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ANALYSIS

Scholar-participated governance as an alternative solution to the problem of collective action in social–ecological systems

Lihua Yang [a,*], Jianguo Wu [b,c,1]

[a] School of Public Affairs, Arizona State University, Phoenix, AZ 85004, United States
[b] School of Life Sciences and Global Institute of Sustainability, Arizona State University, P.O. Box 874501, Tempe, AZ 85287-4501, United States
[c] Sino-US Center for Conservation, Energy, and Sustainability Science (SUCCESS), Inner Mongolia University, Hohhot, China

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ABSTRACT

Different from the three classical and popular models of central authority, privatization, and self-governance—which have been widely researched and applied in social–ecological policymaking in recent years, we propose an alternative model for collective action to resolve the problem of the tragedy of the commons. Our study is based on a series of game theoretic analyses and a field study of combating desertification in seven counties in Northwest China. The results show that scholars who have comparative advantages in knowledge and information over other social actors (such as herders and governments) can help game players resolve their collective action dilemma in social–ecological systems under certain conditions. This positive outcome can be achieved mainly through the participation of scholars as information providers, governmental agents, scholar–entrepreneurs, and pure game players.

1. Introduction

Building resilient, sustainable, or robust social–ecological systems (SESs) is currently an active field in ecological economics, political science, environmental management, resilience research and sustainability science (Adger, 2000; Anderies et al., 2004, 2002; Carpenter et al., 2001; Cumming et al., 2005; Dobson, 1999; Fiksel, 2006; Folke et al., 2002; Fraser et al., 2003; Gallopin, 2006; Gottlieb, 2001; Kamieniecki et al., 1997; Ostrom, 1990; Tompkins and Adger, 2004; Wu, 2006; Young et al., 2006). The collective action dilemma, however, has been an important factor that hinders this endeavor (Crona and Bodin, 2006; Janssen and Ahn, 2006; Ostrom, 1990, 1998; Toleubayev et al., 2007). Different models and metaphors have been developed to describe the collective action dilemma in SESs, such as the state of nature (Hobbes, 1991), the tragedy of the commons (Gordon, 1954; Hardin, 1968), the tragedy of public land (Lüshi Chunjiu, 2000; Shijing, 2003; Yang, 2007b), the prisoner's dilemma (Dawes, 1973, 1975; Pareto, 1935; Tucker, 1983), the free-rider problem (Hume, 1978; Pasour, 1981), externalities (spill-over effects), and underprovided public goods (Samuelson, 1954, 1955). In general, the collective action dilemma is a setting in which individuals, as a group, share a common output but have choices for actions based on their own expectation for maximum short-term individual benefits. Then, the rational choice of an individual is to “free-ride” if other individuals in the group can share regardless of their contribution (Olson, 1971). That is, a collective action dilemma involves conflicts between individual rationality and optimality for a group (Schelling, 1978), and its core problem is how the participants in social dilemmas can avoid the temptation of suboptimal equilibria and move closer to optimal outcomes to gain a cooperators' dividend (Lichbach, 1996).

Over the past century, various models have also been applied to resolve the dilemma of collective action in SESs. These include the Central Authority or Leviathan Model (Hardin, 1978; Hobbes, 1991; Pigou, 1932; Olson 1971), the Privatization Model (Buchanan, 1965; Coase, 1960, 1974; Demsetz, 1970; Gordon, 1954; Savas, 2000; Smith, 1981), and the Community Self-Governance Model (Lichbach, 1996; Ostrom, 1990, 2000). The Central Authority Model argues that governmental control and forceful actions are the major methods to resolve collective action problems and supply public goods, whereas the Privatization Model claims that privatization is an essential way, if not the only way, to resolve the collective action (or social) dilemma. The Community Self-Governance Model emphasizes that community members can realize self-governance of the community's common resources using self-organizing methods under certain conditions.

If we divide the major social actors of an SES into five groups—the public, firms, governments, scholars, and the fifth sector (including religious groups, clans, or many kinds of NGOs) (Yang, 2007a,b), the above-mentioned models each only addresses part of the whole picture. The self-governance model stresses the important functions of the public as well as the fifth sector as spokespersons in collective action, the leviathan model stresses the importance of the government, and the

* Corresponding author. ASU School of Public Affairs Mail Code 3720 411 N. Central Avenue, Ste. 450, United States. Tel.: +1 480 241 6640.
E-mail addresses: Lihua.yang@asu.edu (L. Yang), Jingle.wu@asu.edu (J. Wu).
[1] Tel.: +1 480 965 1063; fax: +1 480 965 6899.

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privatization model stresses the important functions of firms. Importantly, the functions of scholars are essentially neglected. Furthermore, studies have shown that self-governance tends to be successful in some small-scale and homogeneous settings (Sabatier, 1992, p. 249) and often requires high self-organizing capability of community members, a stable and relatively closed inner environment of the community, the nonexistence of the external intervention, numerous historical experiments, and a high degree of moral and religious forces (Yang, 2007a,b). The major problems that undermine the feasibility of the Central Authority Model include: (1) incomplete or inaccurate governmental information, (2) low governmental monitoring capabilities, (3) low governmental sanctioning reliability, (4) high costs of administration, and (5) the possibility of governmental corruption (Ostrom, 1990; Yang, 2007b). The Privatization Model also suffer from several problems: (1) some resources cannot be divided; (2) even for resources that can be divided, they cannot always be divided fairly because of the heterogeneity and nonstationarity of resources; (3) the division of some resources is not economic and often involve high transaction costs; and (4) numerous clashes exist between private and public interests or between short-term and long-term interests (Ostrom, 1990, pp. 12–13; Yang, 2007b).

Therefore, the purpose of this study is to develop a new "Scholar-Participated Governance Model" as an alternative or complementary solution to the collective action dilemma in SESs. Game theoretical analysis is mainly used to demonstrate why this model is necessary and possible. In the following sections, we first review a herder game using a common grazing meadow and analyze the underlying assumptions. Then, we explore scholars' roles in collective action as information providers, agents of government, entrepreneurs, and pure game players in a three-person game. Finally, results of a field study on combating desertification in Northwest China are compared with the findings from the game theoretical analysis.

2. A herder game and the assumptions of research

Ostrom (1990) studied a game of herders sharing a common grazing meadow—a simple example of SES. Suppose that the largest number of grazing animals the meadow can support for an entire season is L, and the "cooperate" strategy is thought of as grazing L/2 animals for each herder. That is, a cooperate strategy is a strategy where each herder considers both his and his opponents' benefit in order to move closer to optimal outcomes to gain his cooperators' dividend. Also, a defect strategy is a strategy where each herder tries to graze as many animals as he thinks he can sell at a profit regardless of his opponent's benefits. Suppose both of the herders obtain 10 units of profit when they take the cooperate strategy, whereas they obtain zero profit if they both choose the defect strategy. If one takes the cooperate strategy and the other takes the defect strategy, the "defector" obtains 11 units of profit, and the "sucker" obtains −1 (see the payoff matrix for Game 1 in Fig. 1). If each herder chooses strategies independently and has no capacity to engage in a binding contract, both of them will choose their dominant strategy (in the sense that the player is always better off when choosing this strategy) to defect and both will obtain zero profit. This is the Hardin herder game with the structure of a prisoner's dilemma game, which is a "non-zero-sum" noncooperative game where each game player has a dominant strategy to defect no matter what the other player chooses. Suppose that the central authority has complete information about the carrying capacity of the meadow (L), can always tell which herder is cheating, and has monitoring capabilities, sanctioning determination, and zero cost of administration, the solution to Game 2 becomes (cooperate, cooperate) when the central authority decides to impose a penalty of 2 profit units on the defector (see Fig. 1, Game 2). Without complete information, however, a central agency would find it difficult to set the grazing intensity or fine to an optimal level.

Now let's assume that the central government has complete information on the carrying capacity of the meadow (L) but incomplete information on the particular actions of the herders, that the probability of the central agency punishing defections is y, and that the probability of the central agency falsely punishing cooperative actions is x (see Fig. 1, Game 3). Several errors made by the central agency include "setting the carrying capacity or the fine too high or too low," "sanctioning herders who cooperate," or "not sanctioning defectors" (Ostrom, 1990, p. 10). If $x=0$ and $y=1$, Game 3 becomes Game 2. If the central agency does not have complete information about the herders' actions, say $x=0.3$, $y=0.7$, Game 3 becomes Game 4 (see Fig. 1, Game 4), which makes the herders face a prisoner's dilemma game again. Furthermore, the equilibrium outcome (−1.4, 1.4) for Game 4 is even lower than (1, 1) in Game 1. The method proposed by Ostrom (1990) is one of self-governance. Under the players' self-governance, the players can negotiate various strategies for sharing the meadow and the costs of implementing the agreement, even though a binding contract is still needed to be enforced by an external actor. When both Player 1 and Player 2 agree upon and conform to a contract, the solution to the fifth game becomes $(10-e/2, 10-e/2)$ (here e is the cost of implementing an agreement). Otherwise, they repeat Game 1(see Fig. 1, Game 5).

Information is about facts and figures; however, knowledge is the understanding of the facts and figures (Frenzel, 1987; Morgan and Peha, 2003). Knowledge represents formless capital that plays an important role in the production and transaction process (e.g., Aghion and Howitt, 1992; Bacon, 1597; Romer, 1990). Hayek (1945, p.519) claims that "the knowledge of the circumstances of which we must make use never exists in concentrated or integrated form, but solely as the dispersed bits of incomplete and frequently contradictory knowledge which all the separate individuals possess." This does not mean that knowledge is equally possessed by all the separate individuals, however. First, unless people are living in an ideal world, the asymmetry of knowledge possession is inevitable. Second, even if some institutional arrangements can be designed to distinctly reduce the degree of the asymmetry of knowledge possession, the limits of human nature, the complex attributes of knowledge, specialization, the division of labor, and individual heterogeneity often make it impossible.

Thus, in our study we assume that although all individuals possess some incomplete and frequently contradictory knowledge, some individuals often have more than others—heterogeneity of knowledge possession at the individual level. Scholars, in our study, are defined as those who have comparative advantages in knowledge over other social actors such as herders, firms, governments, and the fifth sector. The term "scholars" here is a broader concept than "experts" that often refers only to technical persons who can use information to construct an expert–client relationship of influence (Rifkin and Martin, 1997, p. 30 and 37). Different from experts, scholars are not necessarily required to have high levels of skills or specific knowledge of great depth that are usually expected of experts. For instance, in the program of People's Planning in the Kerala in India, a new scholar is defined in a broad sense to include the "wise farmer" in addition to the civil engineer (Fischer, 2000, p. 167). Some researchers also argued that it is important to combine scientific knowledge (often hold by experts) and social knowledge (such as the moral, ethical, cultural, and behavioral dimensions of issues) together and particularly the local "non-scientific" knowledge (often hold by non-experts) should gain legitimacy in policy circles (Eden, 1996; Fischer, 1999, 2000; Pooley and Wilcox, 2000). Furthermore, in concrete local communities, local people also recognize scholars depending on social norms, prestige, past experiences, social status, and so on, rather than only on their knowledge and information (Yang, 2007b). Thus, we broadly define "scholars" on the basis of social actors' comparative advantages in knowledge or information (Yang, 2007b). Scholars include professors, researchers, experts, and stakeholders who possess learnt knowledge.

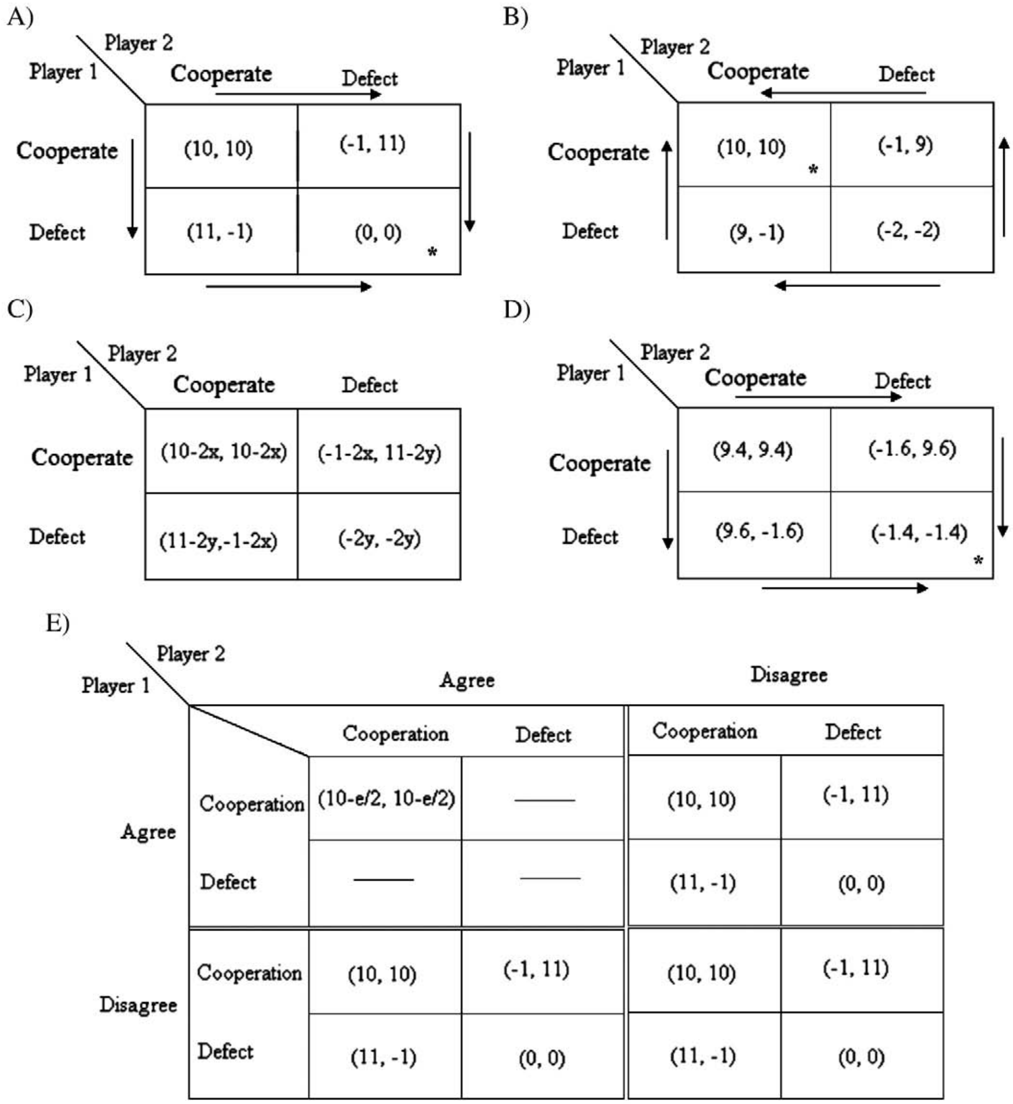

Fig. 1. The five games in Ostrom (1990). A) Game 1—the Hardin herder game. B) Game 2—the central authority game with complete information. C) Game 3—the central authority game with incomplete information. D) Game 4—an example of the central authority game with incomplete information. E) Game 5—self-financed contract-enforcement game. While all these game are illustrated by Ostrom using extensive forms, we recast them as normal forms.

The research question of our study is how scholars' participation can improve people's capability to resolve the problems analyzed by the above five games and also resolve some problems neglected by them. Our purpose, however, is not to directly supply strict mathematical solutions to the prisoner's dilemma, the findings we report here focus on how scholars' participation can change the original situation described by the Hardin herder game and the central authority game with incomplete information and then make cooperative behavior possible. Furthermore, because the situations described by a coordination game and a dictator game are also as important as the prisoner's dilemma in understanding collective action in SESs (reasons will be justified latter), the impact of scholars' participation on these two games will also be considered when necessary. To simplify the analysis, let's first consider a SES with only herders, governments, and scholars, be they resource users or public infrastructure providers (Anderies et al., 2004). There are no firms and the fifth sector. We assume that all these three types of actors are profit maximizers. Herders seek to maximize their returns from *herding* as an economic activity, governments seek to maximize revenues, and scholars seek to maximize their returns economically or socially (for example, sometimes they seek reputation rather than economic gains). Also, both herders and governments are assumed to be players with incomplete information. Particularly, incomplete information on actions of herders is also taken into account. Then, from the perspective of a three-person game, in scholar-participated governance the scholars can play at least four kinds of roles: as information providers for the herders or the governments, as agents of the governments, as entrepreneurs or leaders for the herders, and as pure game players who pursue their own interests. And thus the game analysis can be fitted into the study of these four roles.

3. The scholar as an information provider

Let's first consider a two-player game. Suppose that there is a scholar who has the information about the carrying capacity of the meadow, the particular actions of the two players, and is willing to freely share this information with the public (or sell it as private information) to both of the two players. The costs of this information for Players 1 and 2 are denoted by c_i ($i=1, 2$), and its values are q_i ($-1 \le q_i \le 1, i=1, 2$). In this case, four situations may be considered as follows.

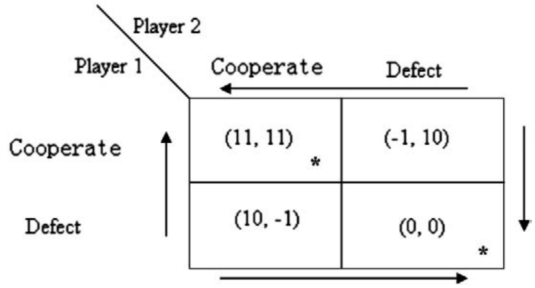

Fig. 2. Game 6—A coordination game.

3.1. Situation 3a: the scholar has the information about the players' particular actions when there is the Hardin herder game

Let's reconsider Game 1. Suppose that the carrying capacity of a meadow is the common knowledge among both of the players, that the scholar freely shares the information about their opponent's particular actions with each of the two players, and that both players simply think that their opponent has probability p_i ($0 \le p_i \le 1$, $i = 1, 2$) to take the cooperate strategy and probability $1 - p_i$ to take the defect strategy before getting the scholar's information. To the original payoff matrix described by Game 1 in Fig. 1, its equilibrium solution is (defect, defect). That is, the two players always take the defect strategy no matter how much p_i is. When the scholar sells the information to the players at cost c_i ($i = 1, 2$) and value q_i ($-1 \le q_i \le 1$, $i = 1, 2$) (q_i as the values of the information for Players 1 and 2 can be deemed as the additional amount for the probability of taking the cooperate strategy by the player's opponent), the equilibrium solution to this game is still (defect, defect) with payoffs ($-c_1$, $-c_2$). That is, although both of the players in informed games change (increase or decrease) their expected utility before playing this game, the real payoffs they get are still kept at (0, 0), or become even worse as being ($-c_1$, $-c_2$). Thus in the Hardin herder game, both of the players, as the rational individuals, will not buy the information from the scholar. The scholar, then, will not have any actual influence on the players' actions, if he only has the information about the players' particular actions.

3.2. Situation 3b: the scholar has the information about the players' particular actions when there is a coordination game

In the Hardin herder game, even if both of the players take the cooperate strategy, their payoffs are (10, 10); but if one cooperates and the other defects, the defector will get 11. Let's consider such a game, when both of the players take the cooperate strategy, their payoffs are (11, 11). If one of them takes the defect strategy then he only gets 10, while the payoff of the other as a cooperator is kept the same (Game 6 in Fig. 2).

If neither of the players knows the information about their opponent's particular actions there are two equilibrium solutions: (cooperate, cooperate) with payoffs (11, 11) and (defect, defect) with payoffs (0, 0). However, if both of them think that their opponent has probability p_i ($0 \le p_i \le 1$, $i = 1, 2$) to take the cooperate strategy and probability $1 - p_i$ to take the defect strategy then:

(1) If both p_2 and p_1 are larger than 0.5 then the game solution is (cooperate, cooperate) with payoffs (11, 11).
(2) If both p_2 and p_1 are less than 0.5 then the game solution is (defect, defect) with payoffs (0, 0).
(3) If p_2 is larger than 0.5, but p_1 is less than 0.5 then the game solution is (cooperate, defect) with payoffs (-1, 10).
(4) If p_2 is less than 0.5, but p_1 is large than 0.5 then the game solution is (defect, cooperate) with payoffs (10, -1).

This is a coordination game which has two pure strategy Nash equilibria and a mixed-strategy equilibrium. In such a game, cooperation might fail, because each player has an alternative which is safer. Because the player will fail to coordinate with non-zero probability, the mixed Nash equilibrium is also Pareto dominated by the two pure Nash equilibria. That is, unlike the pure Nash equilibria, the mixed equilibrium is not an evolutionarily stable strategy. This shows that the collective action dilemma still exists under a situation involving coordination games and solving these games is as important as solving the Hardin herder game to combat the collective action dilemma in SESs. Although with communication or repeated play, this type of coordination game can be solved. Here let's consider how the scholar's information can also change the game solutions. When the scholar sells the information to the players with cost c_i and value q_i, several conclusions are possible:

(1) If both $p_2 + q_2$ and $p_1 + q_1$ are larger than 0.5 then the game solution is (cooperate, cooperate) with payoffs ($11 - c_1$, $11 - c_2$).
(2) If both $p_2 + q_2$ and $p_1 + q_1$ are less than 0.5 then the game solution is (defect, defect) with payoffs ($-c_1$, $-c_2$).
(3) If $p_2 + q_2$ is larger than 0.5, but $p_1 + q_1$ is less than 0.5 then the game solution is (cooperate, defect) with payoffs ($-1 - c_1$, $10 - c_2$).
(4) If $p_2 + q_2$ is less than 0.5, but $p_1 + q_1$ is large than 0.5 then the game solution is (defect, cooperate) with payoffs ($10 - c_1$, $-1 - c_2$).

In summary, the two players' particular actions and payoffs have been strongly influenced by the scholar's information. This is true especially when $q_2 \ge 0.5 - p_2$, $q_1 \ge 0.5 - p_1$, both of the players take the cooperate strategy, and the game solution is (cooperate, cooperate) with payoffs ($11 - c_1$, $11 - c_2$). When $q_2 \ge 0.5 - p_2$, $q_1 \ge 0.5 - p_1$, $c_1 \le 11\ (p_2 + q_2) - 0.5$, and $c_2 \le 11(p_1 + q_1) - 0.5$ both players will buy the scholar's information, which will then drive them to take the (cooperate, cooperate) strategy.

3.3. Situation 3c: the scholar has other valuable information when there is the Hardin herder game

In Situations 3a and 3b, the scholar only has information about the players' particular actions. Now let's consider the situation where the scholar has no information about the players' particular actions but has other types of valuable information, such as the carrying capability of a meadow, the natural characteristics of the meadow, the technology to properly use the meadow, or the knowledge to organize the two players for cooperation. All these kinds of information or knowledge would influence the payoffs the players get from using the meadow. That is, now the values of scholars' information or knowledge are directly deemed as the players' increased or decreased payoffs rather than the additional amount for the probability of taking the cooperate strategy by the player's opponent. For example, due to the scholar's knowledge of the technology to properly use the meadow, the payoffs for Players 1 and 2 may become (12, 12) in Game 1, when both of them take the cooperate strategy. Here, the values of the scholar's information for both Players 1 and 2 are 2.

Let's use v_{1-cc}, v_{1-cd}, v_{1-dc} and v_{1-dd} to represent the values for Player 1 when the players take (cooperate, cooperate), (cooperate, defect), (defect, cooperate) and (defect, defect) strategies respectively, and v_{2-cc}, v_{2-cd}, v_{2-dc} and v_{2-dd} for Player 2, respectively. The costs of this information for Players 1 and 2 are still denoted by c_i ($i = 1, 2$). As a prisoner's dilemma game, in a situation without the scholar, the only solution to Game 1 becomes (defect, defect) with payoffs (0, 0). When the scholar's information is considered, a new payoff matrix is derived (Fig. 3A, Game 7).

Now the payoffs for (cooperate, cooperate) are ($10 + v_{1-cc} - c_1$, $10 + v_{2-cc} - c_2$), for (cooperate defect) are ($-1 + v_{1-cd} - c_1$, $11 + v_{2-cd} - c_2$), for (defect, cooperate) are ($11 + v_{1-dc} - c_1$, $-1 + v_{2-dc} - c_2$), and

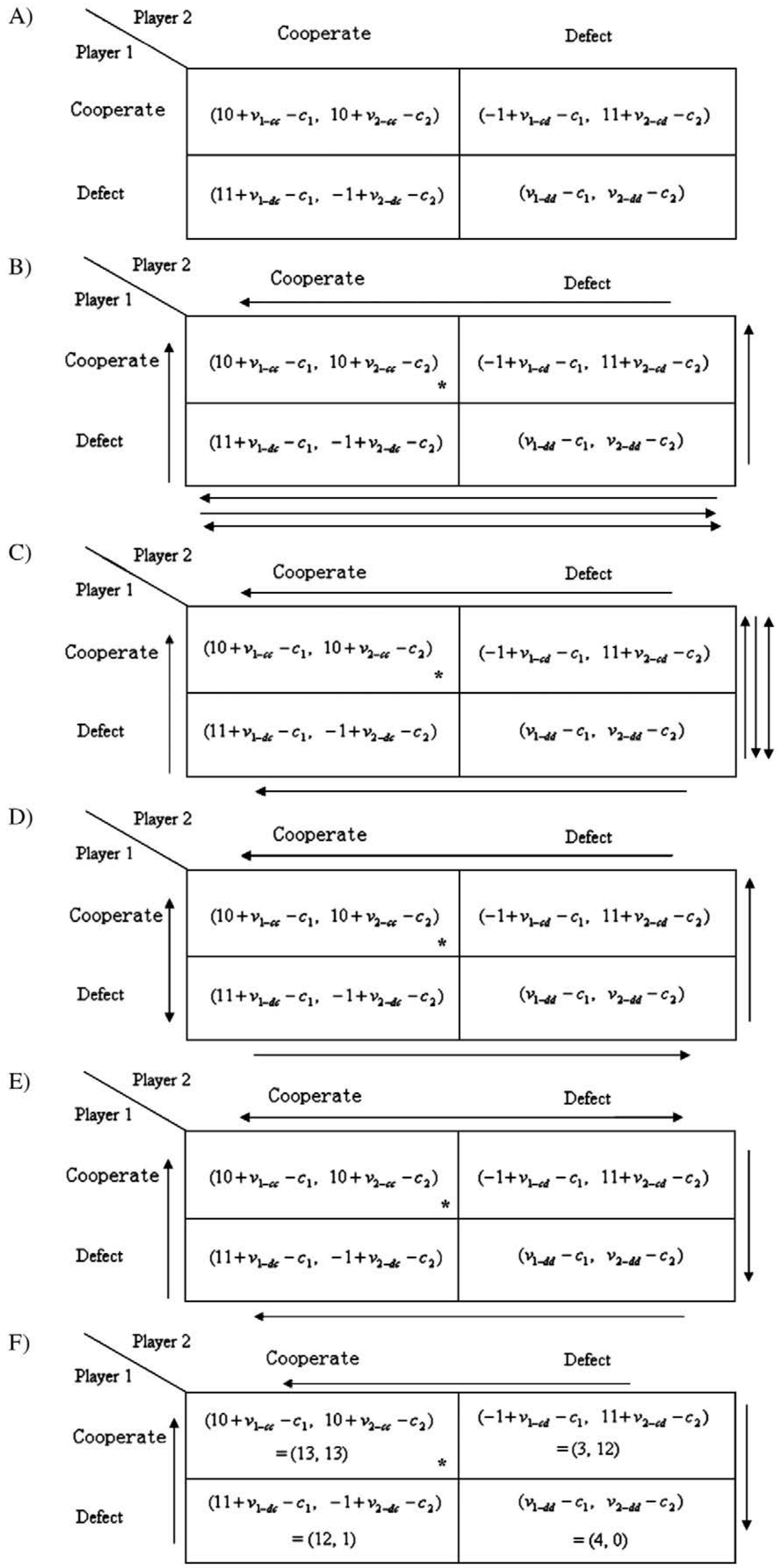

Fig. 3. Game 7—The Hardin herder game with the scholar's information. A) The Hardin game with the scholar's information. B) Cooperation between the two players in the Hardin game with the scholar's information—Setting 1. C) Cooperation between the two players in the Hardin game with the scholar's information—Setting 2. D) Cooperation between the two players in the Hardin game with the scholar's information—Setting 3. E) Cooperation between the two players in the Hardin game with the scholar's information—Setting 4. F) An example of Setting 1.

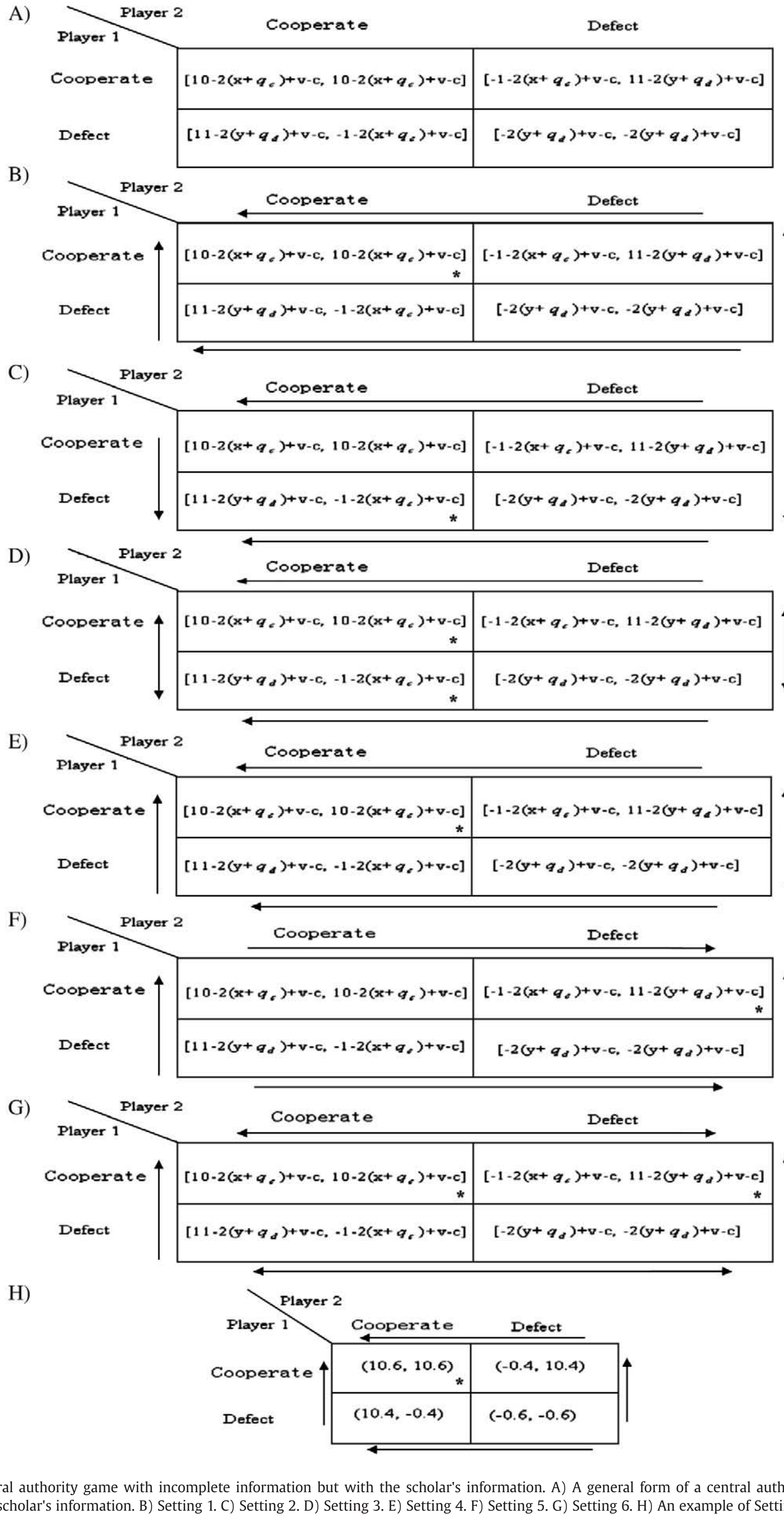

Fig. 4. Game 8—The central authority game with incomplete information but with the scholar's information. A) A general form of a central authority game with incomplete information but with the scholar's information. B) Setting 1. C) Setting 2. D) Setting 3. E) Setting 4. F) Setting 5. G) Setting 6. H) An example of Setting 1.

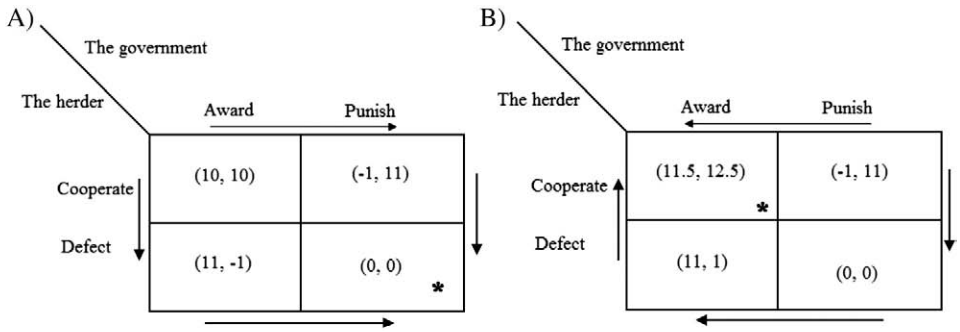

Fig. 5. Game 9—Comparison between the government and the scholar–government as an agent of the government. A) The game between the herder and the government without the delegation. B) The game between the herder and the scholar–government after the delegation.

for (defect, defect) are $(v_{1-dd}-c_1, v_{2-dd}-c_2)$. Under the four settings as described in Appendix A, the unique solution to this game is (cooperate, cooperate) with payoffs $(10+v_{1-cc}-c_1, 10+v_{2-cc}-c_2)$ (see Fig. 3B to E). For instance, as to Setting 1, if $c_1=1$, $c_2=1$, $v_{1-cc}=4>v_{1-dc}=2$, $v_{2-cc}=4>v_{2-cd}=2$, $v_{1-cd}=5>v_{1-dd}=3$ and $v_{2-dc}=3>v_{2-dd}=1$, a new game is shown in Fig. 3F. The unique equilibrium solution to this game is (cooperate, cooperate) with payoffs (13, 13). Thus, even under the situation as described in Game 1, scholar-participated governance can create some conditions for both self-interested players to take the cooperate strategy.

3.4. Situation 3d: the scholar provides information for the government when there is the central authority game with incomplete information

Let's consider a situation where the scholar provides information for the government. In Game 2, the central agency has complete information about the carrying capability of the meadow and the particular actions of the herders; therefore, it can correctly punish defectors. In Game 3 and Game 4 where the central agency only has complete information about the carrying capacity of the meadow but no complete information about the particular actions of the herders, the intervention by the central agency will worsen the situation, unless the probability of correctly imposing sanctions is greater than 0.75. Suppose that the scholar's information helps the central agency improve or reduce its probability to correctly punish defections with q_d $(-1 \le q_d \le 1$, and $0 \le y+q_d \le)$ and its probability to punish cooperative actions with q_c $(-1 \le q_c \le 1$, and $0 \le x+q_c \le)$, and improves the payoffs for both of the players with v. A new payoff matrix is then shown in Fig. 4, Game 8, if we use c to denote the cost of this information. For this game, under Settings 1 and 4 as described in Appendix B, its unique solution is (cooperate, cooperate) (see Fig. 4B and E). For example, for Settings 1, when $y=0.5$, $q_d=0.3$, $x=0.5$, $q_c=-0.3$, $v=2$, and $c=1$, the unique solution to this game is (cooperate, cooperate) with payoffs (10.6, 10.6) (see Fig. 4H). The above analysis shows that scholar-participated governance strongly influences central authority governance through providing the scholar's information. When the scholar's information is valuable, the two herder players will take the cooperate strategy under some certain conditions, even if the information government possessed before was partial.

4. The scholar as an agent of the government

There are three situations needed to be considered here. First, as an agent, the scholar can be a researcher or consultant within the governmental system, or an information provider of the government (Situation 4a). The analysis of this situation is very similar to Situation 3d, when the scholar acts as an information provider. The only difference is that now the scholar becomes an agent of the government rather than an independent third party. Second, the scholar can use knowledge to directly resolve some problems with the herder on behalf of the government (Situation 4b). The analysis of this situation is also consistent with the analysis of Situation 3d. Third, because the government reduces its intervention cost through delegation, the payoff matrix of games can be changed (Situation 4c). This also improves the possibility of the government to resolve the tragedy of the commons. For example, if we change the two players of the Hardin herder game (Game 1) to a herder and the government, and if we let the two governmental strategies be "award" and "punish", then according to the payoff matrix shown in Game 1 the equilibrium solution to this game is (defect, punishment) with payoffs (0, 0) (see Fig. 5A, Game 9). Suppose that the governmental cost is reduced somehow after delegation (for example, due to the lower cost of seeking information and the scholar's good relationship with the herder—this is the scholar's social capital). As its cost decreases 3 units when the scholar–government (used to refer the scholar as an agent of the government) takes the cooperate strategy (i.e., when the herder takes the cooperate strategy, it gets 13 units of payoffs; when the herder takes the defect strategy, it gets 2), and the scholar–government also gives more awards to the herder, say 0.5 (it must be less than 2 in order to make sure that the scholar–government's payoff is larger than 11 getting from a defect strategy), a new payoff matrix results in order to encourage the herder to take the corporative strategy (Fig. 5B). The equilibrium solution to this new game is (Cooperate, award) with payoffs (11.5, 12.5).

When the scholar becomes an agent of the government, the principal–agent problem usually occurs when the interests of the agent and those of the principal diverge under conditions of incomplete and asymmetric information (Grossman and Hart, 1983; Rees, 1985; Rogerson, 1985; Ross, 1973). This problem is not considered in our study, but we believe that the scholar as an agent can help the government resolve the tragedy of the commons problem.

5. The scholar as an entrepreneur

As discussed earlier, when the scholar acts as an information provider in the Hardin herder game, the bargaining–voluntary provision of the collective good cannot be realized. Then, the condition for the bargaining–voluntary provision of the collective good would be that either there is a coordination game or the payoff matrix can be changed in light of the information and knowledge of the scholar. Let's consider two situations.

5.1. Situation 5a: make a binding agreement when there is a coordination game

Suppose that there are three herders using a meadow. A new coordination game is shown in Fig. 6A, Game 10. This game has three pure Nash equilibria: (cooperate, cooperate, cooperate) with payoffs (4, 4, 4), (defect, defect, cooperate) with payoffs (2, 2, −2), and (defect, defect, defect) with payoffs (0, 0, 0). When choosing the cooperate strategy Herder 3 is not sure whether Herder 1 and Herder 2 will take the cooperate or defect strategy. If they take the defect strategy, Herder 3′s payoff will be −2, which is less than 0 (when Herder 3 takes the defect strategy). Thus, both of the cooperate and defect strategies can be Herder 3′s choices. Now let one of the three herders become a scholar–entrepreneur, say Herder 3. Suppose that Herder 3 as an entrepreneur has two methods to influence other game players—(1) the bargains and the voluntary cost-sharing method and (2) coercion or reward as selected incentives (Olson, 1971, pp. 169–178)—and does not require any benefit from his information (that is, the payoff matrix of this game is still kept the same). He will suggest this strategy to the other two herders when he realizes that this will make all of them better off. Because he is generally trusted (or feared) (Olson, 1971, p. 176), the other two herders voluntarily agree with his suggestion after bargaining. Then, they reach a binding voluntary agreement among them to take (cooperate, cooperate, cooperate) strategy to make all of them better off. No one has incentives to break this contract, because if he/she does, the result will make him/her worse. Thus, they always take the cooperate strategy and everyone gains 4 (see Fig. 6B).

Suppose that Herder 3 should pay some costs to get the information and also wants to "get something for himself out of the gains he brings about" as Olson claimed (1971, p. 176). Let's consider the information costs and benefits gains. If the extra gain Herder 3 claims is impartially shared by Herders 1 and 2, the total extra gain he claims to get from Herders 1 and 2 cannot be greater than 2, or finally the payoffs for Herders 1 and 2 are both less than 3 even if all of them take the cooperate strategy. Under bargaining and voluntary arrangement, if the extra gain Herder 3 gets as an entrepreneur is more than the information cost he will always have the incentives to do so. Suppose that the information cost is 0.5 and the extra gain the scholar–entrepreneur gets from Herders 1 and 2 is 0.33 (that is, the information cost is impartially shared by these three players). If the remaining extra gain from the information is impartially shared by Herders 1 and 2 their payoffs become (3.83, 3.83, 3.83) (see Fig. 6C). In this situation, the scholar–entrepreneur gains as much as the other two herders. However, if he claims that he should gain 1.5 after the bargaining, Herders 1 and 2 should afford the cost 0.75 respectively. Then, his gain is 5, and Herder 1 and Herder 2 gain 3.25 respectively (see Fig. 6D). Finally, their payoffs become (3.25, 3.25, 5).

5.2. Situation 5b: make a binding agreement when there is the Hardin herder game

Given a new payoff matrix shown in Fig. 7A, Game 11, the game equilibrium solution is (defect, defect, defect) with payoffs (0, 0, 0). This is a three-person prisoners' dilemma game (or Hardin herder game). Suppose that Herder 3 as a scholar knows that they all take the cooperate strategy and adopt a relative easy new method (for example, a new technology or designed rule to properly use the meadow) to use the meadow with an affordable cost, their payoffs will be, at least, larger than 4. Let's reconsider this game. For example, if the cost to use this easy method for every player is 1, all of them will take the cooperate strategy; then their gain set becomes (5, 5, 5). After subtracting the cost, their payoffs become (4, 4, 4). If their gain set is (6, 6, 6), their payoffs become (5, 5, 5), which makes everyone better off (See Fig. 7B). That is, in light of the suggestions and information provided by Herder 3 as a scholar–entrepreneur, the bargaining–

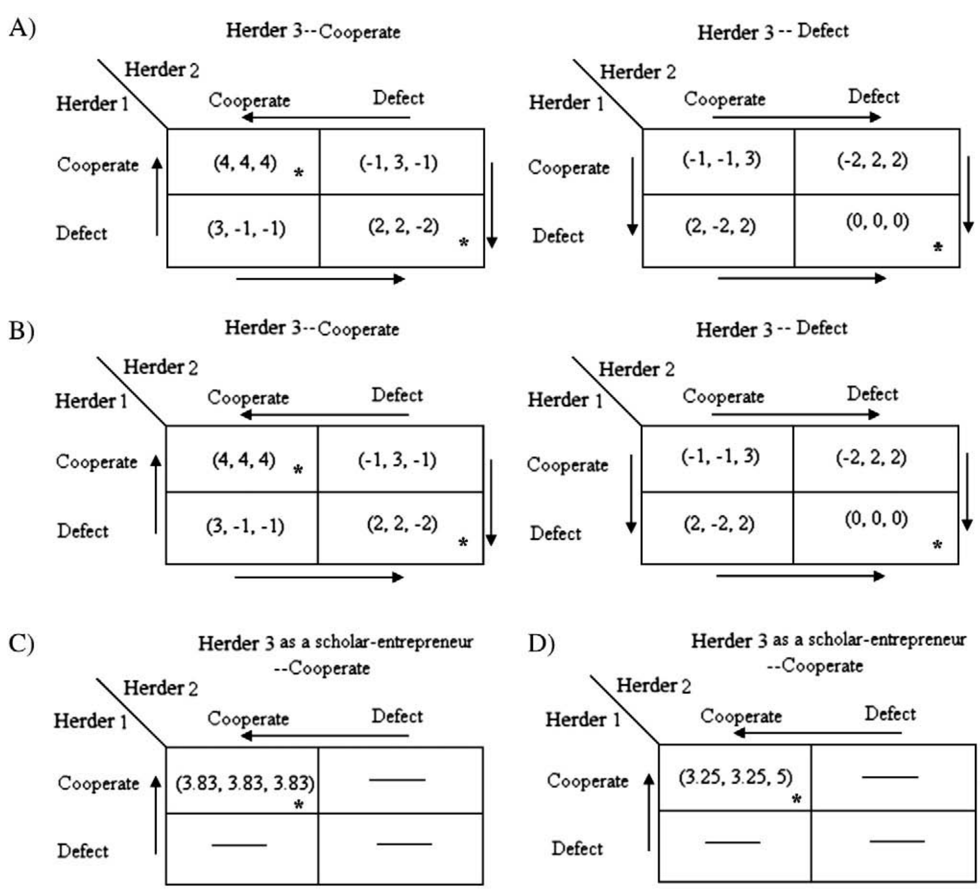

Fig. 6. Game 10—The bargaining–voluntary game with a scholar–entrepreneur in a coordination game. A) A three-herder game without a scholar–entrepreneur. B) A three-herder game with a scholar–entrepreneur who supplies useful information without any cost and also does not require any benefit of this information. C) A game in which a scholar–entrepreneur shares the extra gains of the cooperative strategy with the other two herders. D) A game in which a scholar–entrepreneur gets more extra gains of the cooperative strategy than the other two herders.

voluntary cooperation is realized (see Fig. 7C). Then, this problem becomes the Situation 5a stated above. The only difference is that Herder 3 now not only provides the same information as in Situation 5a but also provides the information about the physical world and tries to use technology to make all of them better off. Certainly, the scholar–entrepreneur can require even more residual benefits (for example, see Fig. 7D), and the bargaining–voluntary cooperation can also be realized.

6. The scholar as a pure game player

Let's consider a situation where the scholar as an independent game player directly competes with the other two players to pursue his own interests. Suppose that the government can have two strategies—intervene or stay out—and that the herder can have two strategies—cooperate or defect—and that the scholar can also have two strategies—accommodate or stay out. Let's consider a game using a meadow among these three actors.

Let's first consider a game between only the government and the herder (i.e., the scholar takes the stay-out strategy). Suppose that the herder gets 2 from using the meadow when he takes the cooperate strategy and gets 3 when takes the defect strategy, the penalty imposed by the government is 3, the intervention cost for government is 1, the government loses 1 due to the damage to its image when it intervenes in the cooperative actions by the herder, and the government gets 0 if it chooses the stay-out strategy. A payoff matrix is shown in Fig. 8A, Game 12. The equilibrium solution to this game is (defect, intervene) with payoffs (0, 2). Then, the government takes all the gains and the herder gets nothing. This will make the government richer and the herder poorer when the herder takes the defect strategy repeatedly in order to survive while the government takes the intervene strategy accordingly to get more benefits. It likes a dictator game where the government as the proposer (acting as the dictator) allocates the entire good to itself and gives nothing to the herder as the responder (Bohnet and Frey, 1999; Bolton et al., 1998; Hoffman et al., 1996). At first glance, except for transferring the benefit from the herder to the government, this is not different from the (cooperate, stay out) outcome from the perspective of the total benefit. Under this situation, however, the herder has to always take the defect strategy to get 3 from nature. This will definitely lead to the tragedy of the commons, and the government as a proposer also fails to maximize its own expected utility in the long run. Then, in order to get the result (cooperate, stay out) as in the situation of the herder's self-governance, the problems become: (1) how can the herder take the cooperate strategy, and (2) how can the government still take the stay-out strategy when the herder takes the cooperate strategy? Trust building and binding agreements (Fowler, 2006; Fowler and Kam, 2007; Lubell et al., 2002; Lubell and Scholz, 2001; Ostrom, 1998; Scholz and Lubell, 1998) may be the two ways to solve this dilemma. If the scholar is highly trusted by both the government and the herder because of his good reputation in addition to his comparative advantages in knowledge and can influence their behaviors as a third party (Yang, 2007a,b), he may help them resolve this game through building trust and making a binding agreement. Let's consider seven situations.

6.1. Situation 6a: the scholar is a peacemaker

As a peacemaker, the scholar tries to balance the actions and benefits between the government and the herder. For example, when the government punishes the cooperate strategy of the herder, he

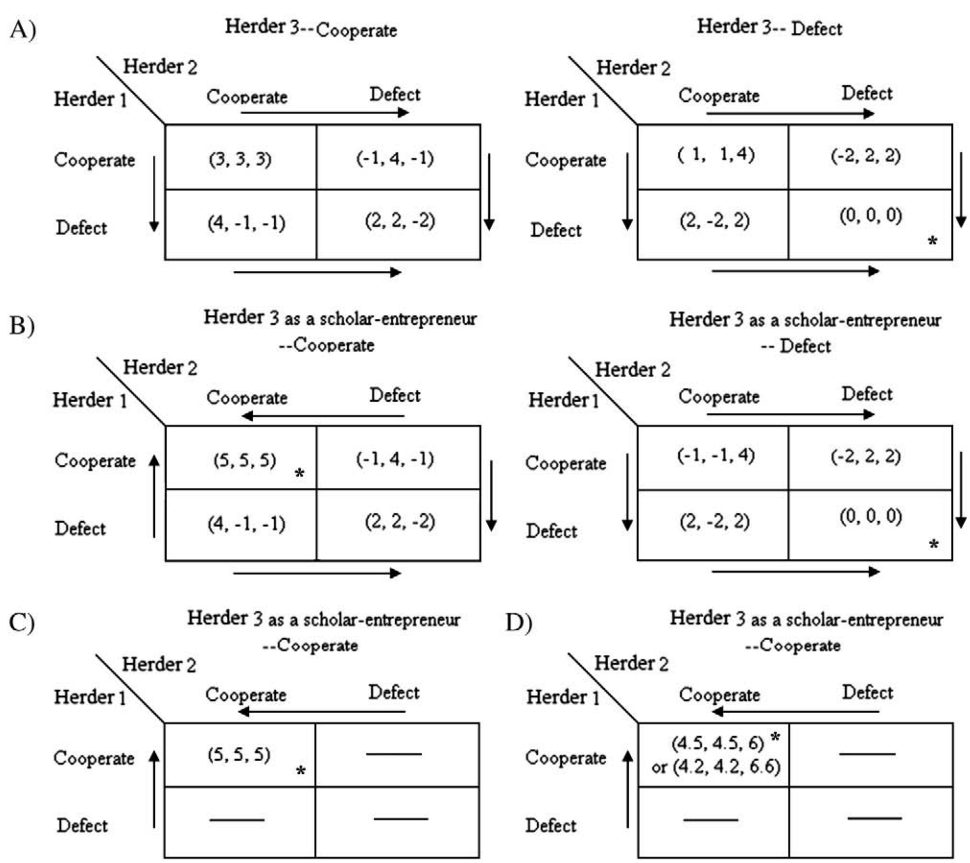

Fig. 7. Game 11—the bargaining–voluntary game with a scholar–entrepreneur in a situation where the original payoff matrix can be changed in light of the scholar's information and knowledge. A) The three-herder game with a scholar–entrepreneur. B) A three-herder game with a scholar–entrepreneur who supplies the useful information including not only about the game itself but also the physical world which can make them all better off when they cooperate. C) The game in which the scholar–entrepreneur shares the extra gains of the cooperative strategy with the other two herders. D) The game in which the scholar–entrepreneur gets more extra gains of the cooperative strategy than the other two herders.

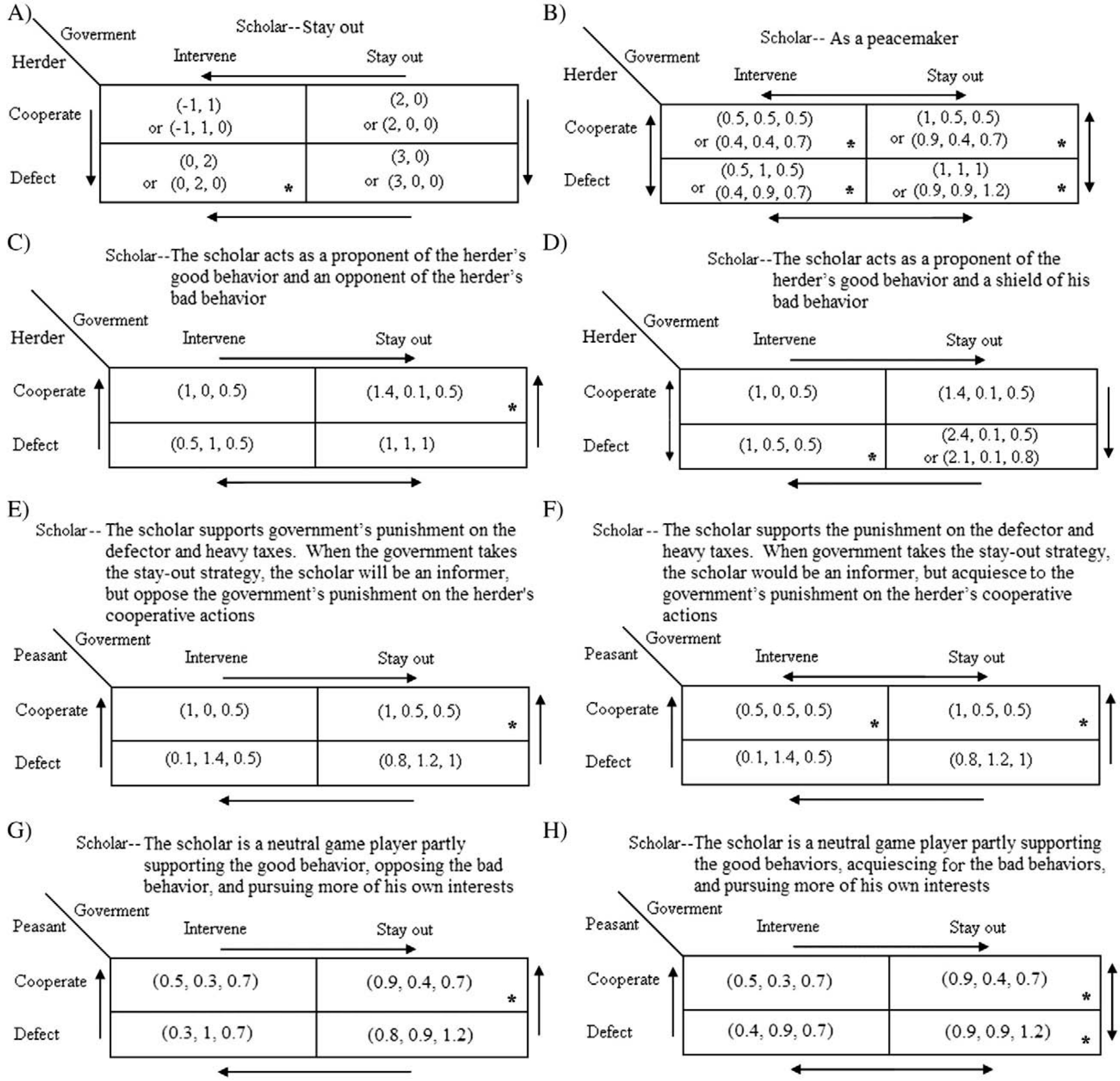

Fig. 8. Game 12—A three-player game among the herder, the government, and the scholar taking different roles. A) A game between the government and the herder when the scholar takes the stay-out strategy. B) A game among the herder, the government, and the scholar as a peacemaker. C) A game when the scholar acts as a proponent of the herder's good behavior and an opponent of the herder's bad behavior. D) A game when the scholar acts as a proponent of the herder's good behavior and a shield of his bad behavior. E) A game when the scholar supports government's punishment on the defector and heavy taxes. When the government takes the stay-out strategy, the scholar will be an informer, but opposes the government's punishment on the herder's cooperative actions. F) A game when the scholar supports the punishment on the defector and heavy taxes. When government takes the stay-out strategy, the scholar will be an informer, but acquiesces to the government's punishment on the herder's cooperative actions. G) A game when the scholar is a neutral game player partly supporting the good behavior, opposing the bad behavior, and pursuing more of his own interests. H) A game when the scholar is a neutral game player partly supporting the good behaviors, acquiescing for the bad behaviors, and pursuing more of his own interests.

persuades the government to return 0.5 units of the benefits to the herder; thus the government only loses 0.5 for the damage to its image. If the scholar gets 0.5 for his benefit, the government gets 0.5. When the government punishes the defect strategy of the herder, he intercedes with the government for the herder, and persuades the government to give back 0.5 units of the benefits to the herder. If the scholar requires a benefit of 0.5 units, the government gets 1. When the government stays out and the herder takes the cooperate strategy, he persuades the herder to give 0.5 units of his benefits to the government (like a tax). Or, he may tell the herder that the government will punish him. If he requires 0.5, the herder gets 1. When the government stays out and the herder takes the defect strategy, he persuades the herder to give 1 unit to the government to avoid its punishment. Or he may tell the herder that if the herder does not want to do that, he will tell the government; then the government will intervene, and the herder can only get 0. If the scholar requires 1 unit for his benefits, the herder, the government, and the scholar all get 1. The scholar himself even can get more as a self-interested individual, as shown in Fig. 8B. However, now there are four equilibrium solutions to this game. That is, all the outcomes can be possible. Although now the scholar's accommodation does not lead to a uniquely better solution from the perspective of the whole SES, his accommodation actually reduces the possibility of "the state of war" between the government and the herder.

6.2. Situation 6b: the scholar acts as a proponent of the herder's good behavior and an opponent of the herder's bad behavior

When the government punishes the cooperate strategy of the herder, the scholar requires the government to return 1 unit of its payoffs to the herder; then the government only loses 0.5 for the damage to its image. If the scholar gets 0.5 for his benefit, the government gets 0. When the government punishes the defect strategy of the herder, and although the scholar dislikes the herder's bad behavior, he intercedes with the government for the herder because of sympathy and persuades the government to give back 0.5 units of its payoffs to the herder. If he also requires a benefit of 0.5 units, the government gets 1, as he is a peacemaker. When the government stays out and the herder takes the cooperate strategy, and although he also persuades the herder to give some benefits to the government, he only suggests a little, say 0.1. If he requires 0.5, the herder gets 1.4. When the government stays out and the herder takes the defect strategy, the scholar may advise the herder to give 1 unit back to the government to avoid punishment. If the scholar also gains 1 unit for his own benefit, the final outcome will be that all parties get 1 (see Fig. 8C). The unique equilibrium solution to this game is (cooperate, stay out, accommodate) with payoffs (1.4, 0.1, 0.5). That is, the scholar helps the game players resolve the collective action dilemma.

6.3. Situation 6c: the scholar acts as a proponent of the herder's good behavior and a shield of his bad behavior

When the herder takes the cooperate strategy, the scholar does the same thing as in Situation 6b. However, when the herder takes the defect strategy, the scholar tries to cover up this behavior. For instance, when the government punishes the herder's defect strategy, the scholar may ask the government to return 1 unit of its payoffs to the herder. If the scholar also requires 1 unit for his own benefit, the government eventually gets 1. When the herder takes the defect strategy and the government takes the stay-out strategy, the scholar pretends to have known nothing about the herder's behavior and only suggests for the herder to give 0.1 units of his benefits to the government. If the scholar requires 0.5, the herder gets 2.4. The scholar also can get more. For example, he can get 0.8, and then the herder gets 2.1(to keep the herder's gain at least equal to 1.4, the scholar's gain cannot be greater than 1.5) (see Fig. 8D). The solution to this game is (defect, intervene, accommodate) with payoffs (1, 0.5, 0.5).

6.4. Situation 6d: the scholar supports government's punishment on the defector and heavy taxes. When the government takes the stay-out strategy, the scholar will be an informer, but opposes the government's punishment on the herder's cooperative actions

A payoff matrix consistent with these statements is shown in Fig. 8E. The equilibrium solution to this game is (cooperate, stay out, accommodate) with payoffs (1, 0.5, 0.5), and the collective action dilemma is resolved. However, now the herder gets less than before while the government gets more taxes.

6.5. Situation 6e: the scholar supports the punishment on the defector and heavy taxes. When government takes the stay-out strategy, the scholar will be an informer, but acquiesces to the government's punishment on the herder's cooperative actions

A payoff matrix consistent with these statements is depicted in Fig. 8F. The two equilibrium solutions to this game are (cooperate, intervene, accommodate) with payoffs (0.5, 0.5, 0.5) and (cooperate, stay out, accommodate) with payoffs (1, 0.5, 0.5). This also helps the game players resolve the dilemma. However, because the herder always takes the cooperate strategy when the government punishes his cooperative actions, the total social benefit is less than when the government takes the stay-out strategy.

6.6. Situation 6f: the scholar is a neutral game player partly supporting the good behavior, opposing the bad behavior, and pursuing more of his own interests

A payoff matrix consistent with these statements is shown in Fig. 8G. The solution to this game is (cooperate, stay out, accommodate) with payoffs (0.9, 0.4, 0.7). Under this situation, the collective action dilemma is also resolved, although scholar himself gets more, while the herder gets less (see Fig. 8G).

6.7. Situation 6g: the scholar is a neutral game player partly supporting the good behaviors, acquiescing for the bad behaviors, and pursuing more of his own interests

A payoff matrix consistent with these statements is depicted in Fig. 8H. The two solutions to this game are (cooperate, stay out, accommodate) with payoffs (0.9, 0.4, 0.7) and (defect, stay out, accommodate) with payoffs (0.9, 0.9, 1.2). Although the collective action dilemma is not completely resolved, this situation at least makes the solution (cooperate, stay out, accommodate) possible.

Certainly, there are other situations which can be analyzed here when the scholar takes the accommodating strategy. The situations stated above are only some special cases. Nevertheless, a clear conclusion emerges that the scholar's accommodation can help the government and the herder build trust or reach a binding agreement between them, thus solving the collective action dilemma under some certain situations (e.g., Situations 6b, 6d, 6e, and 6f). The mechanism in Situation 6b is the best for the herder, the mechanism in Situation 6d is the best for the government, and the mechanism in Situation 6f is the best for the scholar. These findings are also consistent with modern pluralism that claims that a society or political system is at least polyarchical, if not democratic, because multiple actors take part in the process of policy making (Dahl, 1961; Lindblom, 1968, 1977).

7. Comparison with results from a field study

In the above analysis, the SES has only three groups of actors: herders, governments, and scholars. When other actors such as firms and the fifth sector are also included, the above analysis can be extended to five-person games which would be quite complex to analyze. To simplify the analysis, one may focus only on how scholars can help firms and the fifth sector resolve the collective action dilemma together with other game players. Just as the way they work with governments and herders, scholars also can play at least four types of roles when they work with firms and the fifth sector. They can be information and knowledge providers to the firms and the fifth sector, agents of the firms and the fifth sector, scholar–entrepreneurs (or leaders and organizers) of the firms and the fifth sector, and pure game players competing with the firms and the fifth sector. Thus, through scholars' participation many collective action dilemmas among these five social actors in SESs can be resolved under certain conditions.

Game theory is a rigorous tool to theoretically examine how scholar-participated governance can help game players reach a stable equilibrium through changing incentive structure. This rigor, however, also weakens its real-world appliance and relevance for policy making. To examine the validity of the findings from the game theoretic analysis, we conducted a field study in seven counties of Northwest China to gauge the significance of scholars' participation in combating desertification and their different roles. Following a random sampling strategy (see Table 1), our field survey was carried out from June 26 of 2006 to February 12 of 2007. Considering that

Table 1
Questionnaire distribution in the seven counties.

Counties	The number of sent copies	The number of received copies	The number of invalid copies	The number of valid copies
Zhongwei	300	286	6	280
Minqin	370	341	19	322
Jingtai	280	261	25	236
Linze	250	239	0	239
Jinta	300	279	19	260
Guazhou	260	242	5	237
Dunhuang	450	412	12	400
Total	2210	2060	86	1974

some farmers might not be able to read Chinese characters, the questionnaires were randomly distributed to the students in different high schools, who were carefully trained to teach and help their family members to fill out the questionnaires. At the end, we got 1974 valid responses in total.

Six choices were used to evaluate scholars' participation in combating desertification: very important, important, moderately important, dispensable, negative, and unknown. Although in different counties, the percentages of the respondents who indicated that scholars' participation in combating desertification was important are different because of scholars' practical roles and people's recognition, more than 50% of the respondents in all the seven counties indicated that their participation was important (Table 2). This provides empirical supports for our findings of the significance of scholars' participation in resolving the collective action dilemma from the game theoretical analysis.

Furthermore, according to the game theoretical analysis stated above, scholars' roles in combating desertification can be grouped into six types: as information providers for governments and farmers; as scholar–entrepreneurs of farmers; as agents of governments; as information providers, agents and scholar–entrepreneurs of firms; as information providers, agents and scholar–entrepreneurs of the fifth sector; and as pure game players. A multiple-choice question was designed to evaluate this problem (Table 3). The results show that the two most important roles for scholars are information providers for governments or farmers and scholar–entrepreneurs of farmers (supported by over 37% of responders). In the four counties—Zhongwei, Guazhou, Dunhuang and Minqin the role as information providers is the most important, while in the other three counties—Linze, Jingtai, and Jinta the role as scholar–entrepreneurs of farmers is the first. When all counties are considered, acting as pure game players is the third most important role. The fourth important role is acting as agents of governments, which get four votes of the 4th rank, two votes of the 5th rank, and one vote of the 6th rank. These findings are also consistent with their four roles stressed in our three-person game theoretical analysis. This means that these four roles of scholars in resolving collective action dilemma are not only theoretically robust but also empirically valid.

8. Conclusions

Based on a series of game theoretical analyses, this study shows that scholar-participated governance can help game players resolve their collective action dilemma in a three-party (herder, government, and scholar) SES under some certain situations when scholars act as information providers, governmental agents, scholar–entrepreneurs, or pure game players. Furthermore, this analysis can be extended to five-person games including firms and the fifth sector. A filed survey in Northwest China, involving about 2000 respondents, was also conducted to examine the results obtained from the game theoretical analysis. Congruent with the findings of our game theoretical analysis, the results of the field study show that scholars indeed play very important roles in combating desertification, and that the four most important roles of scholars are information providers for governments and farmers, scholar–entrepreneurs of farmers, pure game players, and agents of governments successively. We have summarized the successful situations (in sense that the collective action dilemma is resolved) of the scholars' four roles and their ranks in empirical findings in Table 4.

The four important roles of scholars' participation and their successful situations embody essential elements or conditions that help to account for the success of scholar-participated governance in resolving the collective action dilemma. These findings provide evidence that stronger proactive participation of scholars (including scientists and practitioners) is urgently needed for tackling pressing problems of the collective action dilemmas. From a policy perspective, these findings also give us some concrete instructions to promote scholars' participation and to design new institutions for scholars' participation in resolving pressing environmental problems in the social–ecological systems.

Table 2
The significance of the scholars' impacts.

Counties	Zhongwei	Minqin	Jingtai	Linze	Jinta	Guazhou	Dunhuang
Total evaluation of the scholars' impact	0.7250	0.5580	0.7235	0.7838	0.6372	0.6601	0.8092

Table 3
Percentage of scholars' different roles.

Counties	Zhongwei	Minqin	Jingtai	Linze	Jinta	Guazhou	Dunhuang
Information providers for governments and farmers	0.5036 [1]	0.4099 [1]	0.3798 [2]	0.4435 [2]	0.4500 [2]	0.4300 [1]	0.5000 [1]
Scholar–entrepreneurs of farmers	04679 [2]	0.5124 [2]	0.4341 [1]	0.5439 [1]	0.4654 [1]	0.3767 [2]	0.4050 [2]
Pure game players	0.1464 [3]	0.2422 [3]	0.1705 [3]	0.2050 [3]	0.1308 [3]	0.1467 [3]	0.0725 [3]
Agents of governments	0.0536 [4]	0.0528 [5]	0.0349 [4]	0.0460 [6]	0.0385 [4]	0.0433 [4]	0.0175 [5]
Information providers, agents, and scholar–entrepreneurs of firms	0.0464 [5]	0.0435 [6]	0.0310 [5]	0.1172 [4]	0.0077 [6]	0.0267 [6]	0.0275 [4]
Information providers, agents and scholar–entrepreneurs of the fifth sector	0.0250 [6]	0.0932 [4]	0.0039 [6]	0.0753 [5]	0.0154 [5]	0.0400 [5]	0.0075 [6]

Note: [1] to [6] refer to the ranks.

Table 4
The success situations and ranks of the scholars' four roles.

Situations and ranks	Success situations	Ranks
The four roles		
Information providers	Situations 3b, 3c, and 3d	1
Agents of the government	Situations 4a, 4b, and 4c	4
Entrepreneurs	Situations 5a and 5b	2
Pure game players	Situations 6b, 6d, 6e, and 6f (under situations 6a, 6c, and 6g, although the collective action dilemma is not resolved, its situation is ameliorated)	3

More field studies, however, should be conducted to deepen our understanding on scholar-participation governance. Furthermore, although scholars' participation can resolve game players' collective action dilemma under certain situations, this does not mean that all kinds of scholars' participation will have the same functions. Thus, the difference among various types of scholars' participation also should be carefully studied in order to empirically explore the fundamental principles of successful scholar-participated governance in real-word situations.

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Appendix A

To Player 1, if Player 2 takes the cooperate strategy, whether he takes the cooperate or defect strategy depends on his payoff of taking the cooperate strategy PF_{1cc} $(=11+v_{1-dc}-c_1)$ and payoff of taking the defect strategy PF_{1dc} $(=11+v_{1-dc}-c_1)$. When $PF_{1cc}>PF_{1dc}$, takes the cooperate strategy; when $PF_{1cc}<PF_{1dc}$, takes the defect; when equal, either one. By the same token, if Player 2 takes the defect strategy, when his payoff of taking the cooperate strategy PF_{1cd} $(=-1+v_{1-cd}-c_1)$ is larger than his payoff of taking the defect strategy PF_{1dd} $(=v_{1-dd}-c_1)$, take the cooperate; when $PF_{1cd}<PF_{1dd}$, takes the defect; when equal, either one.

For Player 2, if Player 1 takes the cooperate strategy, whether he take the cooperate or defect strategies depends on his payoff of taking the cooperate strategy PF_{2cc} $(=10+v_{2-cc}-c_2)$ and payoff of taking the defect strategy PF_{2cd} $(=11+v_{2-cd}-c_2)$. When $PF_{2cc}>PF_{2cd}$, takes the cooperate; when $PF_{2cc}<PF_{2cd}$, takes the defect; when equal, either one. By the same token, if Player 1 takes the defect strategy, when his payoff of taking cooperate strategy PF_{2dc} $(=-1+v_{2-dc}-c_2)$ is larger than his payoff of taking defect strategy PF_{2dd} $(=v_{2-dd}-c_2)$, takes the cooperate; when $PF_{2dc}<PF_{2dd}$, takes the defect; if equal, either one.

In sum, the requirements for Players 1 and 2 to simultaneously take the cooperate strategies can be described as follows:

First, there are two strictly necessary conditions: (1) $10+v_{1-cc}-c_1>11+v_{1-dc}-c_1$; (2) $10+v_{2-cc}-c_2>11+v_{2-cd}-c_2$. That is $v_{1-cc}-v_{1-dc}>1$, and $v_{2-cc}-v_{2-dc}>1$.

Then, if $v_{1-cd}-v_{1-dd}>1$, no matter $v_{2-dc}-v_{2-dd}>1$ $v_{1-cc}-v_{1-dc}>1$ is larger, less than, or equal to 1, both of the players take the cooperate strategy (see Fig. 3B, Setting 1).

If $v_{2-dc}-v_{2-dd}>1$, no matter $v_{2-cd}-v_{2-dd}>1$ is larger, less than or equal to 1, both of them take the cooperate strategy (see Fig. 3C, Setting 2).

Second, if $v_{1-cc}-v_{1-dc}=1$, $v_{2-cc}-v_{2-cd}>1$, $v_{1-cd}-v_{1-dd}>1$, and $v_{2-dc}<v_{2-dd}$, the two player also take the cooperate strategy (see Fig. 3D, Setting 3).

Third, if $v_{1-cc}-v_{1-dc}>1$, $v_{2-cc}-v_{2-cd}=1$, $v_{1-cd}-v_{1-dd}<1$, and $v_{2-dc}>v_{2-dd}$, two players still take the cooperate strategy (see Fig. 3E, Setting 4).

All these conditions, however, also require two preconditions: (1) $10+v_{1-cc}-c_1\geq 0$; and $10+v_{2-cc}-c_2\geq 0$. That is, (1) $c_1\leq 10+v_{1-cc}$, and (2) $c_2\leq 10+v_{2-cc}$.

Appendix B

To Player 1, if Player 2 takes the cooperate strategy, whether he takes the cooperate or defect strategy depends on his payoff of taking cooperate strategy $10-2(x+q_c)+v-c$ and payoff of taking the defect strategy $11-2(y+q_c)+v-c$. When $10-2(x+q_c)+v-c>11-2(y+q_c)+v-c$, that is, $(y+q_c)-(x+q_c)$ (denoted by A) > 0.5 (Setting 1), takes the cooperate strategy. When $A<0.5$ (Setting 2), takes the defect; when equal (Setting 3), either one. By the same token, for Player 2, whether he takes the cooperate or defect strategy when Player 1 takes the cooperate or defect strategy also depends on whether A is larger than 0.5 (Setting 4) or less than (Setting 5); if equal (Setting 6), either one. These different settings, where two players will take the cooperate strategy, have been shown in Fig. 4. In short, the requirement for Players 1 and 2 to take the cooperate strategy simultaneously is $A>0.5$. Please also remember other five constraints:

(1) $x+y=1$;
(2) $0\leq y+q_c\leq 1$;
(3) $0\leq x+q_c\leq 1$;
(4) $-1\leq q_d\leq 1$;
(5) $-1\leq q_c\leq 1$.

The other two requirements are:

$$-2(x+q_c)+v-c>0;$$
$$-2(y+q_d)+v-c>0;$$

That is:

$$v-c>2(x+q_c);$$
$$v-c>2(y+q_d).$$

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