Chaos, Solitons and Fractals 104 (2017) 28–32

Contents lists available at ScienceDirect

Chaos, Solitons and Fractals

Nonlinear Science, and Nonequilibrium and Complex Phenomena

journal homepage: www.elsevier.com/locate/chaos

Coevolution of game strategy and link weight promotes cooperation in structured population

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ARTICLE INFO

Article history:
Received 30 May 2017
Revised 24 July 2017
Accepted 30 July 2017

Keywords:
Link weight
Time scale
Structured population

ABSTRACT

Evolutionary prisoner's dilemma game in structured populations on a weighted square lattice, on which the edge weight represents the relationship between agents and adaptively changes in time, has been proved to be an efficient way that can promote cooperation. In fact, such an adaptive link weight introduces a new time scale τ_a, not necessarily equal to the time scale of game strategy τ_ε. Inspired from aforementioned above, we investigate the effect of $w = \frac{\tau_\varepsilon}{\tau_a}$ on the evolution of cooperative behavior. Through numerical simulation, we find cooperation can be promoted effectively with a larger value of w, which is related to the increase of average link weight in the structured population.

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1. Introduction

The ubiquitous cooperative behaviors not only appear in human societies, but also in nature. However, according to Darwin's theory of origin of species [1,2], this altruistic behavior will be inevitably eliminated in the process of evolution, which is inconsistent with the empirical study [3]. Thus understanding the emergence and maintenance of cooperation among the population of unrelated individuals becomes one of the most intriguing challenges across myriad of disciplines, such as mathematics, evolutionary biology, statistical physics, to name but a few [4–6]. As a powerful tool for addressing such an overreaching questions, evolutionary game theory has given us a complete mathematical framework to explore this social dilemma and has received much attention [7–10]. Particularly, the prisoner's dilemma game (PDG), severed as a paradigm for illustrating the so-called social poverty between individuals' interest and social welfare in the case of pairwise interactions, has attracted a lot of interest to study the evolution of cooperation in both theoretical and empirical studies [11]. In its basic version, agents must synchronously decides whether to cooperate (C) or defect (D). They both receive the reward R (punishment P) for mutual cooperation (mutual defection), if a cooperator encounters a defector, the formal receives a suckers' payoff (S) and the latter can get a temptation to defect T. The ranking of these payoff are ordered as $T > P > R > S$ and $2R > T + S$. Obviously, a greedy player is prone to defect to obtain higher payoff regardless the punishment to her partner, further leads to the so-called social dilemma where the person who first switch to cooperation will be punished.

Following a number of attempts to escape the so-called social poverty, Nowak all attributed to five mechanisms: direct reciprocity, indirect reciprocity, kin selection, group selection, spatial reciprocity, in which, the spatial reciprocity has attracted much attention and inspired many fruitful achievements [12–15]. In the pioneering work by Nowak and May [16], players are embedded in space, and allowed only to play with their direct neighbors, thus cooperation can prevail in the structured population. The explanation for this phenomenon is that cooperators can form compact clusters to protect the interior from being exploited by defectors. So far, in this spatial reciprocity framework, many factors that play important roles in the game dynamics have been extensively discovered, such as different topology structure [17–20], co-evolution scenarios [21–24], partner selection [25,26], memory effect [27–29], social diversity [30], and punishment and reward [31–33].

Many previous research has shown that individuals' properties, such as aspiration levels [34], reputations [35], ages [36] or link weights [37], also play an important role in maintaining cooperation. For example, Chen et al. study the coevolution of aspirations and cooperation in spatial PDG, in which individuals can adjust their expected payoff levels, and found that the intermediate aspiration level can mostly facilitate cooperation [34]; considering the limit knowledge of individual's reputation, Wang et al. inves-

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http://dx.doi.org/10.1016/j.chaos.2017.07.023
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tigated the effect of inferring reputation mechanism on the evolution of cooperation [38]; Szolnoki et al. examined how quenched age distributions and different aging protocols influence the evolution of cooperation on square lattice [36]; Huang et al. study the coevolution of game strategy and link weight on regular network, on which the link weight adaptively change in time according to some simple rules, and shown that the fraction of cooperation will be enhanced for this mechanism induces the heterogeneity of players [37], to name but a few. Despite the great progress, these works assume that the individuals immediately update their properties according to some rules after they had update their strategies. In reality, however, it is unreasonable to assign individual with a complete cognitive power, which means that individuals may not have the ability to update their properties in time due to the cost and error of information dissemination or the disturbance of noise. In fact, there exist two independent time scales in game dynamics: the strategy-selecting timescale, which characterizes how frequently individuals update their strategies; and the properties-updating time, which specifies how frequently individuals update their properties.

Here, motivated by the above reasons, we model the population on a weighted square lattice, on which the link weight represents the relationship between players and adaptively change in time according to the following ways: the focal player will reinforces (weakens) the link weights with cooperative (defective) neighbors. We assume that coevolution of game strategy and link weight proceeds together under asynchronous. By implemented Monte–Carlo simulations, we find that the faster individuals update their strategies, the higher the value of cooperation, leading to a conspicuous facilitating effect. In the remainder of this paper, we will first describe our modified model of PDG; subsequently, the main simulation results will be shown on Section 3; and last summarize our conclusion.

2. Methods

We consider the prisoner's dilemma game on a square lattice of size L^2 with Moore neighborhood and periodic boundary conditions. Following a common practice [6], we choose the PD's payoffs as $R=1$, $P=S=0$, and $T=b>1$, satisfying the restricted condition $T>R>P=S$.

In order to account for the dependency relationship among individuals, we define the weight of the edge linking node x and node y as α_{xy}, which is symmetric for node x and node y. For simplicity, α_{xy} is set to 1 for all edges initially and then adaptively changes corresponding to the interaction.

Similar to Fu [35] and Santos [39], the time scale associated with individual strategy updating is defined as τ_ε, while that of weight updating is defined as τ_a. Up to the ratio $w=\frac{\tau_\varepsilon}{\tau_a}$, strategies and weight update asynchronously up as follows: strategy updates with the probability $(1+w)^{-1}$, while weights refreshes with the probability $1-(1+w)^{-1}$.

We implement the evolutionary dynamics in the following way. As initial conditions, we assign to each individual, with equal probability, one of the two available strategies: cooperation (C) or defection (D). Then, at each time step, each player x in the network obtains the payoff P_{xy} by playing with its neighbor y. Then, combing with α_{xy} and aforementioned payoff P_{xy}, player x can get its accumulated utility as $U_x=\sum_{y\in\Omega_x}\alpha_{xy}P_{xy}$, where Ω_x is the set of neighbors of player x. Player x adjusts the link weight with the probability $(1+w)^{-1}$. The link weight increases Δ if y is cooperator, otherwise decreases Δ as the punishment. To be simple, we assume link weights range from 0 to 2. What is notable that, when $\Delta=0$, α_{xy} is always equal to 1, which leads to the traditional case [16,20]. Players x updates its strategy with the probability $1-(1+w)^{-1}$ by picking up a neighbor y and comparing

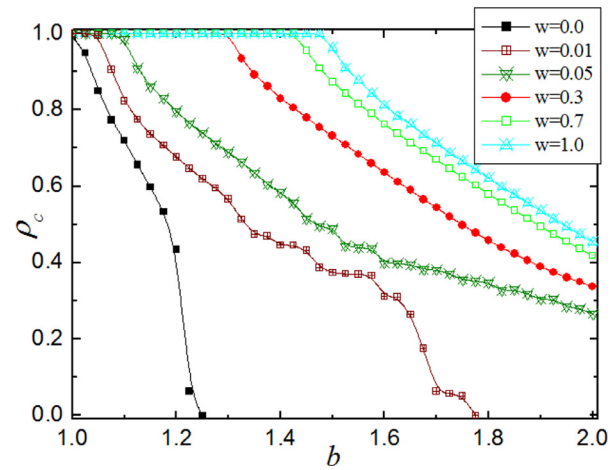

Fig. 1. The fraction of cooperators ρ_c in dependence on the temptation to defect b for different values of time scale w. Compared with the traditional case ($w=0$), it is obvious that the updating time scale ratios w enable cooperators to reach their exclusive dominance even if the temptation is not vary large.

their utilities U_x and U_y. If $U_x\geq U_y$, player x will keep its strategy for the next step. On the contrary, if $U_x<U_y$, player x will adopt y's strategy with the probability:

$$P=\frac{U_y-U_x}{\langle k\rangle D}$$

where D denotes the maximal possible payoff difference between both players $D=T-P$ for the prisoner's dilemma, k is the largest between the degree of player x and player y [20]. To assure that the system has reached a stationary state we make the transient time t equals 51,000. Then we can obtain the presented results by using $L=400$ system size. Moreover, each data were averaged over up to 20 independent runs for each set of parameter values in order to assure suitable accuracy [40].

3. Results

We start by examining the effect of updating time scale ratio w between link weight and individual strategy. Fig. 1 features how fraction of cooperation ρ_c varies in dependence on the temptation to defect b for different values of w. The curve for $w=0$ is the result of traditional evolutionary spatial games, in which the fraction of cooperation decreases fast with b, and dies out at around $b=1.24$. However, if the coevolution of game strategy and link weight is taken into account, situation will change thoroughly that even a small w can promote cooperation. Noteworthy, for $w=0$ cooperation is never a dominant strategy, while for $w>0$ there always exist a threshold value b_c below which cooperators dominate the whole system. Furthermore, the higher value of w, the higher value of critical temptation to defect b_c at which cooperation prevails entirely. The conclusion suggests that the faster individuals adjust relationship between themselves and their friends, the more frequently cooperation behavior emerges.

In order to explore the influence of entangled dynamics of link weight and strategy on the sustainability of cooperation, it is enlightened to report the time courses of ρ_c on the evolution of cooperation. Fig. 2a shows how cooperation evolves for different values of w and fixed b. It is clear that the coevolution of game strategy and link weight makes cooperation become evolutionarily competitive: besides enlarging the size of cooperation, the new mechanism can also accelerated the speed of the cooperation expending. What is attractive that the negative feedback mechanism dominants the cooperation evolution process. Under the traditional case, the negative feedback mechanism dies out that makes the

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