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Incorporating dominant environment into individual fitness promotes cooperation in the spatial prisoners' dilemma game

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ABSTRACT

In spatial evolutionary games, the fitness of each player is usually measured by its inheritance (i.e. the accumulated payoffs by playing the game with its all nearest neighbors), or by the linear combination of its inheritance and its environment (i.e. the average of its all nearest neighbors' inheritance). However, a rational individual incorporates environment into its fitness to develop itself only when environment is dominant in real life. Here, we redefine the individual fitness as a linear combination of inheritance and environment when environment performs better than inheritance. Multiple Monte Carlo simulation results show that incorporating dominant environment can improve cooperation comparing with the traditional case, and furthermore increasing the proportion of prevailing environment can enhance cooperative level better. These findings indicate that our mechanism enhances the individual ability to adapt environment, and makes the spatial reciprocity more efficient. Besides, we also verify its robustness against different game models and various topology structures.

1. Introduction

There exist a larger amount of cooperative phenomena in various natural and social species [1,2]. However, according to Darwinian principle of natural selection, any unselfish and altruistic individual will be at a disadvantage in living environment because selfish individual often defect to maximize their payoff [3]. In order to explain this riddle, exploring the emergence and persistence of cooperative behaviors among selfish individuals has been a significant challenge in various disciplines, e.g. evolutionary biology, behavioral sciences and economics.

$$\begin{array}{cc} & \begin{array}{cc} C & D \end{array} \\ \begin{array}{c} C \\ D \end{array} & \begin{pmatrix} R & S \\ T & P \end{pmatrix} \end{array} \quad (1)$$

As the rankings $T > R > P > S$ and $2R > T + S$ implies that the defector always prevail irrespective of the opponent's strategy, two players will fall into the so-called social dilemma, where each rational player ignores the collective interest to seek the maximal personal one.

Over the past decades, many noticeable researches have proposed various mechanisms to try to get out of this dilemma and explain why the cooperative behavior can be prevalent. In particular, Nowak [16] summarized these as five rules: kin selection [9], direct reciprocity [10,11], indirect reciprocity [12], group selection [13–15] and network (or spatial) reciprocity [16]. Subsequently, many kinds of mechanisms were constantly proposed to explore the persistence and emergence of cooperative behavior, such as network topology structures [4-10], heterogeneity or diversity [17,18,58,59], coevolution [19], environment factors [15,16,20,21], reward [22], punishment mechanism [49], payoff-driven migration [50], multilayer networks [55,57], evidence theory [56], reference selection mechanism [52], inferring reputation [23,24] and social diversity [25], to name only a few. For comprehensive reviews in this field, we recommend some latest reviews [26,27,54]. It is worth mentioning that the network reciprocity [28-35,48-53], which can enhance cooperation greatly, has been paid great attention by many researchers. In details, each player is arranged on a vertex of a square lattice and plays game only with its all direct neighbors, and cooperators can prevent the invasion of defectors by forming compact clusters. This pioneering work has inspired many works to explore the evolution of cooperation and get fruitful achievements, e.g. integrating the environment factor into individuals' fitness [31–33]. However, in real society, a rational individual will consider the environment only when the environment performs better than the inheritance in one's life.

Inspired by these well-known trues, we redefine the fitness of each individual as the linear combination of inheritance (traditional fitness, i.e. the accumulated payoffs by playing the game

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with its all nearest neighbors) and environment (the average of its all neighbors' traditional fitness) by means of a single parameter u. Namely, the individuals will simultaneously consider the two aforementioned factors when the environment performs better than the inheritance, otherwise, only consider the inheritance. Actually, the introduction of u changes the difference of the fitness of each focal player and the one of its any neighbor, in other words, the heterogeneity of individual fitness is changed. It is interesting and challenging to explore whether this mechanism still promote cooperation. By Monte Carlo simulation, we find that incorporating dominant environment can improve cooperation comparing with the traditional case, and furthermore increasing the proportion of prevailing environment can enhance cooperative level better. The rest of this paper is arranged as follows. Section 2 gives an introduction of the two evolutionary game models (PDG, SDG) on spatial lattices in detail and adjusted definition of fitness. Section 3 presents the numerical simulation results and discussions. Section 4 concludes the obtained results.

2. The model

Initially, we consider the spatial structure $L \times L(L \in N^*)$ populations. Each player i $(i = 1, 2, \cdots, L^2)$ is assigned to be the node of this regular $L \times L$ square lattice network with the periodic boundary condition and adjacent to the same amount $k_i(\in N^*)$ neighbors, the strategy s_i of which is either cooperation (C, denoted by $s_i = (1 \quad 0)^T$) or defection (D, denoted by $s_i = (0 \quad 1)^T$) with equal probability.

We employ mainly the so-called weak PDG [34] and use SDG to test the validity of our mechanism. The corresponding payoff matrices are expressed respectively as

$$P = \begin{pmatrix} 1 & 0 \\ b & 0 \end{pmatrix} \qquad S = \begin{pmatrix} r & 1-r \\ 1+r & 0 \end{pmatrix} \tag{2}$$

where the parameter $b \in (1, 2)$ stands for the temptation to defect, and the parameter $r \in (0, 1)$ the so-called cost-to-benefit ratio respectively.

In a round of the PDG, each player will defect to maximize its payoff even though the average payoff 1 of mutual cooperation is less than the average payoff b/2 of mutual different strategies. While, in the SDG, each one will choose the opposite strategy of the co-player. Generally speaking, the SDG is frequently explored as an alternative to the PDG.

In the spatial structure, as the fitness f_i of any player i is often related to its reproduction ability [35,36], it is usually measured by the current accumulated payoffs played the game with its all nearest neighbors Ω_i. Inspired by the previous results, we propose a new definition of f_i, which combines its environment with its inheritance.

First, every player i acquires its accumulated payoff P_i by playing PDG with its all direct neighbors Ω_i, i.e.

$$P_i = \sum_{j \in \Omega_i} {s_i}^T * P * s_j$$

then its fitness is just equal to P_i. Then, the environment of player i is assessed by the average value $\bar{P}_i$ of its all nearest k_i neighbors' payoff P_j, i.e.

$$\bar{P}_i = \frac{\sum_{j=1}^{k_i} P_j}{k_i} \tag{3}$$

Based on the fact that the environment and inheritance are extremely important for individual development and the extents of which to individual development may vary, we evaluate the fitness

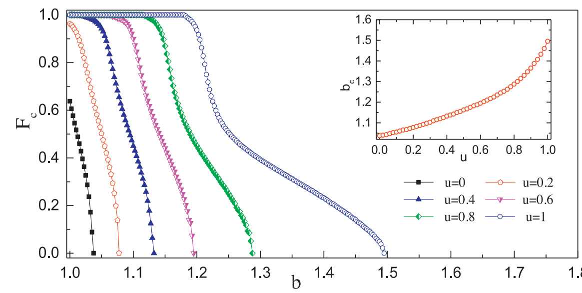

Fig. 1. Outside panel: the trend charts of F_c and b for different values of the adjusting parameter u and $K = 0.1$, which is 0, 0.2, 0.4, 0.6, 0.8, 1 from left to right respectively. Nested panel: the trend chart of critical threshold values of $b = b_c$ (marking the transition to the pure D phase) and u for fixed neighborhood size $k_i = 4$.

f_i of each player i as follow

$$f_i = \begin{cases} P_i, & if\ \bar{P}_i \le P_i; \\ P_i + u \times (\bar{P}_i - P_i), & if\ \bar{P}_i > P_i\ ; \end{cases} \tag{4}$$

where the tunable parameter $u \in [0, 1]$ is used to depict the variable environmental impact on f_i when its environment is performing better than its inheritance.

Obviously, $u = 0$ implies that f_i is equal to P_i, which does not consider the influence of environment and returns to traditional version [37-39], while $0 < u < 1$ implies that f_i is equal to the linear combination $P_i + u \times (\bar{P}_i - P_i)$ when the environment is dominant.

Next, each player i chooses randomly one neighbor j from Ω_i as the imitating object, who obtains its fitness f_j in the same way as f_i.

Finally, player i update its strategy s_i from the chose neighbor j with the following Fermi rule

$$W_{(s_j \to s_i)} = \frac{1}{1 + \exp\left[(f_i - f_j)/K\right]} \tag{5}$$

where $\frac{1}{K}$ denotes the so-called intensity of selection [34,40-47].

3. Simulation results and discussion

We obtain results of Monte Carlo simulation (MCS) results by setting $L = 200$ and in the sense that a new generation of this 4×10^4 players is procreated after one full MCS step, where each player i is restricted to update its strategy once on average. The cooperator rate F_c of each new generation is measured by averaging the last 5×10^3 generations within 3×10^5 generations. In order to eliminate the uncertain factors and assure suitable accuracy, final results were averaged over up to 20 independent runs for each set of parameter values.

It is known to all that cooperators will be eliminated even the temptation to defect is relatively small (i.e. 1.0375) in traditional PDG. Thus, it is meaningful to consider a new mechanism that may sustain cooperation under such conditions. To address this puzzle, we show the frequency of cooperators F_c independence on the temptation b for different values of tuned parameter u in Fig. 1. In the traditional version (i.e. $u = 0$), cooperators soon die out. However, cooperators can prevail and even dominate (i.e. $F_c = 1$) the whole spatial grid for moderate temptation if $u > 0$. Especially, the larger the value of u, the promotive effect on the evolution of cooperation is more obvious. At the same time, the threshold b_c, where cooperators dies out, becomes larger with the increase of u as shown in the insets. From aforementioned results, we can see that compared with the traditional version, our mechanisms incorporating dominant environment can enhance cooperation even the temptation to defect is large.