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Spatial public goods game with continuous contributions based on Particle Swarm Optimization learning and the evolution of cooperation

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HIGHLIGHTS

- Memory and imitation parameters are integrated into the PSO-based learning model.
- Network structure and learning parameters on the cooperation are studied in SCPGG.
- 1-D network is more conducive to promote cooperation than 2-D network in the PSO.
- The PSO is more effective in promoting cooperation than the Fermi rule or the GA.

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ABSTRACT

How to explain the evolution of cooperation in social dilemmas has plagued the theorists of various disciplines. In this paper, we study the public goods game on two structured populations, assuming that each individual can make a continuous contribution in its strategy space. In our model, individuals have memory and imitation ability. They can remember their best history strategy and learn their best neighbors by obtaining the local information. We use the particle swarm optimization (PSO) algorithm to simulate the learning process of individuals. Two network structures of the square lattice and the nearest-neighbor coupled network are considered respectively. We investigate the combined effects of memory, the invest enhancement and the network structure on the average cooperation level of the population. By simulation experiments, we find that the PSO learning mechanism can promote the evolution of cooperation in a large range of parameters under both of the two kinds of networks. Compared with the square lattice network, the nearest-neighbor coupled network can promote the evolution of cooperation in a larger parameter scope. Compared with the Fermi rule and the Genetic Algorithm learning, the PSO learning can induce the population achieve a wider range of cooperation level, which makes it possible to achieve a higher level of cooperation. These results are conducive to a better understanding of the emergence of cooperation in the real world.

1. Introduction

The theoretical model of the public goods game (PGG) can be described as follows. Suppose the number of participants is N. Each participant can choose to invest or not to invest. The investment cost is c. The investment return coefficient is r

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$(1 < r < N)$. Due to the public nature of the investment items, whether invest or not, each participant can use the goods non-exclusively and get the average benefit. When the number of individuals in the group choosing to invest is i, the payoff for investors and non-investors is $\frac{rci}{N} - c$ and $\frac{rci}{N}$ respectively. It is obvious that choosing to invest is a strictly dominated strategy. Rational people will choose to take a free ride of the investors and do not invest themselves. The defection of the whole population will result in a zero income for all of the participants. But if everyone chooses to cooperate, each participant's income can reach the maximum $(r - 1)c$.

The above theoretical model depicts that when private person invests the public goods, there is a conflict between individual rationality and collective rationality. However, through a large number of experiments, behavioral scientists found that although it is a prevalent phenomenon to observe that there were many free riders in the PGG, the reality situation was not as pessimistic as the theoretical model predicts. Self-interest individuals can show a certain degree of cooperation [1]. In addition to human society, biologists have also found that biological groups exhibit large-scale altruistic cooperation even when individuals' interests are conflicting with the collective. These phenomena cannot be reasonably explained in the context of Darwin's theory of evolution. What mechanisms are in place to promote cooperation between humans and between biological groups? This question has plagued scholars of economics, psychology, sociology, biology and other disciplines for many years [2,3]. The evolutionary game theory developed in the past decades has provided an effective tool to study this issue.

In the framework of evolutionary games, many mechanisms have been proposed to resolve this dilemma in the past decades. Such as punishment [4,5], reward [6], reputation [7], optional participation [5,8], spatial interaction [9], and the consideration of trust [10], institution or culture [11], social preference [12], guilty feeling [13], etc. Nowak [14] summarized five main mechanisms for the evolution of cooperation, including kin selection, direct reciprocity, indirect reciprocity, network reciprocity, and group selection.

Among these mechanisms, network reciprocity considering the interactive structure of the population has received the most attention [9,15–17]. Evolutionary games in structured population are also called evolutionary games on networks or spatial evolutionary games. There has been a large number of literature on the evolution of cooperation in spatial public goods game (SPGG). Such as literature on different network structures [17–24], with different strategy update rules [25,26], and on dynamic networks which allows individuals to adjust their interactive objects when their strategies are updated [27–29]. Other literature focus on the network structure and at the same time to consider punishment [30–32], reputation [33,34], optional participation [35,36], emotional influence [37,38], tolerance [39], social impact [40], success-driven effects [41], topology-independent noise [42], group-size effects [43], delayed distribution [44] and so on. The research progress of spatial evolutionary games and the evolution of cooperation can be found in the review articles of Szabo et al. [45] and Perc et al. [46–48].

In the traditional PGG, participants have only two choices of doing invest or not. Investment implies a full degree of cooperation, while no investment implies a full degree of defection. In real situations, cooperation is almost never all or nothing, and participants can show some degree of cooperation. This is the motivation for the continuous PGG (CPGG). In the CPGG, the cooperation is based on the level of individual's investment: an act which is costly, but can benefit other individuals and the group. The dilemma of cooperation in the CPGG remains. The CPGG can be viewed as a generation of the standard PGG in which any levels of investment can be made. Refs. [49–56] studied the CPGG in consideration of the heterogeneity of individual's investment or distribution.

It is worthwhile to mention that the strategy update rules in the spatial CPGG (SCPGG) are different owing to the continuous strategy space. It has been proved that different micro-strategy update rules for individuals will have significant impacts on the macro evolutionary results of the system. In the discrete strategy situation, there have been many agent-based strategy update rules. The rules can be based on replication, imitation or learning [45]. For example, replication rules based on the Moran process [15,16]; imitation rules based on the Fermi process [34–38,40,57,58]; and learning rules based on the directional learning [59], win–stay–lose–shift [60], aspiration [61], and so on [62]. However, in the continuous situation, very few rules have been proposed.

The strategy updating process of individuals in the spatial evolutionary games is similar to particle's behavior in the particle swarm optimization (PSO) algorithm. Inspired by this observation, the PSO has been introduced into the individual's strategy updating process in evolutionary prisoner dilemma games [63–65]. Different from these studies, we apply the PSO learning algorithm to the SCPGG in this paper. We focus on different network structures and different learning rules on the cooperation of the population. In our model, each individual in the structured population is regarded as a particle. Each particle updates its strategy by combining its past best strategy with the current best strategy in its neighborhood. The combination coefficients can be seen as the memory and imitation parameters. We focus on the effects of both memory and imitation in the learning process. We study the SCPGG on the square lattice and the nearest-neighbor coupled network respectively, to investigate the cooperation behavior of the population on these two different networks. We also compare the PSO learning and other learning rules to show the effectiveness of the PSO in promoting cooperation.

The remainder of the paper is organized as follows. In Section 2, we describe the model of the continuous evolutionary public goods game on networks and the PSO learning for individual's strategy updating. The main simulation results and some comparisons are presented in Section 3. Finally, we summarize the conclusions in Section 4.