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Research paper

Effect of self-organized interdependence between populations on the evolution of cooperation

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ABSTRACT

In this article, based on interdependent networks, the effect of self-organized interdependence on the evolution of cooperation is studied. Different from the previous works, the interdependent strength, which can effectively improve the fitness of players, is taken as a kind of limited resources and co-evolves with players' strategy. We show that the self-organization of interdependent strength would spontaneously lead to power law distribution at the stationary state, where the level of cooperation in system can be significantly promoted. Furthermore, when intermediate quantity of interdependence resources existing in system, the power law distribution is most evident with the power $\beta \approx 1.72$, meanwhile the level of cooperation also reaches the maximum value. We discuss the related microscopic system properties which are responsible for the observed results and also demonstrate that the power law distribution of interdependence resources is an elementary property which is robust against the governing repeated games and the initial resources allocation patterns.

1. Introduction

Evolutionary game theory, as an extension of classical paradigm, focus on the dynamics of repeated games with players of bounded rationality. In this community, a puzzling and amazing question is how to understand the emergence and persistence of global cooperation in populations when defective actions could provide more inviting short-term benefits for selfish individuals. Since Nowak and May proposed the discovery of network reciprocity [1], i.e. cooperators in structured populations spontaneously aggregate into compact clusters to defense the invasion of defectors, the structure of the interactions among individuals has been seen as a key role to ascertain the evolution of cooperation. Although some existing results have shown that network reciprocity may be limited to promote cooperation in some scenarios [2], undoubtedly, it still provides a way out for explaining the surviving of cooperative behaviors in harsh environment. Recently, related works, involving various social dilemmas such as the prisoner's dilemma game (PDG) [3,4], snowdrift game (SG) [5,6] and public goods game (PGG) [7,8], as well as different structured populations including lattice [9,10], small-world [11,12], scale-free [13,14] and hierarchical networks [15], have been proposed.

As network science evolves, to unravel the intricate variability of complex systems and make a highly integrative understanding of their dynamics, multilayer networks are gradually attracting more attentions.

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Differently from the traditional single-layer network, a multilayer network typically consists of $M(M \geq 2)$ layers, where nodes residing in each layer are connected by internal links, meanwhile, there are also external links that connect counterparts from other networks. Populations in society can be seen as the assembly or projection of multiple interdependent complex social networks, where nodes can be on behalf of individuals and links representing different kinds of social ties such as family relatives, friends and work collaborators [16,17]. Besides social networks, various complex systems in reality including such as transport networks [18] and biological systems [19], possess the properties of multilayer structure. When having an insight into the deep topological structures of systems, multiplayer networks can be further subdivided into interdependent networks, multiplex networks and interconnected networks [20]. For instance, in a multiplex network, all the layers contain the same set of nodes. But, as to the interdependent networks, nodes would represent different entities on each layer. In recent years, investigation of evolutionary game on multilayer networks, especially interdependent networks, have made rapid progress. In [21], Wang et al. proposed the concept of interdependent network reciprocity, which can effectively improve the high level of cooperation beyond the effect of traditional network reciprocity on isolated network; in [22], Santos et al. carried out two different repeated games, i.e. PDG and SG, on interdependent networks and explored the evolutionary dynamics; in [23], Szolnoki et al. demonstrated that strategy choice as information shared between players residing on different layers of interdependent networks could reinforce the evolution of cooperation; in [24], Gómez-Gardeñes et al. analytically and numerically analyzed cooperative behaviors of evolutionary game implemented on interdependent networks for well-mixed populations. Besides, various kinds of interactions between players staged on different interconnected populations, such as biased utility functions [8], probabilistic interconnection [25] and heterogeneous coupling [26], have been proposed and their mechanisms to affect the evolution of cooperation have also been discussed. Furthermore, some characteristics of evolutionary dynamics on interdependent networks, such as optimal interdependence [27], spontaneous symmetry breaking [9] and the spreading of cooperative behavior [28], have been shown as well.

In this article, mainly based on interdependent networks, we focus on self-organized interdependence between structured populations and its effect on the evolution of cooperation. In the previous studies, there existed some related discussion about self-organization on interdependent networks. In [29], Wang et al. introduced a utility threshold E, by comparing with the payoff of players, to determine whether players can have an external link as a reward to connect the corresponding players on the other network. Researchers found the self-organization of the two coupled networks could promote the level of cooperation when the utility threshold was chosen in a proper interval. Subsequently, teaching activity was involved in the co-evolution of strategy and network interdependence [30], where the threshold to establish an external link is not evaluated by payoff of players but their teaching activity. Therein, the spontaneous emergence of a two-class society is observed, that can be beneficial for the cooperative behaviors. Now, from a quite different perspective, we further investigate the effect of self-organized interdependence. As to the existing results, irrespective of utility or teaching activity, a presented threshold is always necessary to determine whether external links can be established or removed. And, for all of external links existing between pairs of players residing on different layers, the corresponding interdependent strength would take the identical value and be fixed without any regulation during the evolution. In our work, since external links could provide additional fitness for players from outside of their home network and provide them more advantage in the process of evolution, interdependent strength of external links is considered as a kind of wealth or resource which is limited but can be continuingly reallocated among players (hereinafter, resources refer to any forms of valuable things, such as time, space, money, food and so on). A fairly concise and strategy-independent rule is provided to carry out the co-evolution of strategy and interdependence. For easily comparing our results with previous results, the weak prisoner's dilemma game is implemented on interdependent networks. Initially, a certain quantity of interdependent strength (it also can be seen as a number of interdependence resources and the total amount would remain unchanged) are averagely allocated to each player. During the interaction phase at each round of game, a winner can gain a basic unit of interdependent strength from the randomly chosen rival. As we will show, interdependence resources at stationary state would spontaneously self-organize into power law distribution and consequently the evolution of cooperation can be effectively promoted well past the boundaries imposed by traditional network reciprocity [1] and interdependent network reciprocity [21]. We also would demonstrate that power law distribution of self-organized interdependence is robust to the initial resources allocation patterns and the governing social dilemmas.

This article is organized as follows. In Model, the structure of interdependent networks and the related description of simulation are given. Next, we present the main results and discuss their implications. Finally, a concluding remark is given.

2. Model

In this article, the applied model is composed of two square lattices of size $L \times L$ with periodic boundary conditions, where each player x in system has four interlinks to its nearest local neighbors at the same layer and one external link to the corresponding player x' on the other layer. External links can be taken as a kind of virtual but not physical connection which bridge players residing on different layers. Parameter $\alpha \in [0, 1]$ is utilized to indicate the interdependent strength of external links, where $\alpha = 0$ means there is not interdependence between the pair of players, and $\alpha = 1$ would be the strongest strength of interconnection. In our discussion, interdependent strength is treated as limited resource, since the stronger it be, the higher fitness players would obtain (the method to calculate the fitness of players is presented in the