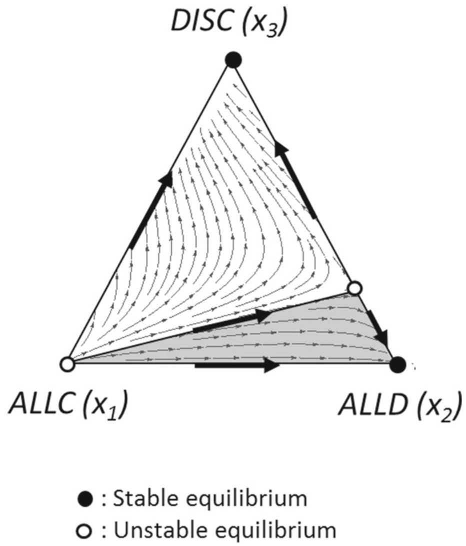

Fig. 1 Numerical Phase Plot of *ALLC*, *ALLD*, and *DISC* . The pure *ALLD*, (0,1,0), and the pure *DISC*, (0,0,1), are stable equilibria. A mix of *ALLD* and *DISC*, $(0,1-c/qb,c/qb)$, and the pure *ALLC*, (1,0,0), are unstable equilibria. $b=1.0$. $c=0.2$. $q=0.8$

4 Cooperation under academic commercialization

4.1 Increasing defection

Based on the above model, this section examines the impact of commercialization on the cooperation behavior of non-commercial academics. To model the commercialized environment, this study introduces a player type, *COM* (Table 1), representing commercial academics 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 decreases the commercial profit. They would rather sell their resources than give them away for free. Thus, their behavior is the same as that of *ALLD*. This is a simplification of the empirical observation that commercial academics tend to withhold their resources (Walsh et al. 2007; Campbell et al. 2000). I further assume that the transition between commercial and non-commercial academics should occur significantly slowly compared to that among non-commercial academics. In reality, starting commercial activities takes various kinds of initial time-consuming effort such as patenting, business planning, and fund raising; once starting a business, they would not abandon it immediately when it makes a loss. Thus, in the following analyses, the rate of adjustment between *COM* and other types is set infinitely small. In other words, the frequency of commercial academics is exogenously controlled, and the evolutionary dynamics of only non-commercial academics are analyzed.[6]

[6] The transition between non-commercial and commercial academics is discussed in the Supplementary Material.

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

$$P_2 = bg_2q\,x_3, \tag{4a}$$

$$P_3 = -cgq + bg_3qx_3. \tag{4b}$$

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 are described as $\dot{z_1} = z_i\left(P_i - \overline{P}\right)$ where $\overline{P} = \sum z_i P_i$. To examine the impact of *COM*, Fig. 2a illustrates the reputation, rate of receiving cooperation, payoff, and phase diagram for *DISC* (black) and *ALLD* (gray) with and without *COM* (solid and dashed, respectively). The invasion of *COM* improves the reputation of both types with a greater extent for *ALLD* (Column 1). *ALLD* gains in reputation because it always refuses to help *COM*, who is likely to be bad. While *DISC* recipients become more likely to be denied due to the invasion of *COM*, *ALLD* recipients are less affected thanks to improved reputation (Column 2). This is directly reflected in the payoff for each type (Column 3). The intersection of the payoff curves is the unstable interior equilibrium, which corresponds to the z_3-intercept (z_3^*) in the phase diagram (Column 4). With a greater frequency of *DISC* than the equilibrium, *DISC* earns higher payoff than *ALLD*, growing its frequency until it dominates the whole population. On the other hand, a smaller *DISC* frequency leads to pure *ALLD*. Since the invasion of *COM* causes a rightward shift of the equilibrium, it enlarges the basin of attraction for *ALLD*. The transition of this equilibrium (Column 5) suggests that a greater frequency of *COM* creates a more favorable condition for *ALLD*. Formally, $dz_3^*/dx_0 > 0$ (proof in Math Appendix A).[7]

In summary, the commercialized 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 cooperate, directly decrease the cooperation benefit for cooperators. Second, commercial academics compromise the reputation mechanism. Academics gain reputation by cooperating with good academics or not cooperating with 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 common. Therefore, with an increasing number of commercial academics, even non-commercial academics are more inclined toward defection.

[7] In reality, the frequency of each type is unknown. From the fact that indirect reciprocity is widely observed in resource sharing, I assume that the frequency of *DISC* is greater than the unstable equilibrium and the dynamics move 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 are reversed toward the non-cooperative regime.

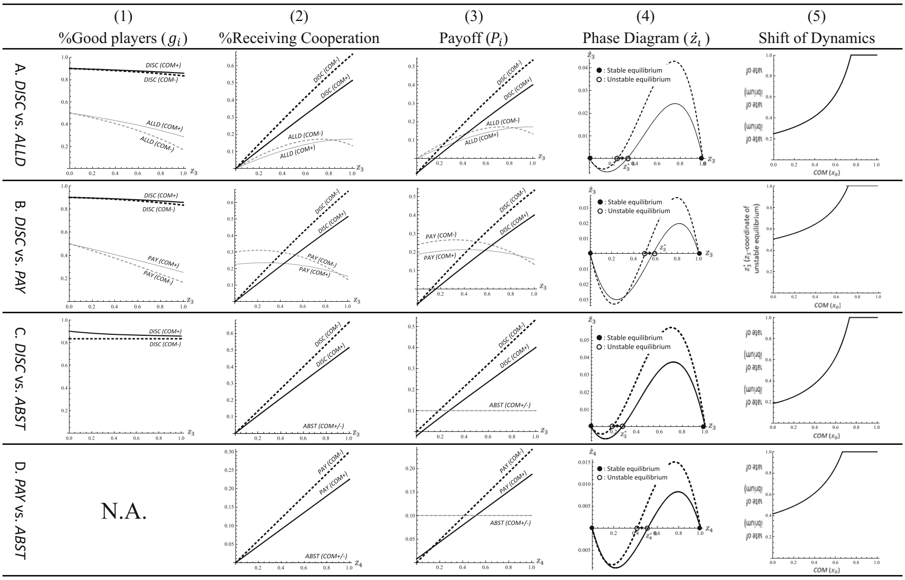

Fig. 2 Impact of *COM* on Evolutionary Dynamics . Solid line: x_0=0.25 (with *COM*) and dashed line: x_0=0 (without *COM*) in Columns 1–4. In Column 4, to the right of unstable interior equilibria, the dynamics move rightwards, while, to the left, it moves leftwards. The z_i coordinate of unstable equilibria is denoted by z_i^*. In Column 5, z_i^* is illustrated as a function of the frequency of *COM* (x_0). b=1.0. c=0.2. β=γ=0.3. σ=0.1. p=0.3. q=0.8

Prediction 1 With a greater prevalence of academic commercialization, academics become less willing to engage in unconditional cooperation.

4.2 Bilateral rewarding

In the face of malfunctioning indirect reciprocity, recipients who need others' resources have a few alternatives. For one, they can directly offer some rewards to donors, such as coauthorship, acknowledgments in their publications, and a promise of future support (Shibayama and Baba 2011). This can be appealing to self-regarding 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. The literature suggests that bilateral rewarding could sustain cooperation (Sefton et al. 2007; Sigmund et al. 2001). To incorporate this possibility, I extend the Donation Game with the option of bilateral reward, where a recipient who receives cooperation may return a part of his benefit to the donor. For this, the fourth type, *PAY*, which favors reward-based cooperation is added (Table 1).[8] *PAY* is also myopically self-regarding; *PAY* donors cooperate only for their own benefit (i.e., when reward is expected and it exceeds the cooperation cost), and *PAY* recipients

[8] This setting is similar to Trust Game (Berg et al. 1995) but is different in that donors can know whether recipients are willing to reward through negotiation.

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 academic cooperation, unlike economic exchange, money is almost never used and a universal currency does not exist (Shibayama and Baba 2011). Thus, as in barter exchange, two players have to find each other's resources valuable simultaneously. However, such barter exchange may be difficult in academia, where individuals specialize in a narrow research area and recipients may possess nothing valuable for donors. Coauthorship in expected publications might function as a currency, where a recipient gives away a certain credit in his publication, but 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 his recipient's reward valuable. For simplicity, I assume that the contract of bilateral rewarding is binding,[9] and thus *PAY* is immune to the risk of non-reciprocity.

With this setting, I analyze how gratis cooperation competes with reward-based cooperation under the commercialized regime. I focus on the evolutionary dynamics of *DISC* and *PAY*.[10] The payoffs of both types are given by

$$P_3 = -cgq + bg_3qx_3, \tag{5a}$$

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

where x_4 denotes the frequency of *PAY*. Figure 2b illustrates how the invasion of *COM* affects the dynamics. The reputation of *DISC* is not largely affected while that of *PAY* is improved. Successful transaction for *DISC* declines to a greater extent than for *PAY*. Taken together, the payoff of *DISC* decreases to a greater extent especially when the frequency of *DISC* is high. The phase diagram shows that the unstable equilibrium shifts rightwards. Therefore, the invasion of *COM* expands the basin of attraction for *PAY* (i.e., $dz_3^*/dx_0 > 0$), producing a more favorable condition for *PAY* than for *DISC* (see Math Appendix B).

This result 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 direct rewarding. This bilateral transaction resembles an economic exchange, but only incomplete economic exchange is achievable due to the limitation of barter exchange (modeled as low p). Consequently, the shift toward reward-based cooperation can result in a socially undesirable state with fewer

[9] 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 discounted value of the reward.
[10] *ALLC* is dominated by *DISC* and *PAY*, and *ALLD* is dominated by *PAY*.

fulfilled transactions.[11] Even so, academics would resort to such a suboptimal option to avoid being exploited by free riders.

Prediction 2 With a greater prevalence of academic commercialization, 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. In reality, however, 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 preferable to being exploited by defectors. In addition, making a request of itself can incur some cost; for example, academics may have to reveal their research plan to donors, which could reduce their scientific lead, and they have to spend time to negotiate the conditions under which the resources are used. Such a cost becomes 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 (Hauert et al. 2002). *ABST* players do not engage in Donation Games at all and forgo potential benefit from cooperation. Instead, they devote full effort to their own work, whereby they earn a constant benefit (σ) by saving the cost of participating in cooperation.

For mathematical tractability, I analyze evolutionary dynamics for two types at a time. First, the dynamics between *DISC* and *ABST* with the existence of *COM* are illustrated in Fig. 2c. The payoffs of *DISC* and *ABST* are given by

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

$$P_5 = \sigma, \tag{6b}$$

where g_{-5} denotes the mean reputation of non-*ABST* players. The invasion of *COM* decreases successful transaction and the payoff of *DISC*, while *ABST* gains constant payoff. Thus, under the commercialized regime, indirect reciprocity becomes more vulnerable to loners, who earn the minimum payoff by avoiding cooperation. That is, the basin of attraction for *ABST* expands; i.e., $dz_3^*/dx_0>0$ (see Math Appendix C).

Next, the dynamics between *PAY* and *ABST* are examined. The payoff of *PAY* is given by

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

Similarly, Fig. 2D shows that the invasion of *COM* creates a more favorable condition for *ABST* than for *PAY*. With limited efficiency of rewarding (low matching

[11] I assume that this is the case though it needs empirical investigation. The rate of receiving cooperation is $q/(2-q)$ at the pure *DISC* equilibrium and p at the pure *PAY* equilibrium when no *COM* exists. Thus, reward-based cooperation is socially less desirable than indirect reciprocity if $p<q/(2-q)$ (e.g., $p<0.67$ if $q=0.8$).

rate, p, or low reward value, β), the basin of attraction for *ABST* expands; i.e., $dz_4^*/dx_0>0$ (see Math Appendix D), and cooperation based on bilateral rewarding becomes more likely to be invaded by loners.

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

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

For a holistic view, I examine the dynamics of *DISC*, *PAY*, and *ABST*.[12] Figure 3a shows numerical phase plots with and without *COM*. The phase space is divided into three regions that converge into each of the three types. Figure 3b illustrates the area percentage of each region as a function of *COM* frequency, suggesting that the basin of attraction for *ABST* consistently increases at the sacrifice of *DISC*, and that it also affects *PAY* with a high frequency of *COM*. In addition, I examine the sensitivity to parameter settings.[13] Results suggest that the basin of attraction for *DISC* consistently shrinks with increasing frequencies of *COM*, and that *DISC* is particularly vulnerable with low reputation availability (q). As for the balance between *PAY* and *ABST*, 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*.

5 Interventions

With the above predictions for possible deterioration of indirect reciprocity under commercialization, what policy interventions should be taken? A simplistic approach may be to reverse the trend of commercialization. Though completely abandoning it is unrealistic, reducing the incentive of commercial participation may be feasible. In fact, for example, some scientific 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 intervention 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 sometimes observed in reality, where the introduction of economic incentives changes the framing of games and destroys social norms (Gneezy and Rustichini 2000; Frey and Jegen 2001).

More proactive incentive mechanisms may be feasible. Literature suggests that centralized rewarding and punishing contribute to sustaining cooperation (Gintis et al. 2005; Ostrom 1990). Mechanisms to officially punish defectors do exist in academia, though their effect may be unclear (National Academy of Sciences 2003).

[12] Because *ALLC* is dominated by *DISC* and *PAY*, and *ALLD* is dominated by *PAY* and *ABST*, the dynamics of these three types are of the ultimate interest.

[13] See the Supplementary Material.

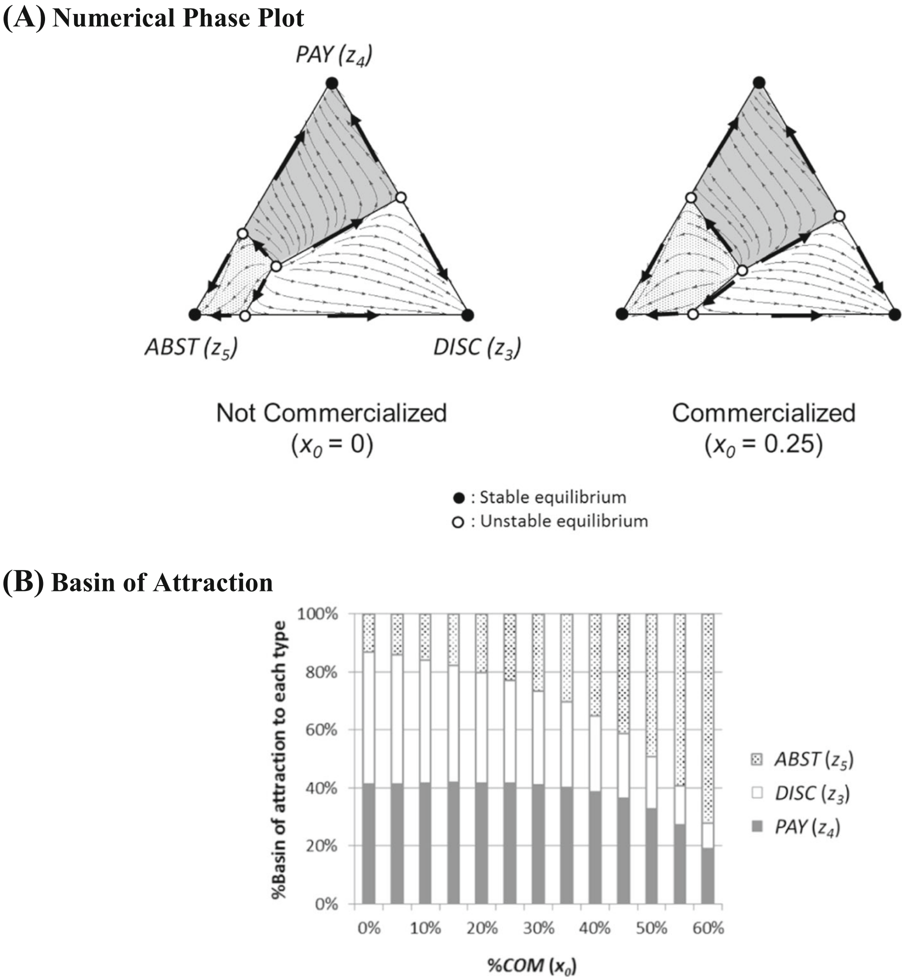

Fig. 3 Impact of *COM* on *DISC*, *PAY*, vs. *ABST*. The area percentage of the basin of attraction is numerically computed as follows. For each lattice point in the phase space with the interval of 0.02 (1,326 points) as the initial state, the coordinate (z_3, z_4,z_5) at t=10,000 is computed based on $\dot{z_i} = z_i\left(P_i - \overline{P}\right)$. 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 convergence to each type is used as the area percentage of the basin of attraction. b=1.0. c=0.2. $\beta=\gamma$=0.3. σ= 0.1. p=0.3. q=0.8. Mathematical detail is given in the Supplementary Material

Alternatively, the central authority could reward cooperators by awards, research funds, and so forth. In what follows, the effectiveness of centralized rewarding is examined.

First, dynamics between *DISC* and *ALLD* are examined. 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., cooperation with good recipients is not distinguished from that with bad recipients), and that this fact is publicly known. I slightly modify *ALLD*'s behavior to make this analysis more meaningful. That is, *ALLD* donors defect if $r < c$, but they cooperate if $r > c$ as if they were *ALLC* because cooperation is more profitable than defection. I assume that *DISC*'s behavior is not affected since cooperation with bad

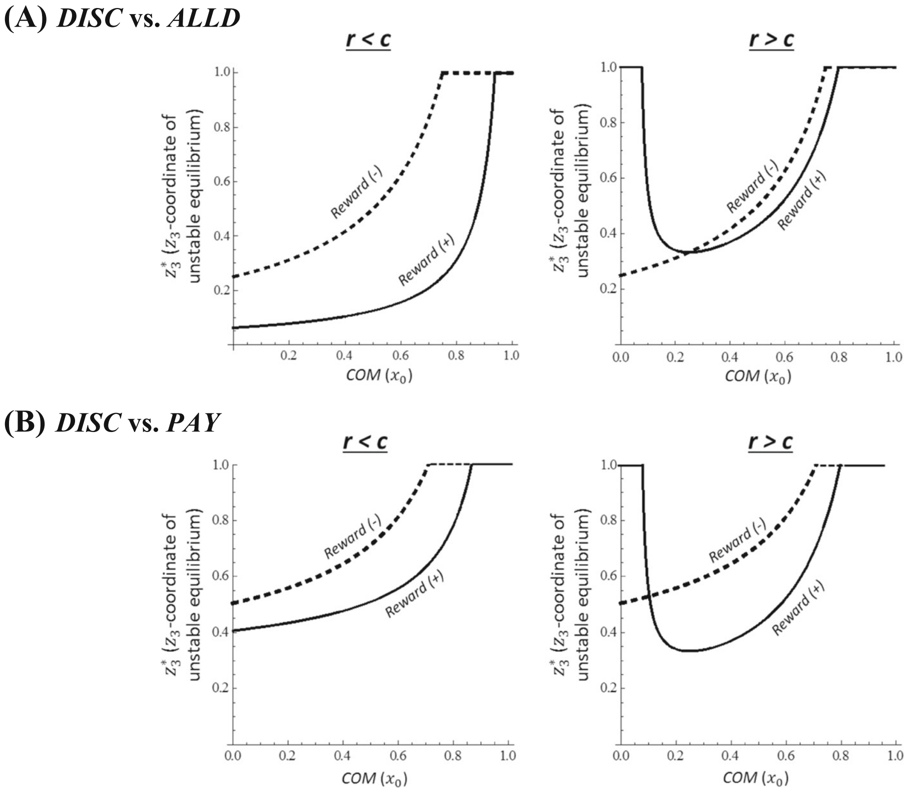

Fig. 4 Effect of Centralized Rewarding. The curves illustrate unstable interior equilibria as a function of the frequency of *COM* (x_0). Solid line: centralized rewarding is implemented. Dashed line: centralized rewarding is not implemented. The frequency of *DISC* is decreasing ($\dot{z}_3<0$) below the curves and increasing ($\dot{z}_3>0$) above them. Thus, centralized rewarding is effective between the two curves as a means to reinforce deteriorated indirect reciprocity. 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 $r>c$. Details are given in the Supplementary Material

recipients, rewarded or not, is against the norms of open science. Figure 4A shows the shift of evolutionary dynamics by illustrating the coordinate of the unstable equilibrium (z_3^*) as a function of *COM* frequency (x_0). If $r<c$ (left), the curve shifts downwards, indicating that the reward increases the basin of attraction for *DISC*. This is an apparent result because *DISC*'s payoff increases by rewarding while *ALLD*'s does not. Centralized rewarding should be used when *DISC*'s frequency is between two curves, where the dynamics head toward the defecting equilibrium (pure *ALLD*) without reward but toward the cooperative regime (pure *DISC*) with reward. Thus, even after the invasion of *COM* created a favorable condition for *ALLD*, *DISC* could regain its advantage with the aid of centralized rewarding. However, when $r>c$ (right), the effect of rewarding is rather limited because *ALLD* also receives a reward. Rewarding could even facilitate *ALLD* to dominate *DISC* (where the solid curve exceeds the dashed curve). This suggests that the central authority must choose an adequate (not too large) size of reward to maintain indirect reciprocity. Second, the dynamics between *DISC* vs. *PAY* are analyzed. I assume that centralized rewarding is given only for gratis cooperation; i.e., if *PAY* receives a bilateral reward, it is not additionally rewarded by the central authority. With this assumption, *PAY*'s behavior is not affected if $r<c$, but *PAY* acts like *ALLC* if $r>c$ to exploit centralized rewarding.[14] Figure 4b shows a similar result; while modest rewarding increases the basin of attraction for *DISC* (left), excessive rewarding can be counterproductive (right). The left graph shows a narrow margin between two curves, suggesting that centralized rewarding is effective in rather limited situations compared to *DISC* vs. *ALLD*. In both cases, an inadequate size of rewarding can make a negligible or even negative effect.[15] When too large rewarding helps *ALLD* or *PAY* to prevail, the level of cooperation becomes high. Though this may appear socially acceptable, it has two problems. First, it instantly collapses when the centralized rewarding ceases. Thus, it cannot be a solution unless the rewarding mechanism is cheap and sustainable. Second, the central authority may be able to reward only specific forms of cooperation. However, the norms behind indirect reciprocity can be more general, and losing them could affect some forms of cooperation that are not covered by rewarding.

A different approach to sustain cooperation is to transfer the cooperation cost from donors to recipients. The cost for donors consists of the direct cost for cooperation and the indirect cost for forgoing scientific lead that could have been maintained by denying sharing. The former can be mitigated by charging recipients minimum fees.[16] However, the cost transfer rarely occurs in reality for some reasons: collecting fees of itself is costly, fair pricing is difficult, and money payment is sometimes prohibited. In this regard, universities or third parties could act as an agent for academics in collecting fees and supplying resources. In fact, central repositories play this role, where donors store their resources in repositories and recipients receive them at cost. Many repositories are already in operation, such as Jackson Laboratory and American Type Culture Collection, though their contribution is still minor (Furman and Stern 2011).

6 Discussion and conclusions

The current economic policies have encouraged academics to engage in commercial activities as a means to increase the contribution of academic science to technological innovation and economies (e.g., Etzkowitz 1998; Poyago-Theotoky et al. 2002), but their potential inconsistency with the norms and practices of open science has been concerned (Dasgupta and David 1994; Nelson 2004). While prior literature shows that commercial academics are less willing to cooperative in favor of commercial profit (Walsh et al. 2007; Campbell et al. 2000), the current study suggests that the commercialized regime could broadly affect ordinary academics and 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; Sigmund 2010) and examines the influence of increasing commercial academics. The analyses predict that growing

[14] This is the case even if $c<r<\beta$ because recipients would deny bilateral private reward knowing that *PAY* donors would cooperate for centralized reward anyway.

[15] The effect of different sizes of centralized rewarding is examined in detail in the Supplementary Material.

[16] This also has a similar effect to centralized rewarding. For donors, the cooperation fee paid by recipients is equivalent to the reward paid by the centralized rewarding. For recipients, fee payment can be understood as reduction of cooperation benefit.

commercialization could lead to three behavioral changes in cooperation. First, even non-commercial academics could become unwilling to cooperate gratis because increasing commercial academics lower the expected benefit from indirect reciprocity and weaken the reputation mechanism behind indirect reciprocity. Then, the malfunctioning indirect reciprocity could force academics to rely on bilateral rewarding (e.g., coauthorship). That is, cooperation becomes based more on short-term personal profit despite the limitation of barter exchange. Third, consequently, academics might be discouraged from participating in cooperation and would rather work independently. This study also examines potential interventions to mitigate these problems; centralized rewarding may be effective but requires delicate implementation.

Though prior empirical studies have rarely tested the effect of commercialization on ordinary academics, the predictions of this study are consistent with some previous observations. For example, Walsh et al. (2007) reported that the defection rate in resource sharing in American genomics increased from 10 % in 1997 to 18 % in 2003, though its cause was not identified. Shibayama et al. (2012) show an association between the defection rate in resource sharing and the frequency of commercial academics by comparing several scientific fields. Shibayama et al. (2012) also compare gratis cooperation and reward-based cooperation and find a positive correlation between the rate of reward-based cooperation and the frequency of commercial academics. Focusing on knowledge sharing, Haeussler (2011) attributes defection to weak norms of open science. The predictions of the current study as well as these empirical observations imply that the commercialized regime could broadly deteriorate open science, which is believed to be the foundation of science (Merton 1973; Dasgupta and David 1994). That is, although the policy intention of academic commercialization is to facilitate the practical application of scientific discoveries made in academia, it could damage the very source of scientific discoveries.

The desirability of open science needs cautious examination. One may argue that economic exchange is more efficient than indirect reciprocity. I argue that the extreme specialization of academic science seems to make barter exchange unfeasible, which justifies the necessity of indirect reciprocity. More in general, the weakening norms of open science could cause an even broader impact on practices in science. For example, it might facilitate other types of self-regarding behavior such as secrecy and misconduct, though this is open to empirical investigation. In addition, open science has its own limitation; for example, cooperation with unproductive academics can collectively cause a loss (i.e., $b<c$), which might be addressed by economic exchange. Therefore, the balance between the emerging norms of commercialization and traditional norms of open science needs to be examined from a broader perspective.

This study offers some implications for future empirical research. First, the general impact of commercialization on behavior of non-commercial academics needs more empirical investigation. The behavior of ordinary academics in diverse contexts (e.g., different scientific fields, countries) and its intertemporal transition should be examined. Cooperation based on bilateral rewarding and abstention from cooperation are of both theoretical and practical interest. Future research should inquire into the conditions of cooperation in detail and identify the determinants of cooperation forms and propensity to participate in cooperation. The parameters employed in this study give some hints for empirical studies. The extent to which academics share the social information about their peers (availability of reputation, q) should be studied. The efficiency of private rewarding (the matching rate, p) and the values of bilateral and centralized rewarding (β, γ, and r) should be investigated. The cost structure of cooperation also needs more empirical basis: i.e., the breakdown of the cooperation cost (c) into direct cost for preparing resources and perceived cost for forgoing scientific leads.

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Mathematical appendix

Prediction 1

$g=\frac{1}{2-qz_3(1-x_0)}$ by solving $g_2=g_0=1-g$, $g_3=1-(1-q)g$, and $g=x_2g_2+x_3g_3+x_0g_0$. 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 $z_3^*=\frac{c}{qb(1-x_0)}$. $\frac{dz_3^*}{dx_0}=\frac{c}{qb(1-x_0)^2}>0$.

Prediction 2

I assume that recipients of self-regarding types (*PAY* and *COM*) accept paying bilateral rewards, but that *DISC* does not because it violates the norms of open science.[17] 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 $g=x_3g_3+x_4g_4+x_0g_0$.

Formally, Prediction 2 states $\frac{dz_3^*}{dx_0}>0$, where z_3^* is the solution of $P_3-P_4=0$ for z_3. From (5a) and (5b), $P_3-P_4=b(g_3-g_4)qx_3-p(\beta-c)x_0-p(b-\gamma+\beta-c)x_4-cgq$. This is rearranged as $\frac{f(z_3,x_0)}{h(z_3,x_0)}$, where f and $h>0$ are polynomials of x_0 and z_3.[18] Since $\frac{dz_3^*}{dx_0}>0$ is not analytically provable, I indirectly show this by simulation. From the whole parameter regions, $c\in(0,b)$, $q\in(c,1)$, $p\in\left(0,\frac{q}{2-q}\right)$,[19] $\beta\in[c,b]$, $\gamma\in[0,\beta]$, and $x_0\in[0,1)$, I randomly choose a set of parameters, with which $f(z_3,x_0)=0$ is numerically solved for z_3. If a solution

[17] Even if *DISC* recipients are allowed to pay bilateral rewards, Prediction 2 holds for most of the parameter region, but in a small parameter region, *DISC* gains advantage to *PAY* when *COM* invades.

[18] Details are given in the Supplementary Material.

[19] 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. 11.

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 in (0,1),[20] where $z_3^{**}>z_3^*$ always holds. This implies $\frac{dz_3^*}{dx_0}>0$. Because f is a cubic polynomial of z_3 whose leading coefficient >0 and $f(0,x_0)<0$, z_3^* is the unstable equilibrium; i.e., $P_3-P_4<0$ if $z_3<z_3^*$ and $P_3-P_4>0$ if $z_3>z_3^*$.■

Prediction 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, he always defects, so payoffs for both sides are zero. When *ABST* is chosen as a recipient, he does not ask for cooperation, where the payoff for *ABST* is σ while that for a donor is zero. As the donor neither defects nor cooperates, his 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 $g_{-5}=\frac{x_3g_3+x_0g_0}{x_3+x_0}$.

Prediction 3 is formally $\frac{dz_3^*}{dx_0}>0$, where z_3^* is the solution of $P_3-P_5=0$ for z_3. From the reputation equations, (6a), and (6b), $P_3-P_5=\frac{q\left\{(b-c)(1-x_0)^2z_3^2+(b+q-2c)(1-x_0)x_0z_3-cx_0^2\right\}}{(2-q)(1-x_0)z_3+2x_0}-\sigma$. Let $k(z_3,x_0)=P_3-P_5$. Since $k(z_3^*,x_0)=0$, $\frac{dz_3^*}{dx_0}=-\frac{\partial k}{\partial x_0}/\frac{\partial k}{\partial z_3}$. As $\frac{\partial k}{\partial z_3}>0$ is easily shown, proving $\frac{\partial k}{\partial x_0}<0$ suffices. $\frac{\partial k}{\partial x_0}$ is rearranged as $\frac{k_2(z_3,x_0)}{k_1(z_3,x_0)}$, where $k_1>0$ and k_2 are polynomials of x_0 and z_3.[21] As $\frac{\partial k_2}{\partial x_0}<0$ is easily shown, it follows that $\frac{\partial k}{\partial x_0}<0\ \forall x_0 \Leftarrow k_2(z_3,0)<0 \Leftrightarrow z_3>\frac{(qb-2c)(1-q)}{(2-q)(b-c)}$. Since $k(z_3^*,x_0)=0$, the sufficient condition for $\frac{\partial k}{\partial x_0}<0\ \forall x_0$ is $z_3^*\big|_{y=0}=\frac{(2-q)\sigma}{q(b-c)}>\frac{(qb-2c)(1-q)}{(2-q)(b-c)}\Leftrightarrow c>\frac{qb}{2}$ or $\sigma>\frac{q(1-q)(qb-2c)}{(2-q)^2}$. Otherwise, $\exists x_0^*\in(0,1)$ s.t. $\frac{\partial k}{\partial x_0}<0$ $\left(x_0>x_0^*\right)$ and $\frac{\partial k}{\partial x_0}>0$ $\left(x_0<x_0^*\right)$.[22] In sum, if c or σ is sufficiently large, *COM* offers a favorable condition for *ABST* regardless of *COM*'s frequency. Otherwise, with a minimal frequency of *COM*, *ABST* gains advantage over *DISC*.

Prediction 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.

[20] No incident was found where two or three solutions were in (0,1).
[21] Details are given in the Supplementary Material.
[22] x_0^* is the solution of $\partial k/\partial x_0=k=0$ for x_0. A Monte-Carlo simulation shows that x_0^* is negligibly small; the maximum of x_0^* of 10,000 runs was $x_0^*=0.012$. Thus, a very small frequency of *COM* is enough to negatively affect *DISC*.

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