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Heterogeneous fitness promotes cooperation in the spatial prisoner's dilemma game

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ABSTRACT

Many literatures suggest that incorporating the environment of a focal player (denoted by the average payoff of its all immediate neighbors) into its fitness can promote cooperation in spatial evolutionary games. However, the immediate neighbors influence the focal one to varying degree. Inspired by these, we quantify the focal player's environment with a weighted average payoff of its all immediate neighbors via two interdependent parameters. Numerous simulations show that two moderate parameter pairs favor cooperation, in addition, when the contribution of all immediate neighbors' payoffs to the environment is negative, the cooperation is promoted remarkably. The generality of this mechanism is verified on different networks and more games. Our work might shed light on the understanding of the evolution of cooperative behaviors in real life.

1. Introduction

Cooperative behaviors are ubiquitous in animal and human societies [1–3], e.g. animals cooperate in families to raise their offspring and in groups to prey and to reduce the risk of predation. Understanding these behaviors has attracted the interest of many researchers from various fields, ranging from mathematics, biology, physics, economics, behavioral or social sciences. Although cooperation will reduce individual fitness during fierce competition [5] under the Darwin's notion of survival of the fittest [4], why are cooperative phenomena so common in nature and society? Evolutionary game theory has been proven to be one of the most fruitful tools to explore the emergence and maintenance of cooperative behaviors among selfish individuals [1–3,5]. Specially, some evolutionary models are often used as the metaphors of many social dilemmas, e.g. prisoner's dilemma game [6–11], snowdrift game [6,12–16], public goods game [17–21] and stag-hunt game [22]. These games can be modeled in term of symmetric two-player games: two players simultaneously choose one strategy between cooperation and defection; they will receive the reward R if both cooperate, and the punishment P if both defect; however, if one defects while the other cooperates, the defector receives the temptation T while the cooperator gets the sucker's payoff S. It is convenient to use the payoff matrix

$$\begin{array}{cc} & \text{player 2} \\ & \begin{array}{cc} C & D \end{array} \\ \text{player1} \begin{array}{c} C \\ D \end{array} & \begin{pmatrix} R & S \\ T & P \end{pmatrix} \end{array} \tag{1}$$

Among these games, the prisoner's dilemma game has obtained most outstanding achievements in theoretical and experimental researches [2,24,53,58]. If $T>R>P>S$ and $2R>T+S$, we have the prisoner's dilemma game, where defection is optimal for each selfish player irrespective of the opponent's strategy, and individual rationality contradicts with collective rationality. When two rational players play the one-shot prisoner's dilemma game, the choice between collective benefit and individual benefit is inevitable dilemma.

Over the past decades, numerous mechanisms have been proposed to solve this puzzling dilemma, including spatial reciprocity (network reciprocity), game models and strategy updating rules. In particular, Nowak summarized five prominent mechanisms promoting cooperative behavior [23]: kin selection, direct reciprocity, indirect reciprocity, group selection and network reciprocity. The spatial structure was firstly introduced by Nowak and May in their pioneering work [24]. They showed that the introduction of spatial reciprocity, where each player interacted with its all immediate neighbors, and was occupied by the player with the highest payoff among the previous player and the immediate neighbors, clustered the cooperators on square lattice and so promote cooperation

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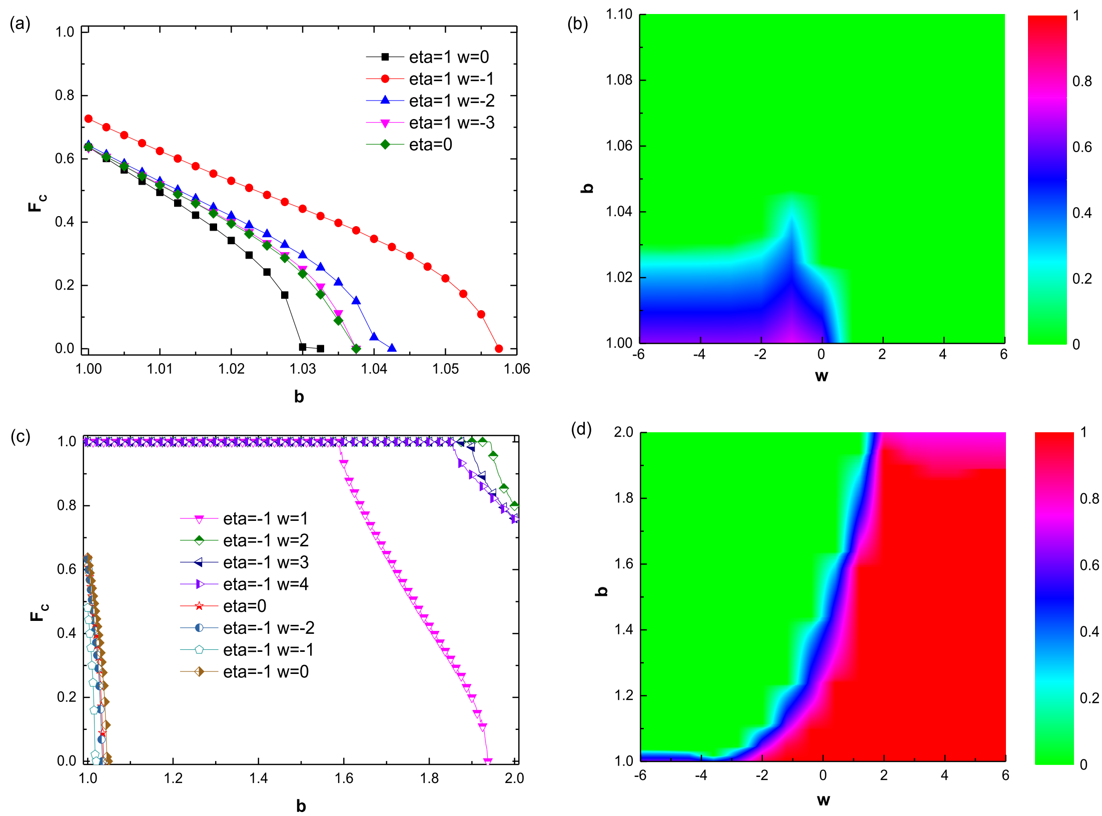

Fig. 1. The trend charts of the frequency of cooperator F_c in dependence on the temptation b for different values of w and η. Panels (a) (b) and (c) (d) shows the results of $\eta = 1$ and $\eta = -1$, respectively. Comparing to the traditional version ($\eta = 0$), we can see that there are two optimal parameter pairs (η, w), namely (1,−1) and (−1,2), to promote remarkably cooperation. All the results are obtained for $K = 0.1$.

by protecting the cooperators against the exploitation of defectors. Along their idea, many kinds of mechanisms have been extensively and constantly suggested, such as heterogeneous interactions networks [25–27], heterogeneous individual fitness [11,28,29], co-evolution [30], reward [31], punishment [32], multilayer networks [33–35], mobility [36], reference selection mechanism [37–39] and inferring reputation [40–42] (for some latest reviews see [30,43–46]). It is noticeable that when various heterogeneities are considered [11,25–29,50,51], cooperation can be promoted markedly. The authors [50,51] discovered that the heterogeneous resources and graphs could promoted cooperation. Wang et al. [57,62,63] proved that measuring symmetrically the environment of a focal player by the average payoff of its all immediate neighbors made cooperators prevail over defectors.

Though many heterogeneities have been verified to promote cooperation in recent literatures [7,28,29,47,48–50], the effect of the heterogeneity on measuring the environment remains largely unexplored. Beyond that, for one thing, the environment plays an important role in individual development, and the impact of different environments on individual growth is different in real life. For example, different credit courses promote the development of students in varying degrees, and the weighted average score of the course is more objective than the average score of the course. For another, the influence of all immediate neighbors of a focal player on the focal player is not the same in the spatial evolutionary game. Inspired by these facts, it is natural and meaningful to measure the environment by the weighted average payoff. Different with the homogenous version (the average payoff), the weighted average payoff is an heterogeneous measure of individual environment. Hence, we give a new mechanism of heterogeneous fitness by incorporating the heterogeneous environment into the traditional fitness (the accumulated payoff) by two interdependent parameters η and w.

It is interesting and challenging to explore how this mechanism impacts the evolution of cooperation. By Monte Carlo simulations, we find that some moderate pairs (η, w) (i.e.$(-1, 2),(1, -1)$) can substantially promote cooperation, and furthermore the highest cooperation levels can be achieved at the former pair. Moreover, we verify the robustness of these findings for different game models and for different networks.

The remainder of this paper is structured as follows. In Section 2, we describe the spatial evolutionary game and strategy updating rule. Section 3 analyzes the main results by multiple numerical simulations. In Section 4, we summarize our concluding remarks and discussions.

2. The model

In this study, we consider an evolutionary prisoner's dilemma game, where the players occupy the nodes of a regular $L \times L$ square lattice with periodic boundary conditions. Initially, each player i is initially assigned to be either a cooperator or a defector with equal probability, which can be expressed as

$$s_i = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \text{ or } s_i = \begin{pmatrix} 0 \\ 1 \end{pmatrix}. \quad (2)$$

Following the notation suggested in previous literatures [19,52], we rescale the payoff matrices of prisoner's dilemma game in Eq. (1) as follows

$$M = \begin{pmatrix} 1 & 0 \\ b & 0 \end{pmatrix}, \quad (3)$$

where $b \in (1,\ 2)$ stands for the temptation to defect. In single round of prisoner's dilemma game, each rational player will defect to maximize personal payoff, although the average payoff 1 of mutual