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Continuous spatial public goods game with self and peer punishment based on particle swarm optimization

Ji Quan [a,*], Xiukang Yang [a], Xianjia Wang [b]

[a] School of Management, Wuhan University of Technology, Wuhan 430070, China
[b] School of Economics and Management, Wuhan University, Wuhan 430072, China

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ABSTRACT

How cooperative behavior emerges and evolves in human society remains a puzzle. It has been observed that the sense of guilt rooted from free-riding and the sense of justice for punishing the free-riders are prevalent in the real world. Inspired by this observation, two punishment mechanisms have been introduced in the spatial public goods game which are called self-punishment and peer punishment respectively in this paper. In each situation, we have introduced a corresponding parameter to describe the level of individual tolerance or social tolerance. For each individual, whether to punish others or whether it will be punished by others depends on the corresponding tolerance parameter. We focus on the effects of the two kinds of tolerance parameters on the cooperation of the population. The particle swarm optimization (PSO)-based learning rule is used to describe the strategy updating process of individuals. We consider both of the memory and the imitation in our model. Via simulation experiments, we find that both of the two punishment mechanisms could facilitate the promotion of cooperation to a large extent. For the self-punishment and for most parameters in the peer punishment, the smaller the tolerance parameter, the more conducive it is to promote cooperation. These results can help us to better understand the prevailing phenomenon of cooperation in the real world.

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1. Introduction

The phenomenon of cooperation in human society and biological populations is a miracle. The explanation of the emergence and maintenance of cooperation in accordance with Darwin's theory of evolution remains a puzzle for academia [1,2]. The plight of cooperation can be well described by the model of prisoners' dilemma game with two people interacting or the public goods game (PGG) with many people participating. Theoretical scholars from multiple disciplines have tried to interpret the cooperation dilemma from different perspectives. Many cooperation mechanisms have been proposed, namely the punishment [3–7], the reward [8–10], the reputation [11–13], the optional participation [14–16], the population structure [17,18], and the recently proposed mechanisms of insurance compensation [19] and communication structure [20], and so on. Nowak has summarized five main mechanisms for the evolution of cooperation, including kin selection, direct reciprocity, indirect reciprocity, network reciprocity, and group selection [21]. We focus on the punishment and network reciprocity mechanisms in this paper.

Punishment, as a viable way to change human's behavior, is regarded as an important mechanism to maintain cooperation in human society. By behavioral experiments, experimental economists have found that punishment can significantly enhance the level of cooperation in the PGG [22]. Different forms of punishments have attracted the broad interest of scholars and various forms of costly punishments have been studied in the evolutionary PGG [23–29]. For example, the introduction of punishing strategies of punishing cooperators and punishing defectors [23,24]; the introduction of the moralists who cooperate while punishing non-cooperative behavior and immoralists who defect while punishing other non-cooperative behaviors [25]; self-organized punishment that allows players to adapt their sanctioning efforts in dependence on the success of cooperation [26]; conditional punishment that bind the fine on the number of other punishers [27]; probabilistic sharing of the responsibility to punish defectors [28]; and so on.

Network reciprocity mechanism considering the interactive structure of the population has also attracted widespread interest of researchers. Evolutionary games on networks are also termed spatial evolutionary games, in which the relationship between

* Corresponding author.
E-mail address: quanji123@163.com (J. Quan).

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individual's micro-behavior and the system's macro-phenomenon need to be investigated, just like the propagation dynamics model in complex systems [30]. There has been a large amount of literature on the evolution of cooperation in spatial PGG (SPGG). Such as literature on different network structures [31–36], using different strategy update rules [37,38], and on dynamic networks which allows individuals to adjust their interactive objects when their strategies are updated [39–41]. Other literature focus on both network structure and other mechanisms, such as punishment [42–45], reputation [46,47], optional participation [48,49], emotional influence [50–52] and social impact [53]; and so on. The research progress of spatial evolutionary games and the evolution of cooperation can be found in review articles of Szabó et al. [54] and Perc et al. [55–57].

Both mechanisms of the punishment and network reciprocity are analyzed in this paper. A recent study shows that the punishment may diminish the benefits of network reciprocity in social dilemma [58]. In our model, we have also investigated the effect of punishment in the network reciprocity and the conclusion is different. Different from their research, we consider two forms of punishments: self-punishment which stems from the sense of guilt when one takes a free ride of others, the phenomenon of which has already been verified by public good experiments [59,60], and peer punishment which stems from the sense of justice. In both cases, the punishments can be adjusted by some tolerance parameters. The peer punishment we have discussed is comparable to some former studies [23–25,27,28], but there are also some differences. As strategies in the standard PGG are discrete, the corresponding peer punishment punishes other individuals deterministically [23–25] or by probability [27,28]. But in our study, individuals have continuous strategic space. For an individual A, whether to punish individual B in the group game depends on a social tolerance parameter. Only if B's investment is small enough (compared with A, the different part exceeds the social tolerance parameter), then it will be accordingly punished by A. Therefore, the peer punishment in our paper is based on social tolerance and it has more flexibility. When the social tolerance is close to 1, each individual will not punish others. Social tolerance here can be used as a parameter to adjust whether to punish others for individuals. It can be seen as a continuous model of the traditional public goods game with and without punishment. In this paper, we focus on the effects of the two kinds of tolerance parameters on the cooperation of the population.

It is worth mentioning that individuals' strategy updating rules or learning mechanisms will also have significant impacts on the evolutionary equilibrium of the system. In evolutionary games with discrete strategies, many learning mechanisms have been proposed, such as the Fermi rule [23,24,26,36,43,44], the Moran process-based rule [61,62], the directional learning rule [63], the win-stay-lose-shift rule [64–67], the aspiration-based rule [68–72]. However, in the continuous strategy situation, few learning rules are proposed. We observe that in the continuous spatial evolutionary games such as the SPGG, the strategy updating process of individuals has many characteristics in common with particle's behavior in the particle swarm optimization (PSO) algorithm. Firstly, individuals and particles both have strategies. In the SPGG, the individual's strategy is its investment; in the PSO, the particle's strategy is its position. Secondly, individuals and particles both have fitness values which are determined by their strategies. Thirdly, both individuals in the SPGG and particles in the PSO adjust their strategies based on their fitness. Fourthly, both individuals in the SPGG and particles in the PSO adjust their strategies through learning. In the PSO, the particle can learn the best positional information in their history and the position of the most adaptable particle. Therefore, in the SPGG, it is natural to assume that individuals can learn their best historical investment and the strategy of the most successful neighbors. Inspired by this observation, we have adopted the PSO-based individual learning rule in our model. In fact, the PSO has been introduced into the individual's strategy updating process in the evolutionary games [73,74]. We focus on the effects of memory and imitation in the PSO-based learning process on the cooperation of the population.

The remainder of the paper is organized as follows. In Section 2, we describe the model of the continuous SPGG with two types of punishment and the PSO-based learning for individual's strategy updating. The main simulation results for the two punishment situations are presented in Section 3. In Section 4, we give some model extensions. Finally, we summarize the conclusions in Section 5.

2. Model

In our model, individuals are located on the nodes of a network and playing games with their direct neighbors. The network structure defines the objects that each individual can interact with. The strategy of each individual is the amount of its investment. The investment is continuous. They can choose any amount that does not exceed the maximum value. At every stage, each individual needs to participate in multi-group of PGGs at the same time. One is the group that is centered on himself (a group of nodes that directly connected to him), and other groups are centered on each of his direct neighbors. We assume that the strategy of individuals in the multiple games at the same time remains the same.

We only discuss homogeneous networks on which all nodes have the same degrees in this paper. Let $g_i(t)$ denote the strategy of individual i at time t, then the payoff of individual i participating in the game that centered on himself is:

$$\pi_{ii}(t) = \pi_0 - g_i(t) + \sum_{j\in\Omega_i\cup i} \frac{rg_j(t)}{|\Omega_i|+1} \tag{1}$$

where Ω_i is the neighbor set for individual i. π_0 is the total amount that each individual can invest in one game. We set $\pi_0 = 1$, $0 \le g_i(t) \le \pi_0$. r is the investment amplification factor, $1 < r < |\Omega_i| + 1$; $|\Omega_i|$ is the number of neighbors for individual i.

The payoff of individual i participating in the game that centered on his neighbor j is:

$$\pi_{ij}(t) = \pi_0 - g_i(t) + \sum_{k\in\Omega_j\cup j} \frac{rg_k(t)}{|\Omega_j|+1} \tag{2}$$

The total payoff $\pi_i(t)$ of individual i at time t is the sum of payoffs from all the $|\Omega_i|+1$ round games it participated at time t.

$$\pi_i(t) = \pi_{ii}(t) + \sum_{j\in\Omega_i} \pi_{ij}(t) \tag{3}$$

In the following, we consider two forms of punishment respectively.

2.1. Self-punishment

For the self-punishment, we assume that the individual will have a sense of shame when his contributions are smaller below a certain criteria compared with his peers. This negative emotion in PGG has been already verified by behavior experiments in both psychology and economics literature [59,60]. The bad feeling will reduce individual's fitness. We think this feeling of shame is derived from the mutual comparison of the amount of investment between individuals. Therefore, we assume that the fitness reduction is a function of the number of individuals whose investment

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