Physica A 513 (2019) 399–408

Contents lists available at ScienceDirect

Physica A

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

Effects of updating rules on the coevolving prisoner's dilemma

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HIGHLIGHTS

- Effects of strategy updating rules on the coevolving prisoner's dilemma are studied.
- Cooperation is enhanced when the focal agent serves as a strategy recipient.
- Cooperation is suppressed when the focal agent serves as a strategy donor.
- Effect of the intensity of selection differs according to the updating rules.

ARTICLE INFO

Article history:
Received 27 September 2017
Received in revised form 17 April 2018
Available online xxxx

Keywords:
Coevolving network
Evolutionary game
Prisoner's dilemma
Cooperation

ABSTRACT

We studied the effect of three strategy updating rules in coevolving prisoner's dilemma games where agents (nodes) can switch both the strategy and social partners. Under two node-based strategy updating rules, strategy updating occurs between a randomly chosen focal node and its randomly selected neighbour. The focal agent becomes the strategy recipient and may imitate the strategy of the neighbour according to the payoff difference, i.e. voter-model-like dynamics (VMLD), or becomes a strategy donor and thus may be imitated by the neighbour, i.e. invasion-process-like dynamics (IPLD). For edge-based updating rules, one edge is selected, and the roles of the two connected nodes (donor or recipient) are randomly decided, i.e. edge-based dynamics (EBD). A computer simulation shows that partner switching supports the evolution of cooperation under VMLD, which has been utilised in many studies on spatial evolutionary games, whereas cooperators often vanish under IPLD. The EBD results lie between these two processes. This difference is prominent among nodes with large degrees. In addition, partner switching induces a non-monotonic relationship between the fraction of cooperators and intensity of selection under VMLD and EBD, and a weak or strong selection supports cooperation. In contrast, only a strong selection supports cooperators under IPLD. Similar differences in the enhancement of cooperation are observed when games are played on static heterogeneous networks. Our results imply that the direction of imitation is quite important for understanding the evolutionary process of cooperation.

1. Introduction

The evolution of cooperation is an actively studied subject in physical and biological science [1–3]. In social interactions, cooperators must pay a cost for the benefit of others. Despite the benefit of mutual cooperation, natural selection appears to hinder the evolution of cooperation because non-cooperative individuals can receive the benefit of cooperation without bearing the cost of a cooperative act. The prisoner's dilemma is a widely adopted framework that represents this social

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https://doi.org/10.1016/j.physa.2018.09.046
0378-4371/

dilemma. In the prisoner's dilemma game, two players (agents) simultaneously choose whether to cooperate (C) or defect (D). They will receive R if both choose cooperation and P if both choose defection. If one player cooperates and the other one defects, the cooperator receives S and the defector receives T. Because the order of the payoff is $T > R > P > S$, players should choose D regardless of the partner's choice if they wish to maximise their own payoff. This temptation leads to mutual defection, although the realised payoff (P) is smaller than the result of mutual cooperation (R). However, this prediction contradicts the widely observed cooperation in actual human society.

Many models have been proposed to study the evolutionary origin of cooperation, including the effect of the network (spatial) structure. In their pioneering work, Nowak and May [4] showed that cooperation proliferates if the players are located on a two-dimensional lattice. Subsequent studies introduced complex networks that incorporate the properties of actual networks, such as high clustering and degree heterogeneity, and defined the effects of them on the evolution of cooperation. Notably, a scale-free network gives a unified explanation on the emergence of cooperation in the prisoner's dilemma as well as other games [5–7]. These studies highlight the importance of the heterogeneity in degree (i.e. the number of neighbours of each node). Following works examined the robustness of this phenomenon under wider conditions [8–11]. In addition, the effect of the network structure on the evolution of cooperation was investigated in other networks, including random regular graphs [12], small world networks [13–15] and actual social networks [16–18]. Furthermore, the role of networks in resolving social dilemma was investigated in combination with other mechanisms, including voluntary participation [19,20], heterogeneous teaching activity [21–23], time scale for strategy updating [24–26], payoff aspiration [27–29], conformity [30–32] and punishment [33–36].

In addition to analysing the effect of static networks, recent literature analysed a coevolutionary game where both the network structure and the players' strategy evolve. In coevolutionary games, agents can sever the relationship with a current neighbour and construct a new link with other agents [37–53]. In many of these models, the criterion of the continuation of the relationship depends on the agents' strategy or payoff from the game. These studies showed that the possibility of partner switching (link adaptation) greatly enhances the evolution of cooperation compared to static graphs. The effect of coevolution was also studied with other games, including the snowdrift game [54,55], stag hunt game [56] and ultimatum game [57–59].

In many of these studies, it is assumed during strategy evolution one randomly chosen *focal* agent (node) decides whether to imitate the strategy of a randomly chosen neighbour by comparing their payoff from games [60]. This means that the role of a focal agent is fixed to a strategy recipient, whereas that of a neighbour is fixed to a strategy donor. Some previous studies have considered the different situations [61,62] and showed that the direction of strategy imitation can influence the evolutionary outcomes. For example, one study found that cooperation is enhanced on various lattices if the focal agent is a recipient as opposed to a donor [60]. Although strategy updating rules in these studies were all based on the premise that fitter strategies are more likely to proliferate in the population, the ensuing cooperation levels can differ. Hence, because the details of evolutionary processes, such as strategy updating rules, can affect outcomes, the robustness of evolutionary outcomes have been compared between various rules [63]. For example, some studies dealt with models other than the prisoner's dilemma, and investigated whether the direction of copying (imitation) affects fixation probability of an advantageous mutant [64,65]. In addition, a recent study showed that strategy updating rules can change the consequences of evolutionary processes in well-mixed populations with mutations [66], and coevolution of strategies and updating rules has been considered [67]. In addition, strategy updating rules that are not informed by imitation of fitter individuals have been investigated [68].

In contrast to the preceding literature that examined the evolutionary process on static networks, our current work investigates the effect of strategy updating rules in coevolutionary games. Although many previous studies assume a specific strategy updating rule, such as VMLD, and showed that cooperation is enhanced in combination with network evolution, the roles of updating rules in these phenomena have not been elucidated. Because network coevolution supports cooperation [69], further studies are warranted to investigate dependences on the details of these models.

Herein, we study the effect of the combination of link adaptation and three strategy updating rules. Three updating rules used in this study arose from research on network interactions. Node-based strategy updating occurs under the first two rules: voter-model-like dynamics (VMLD) and invasion-process-like dynamics (IPLD) [60]. Specifically, under these two dynamics, one *node* (agent i) is selected randomly, and then one neighbour of that node (agent j) is selected randomly. Strategy updating occurs by comparing the payoff of these two agents. Under VMLD, agent i copies the strategy of neighbour j with higher probability if agent j earns a larger payoff when compared with agent i. In contrast, under IPLD, neighbour j may imitate the strategy of agent i. Therefore, a randomly chosen neighbour (j) serves as a strategy donor under VMLD and a strategy recipient under IPLD. The last rule is edge-based dynamics (EBD). Under this rule, one *link* (E_{ij}) is selected randomly, and the role of the two connected agents (donor or recipient) is randomly assigned. The payoff of these two agents is compared, and a recipient copies the donor's strategy with higher probability if a donor earns a larger payoff. Unlike other two rules, EBD does not fix the roles of the focal agent and its neighbour in strategy transmission, and is eclectic. In the present analyses, VMLD and IPLD are sometimes biased towards enhancing and suppressing cooperation, respectively. Hence, in these cases, EBD with an intermediate feature may serve as a less biased rule.

Here, we first detail our coevolutionary model and the three strategy update rules. We next report the results of a computer simulation. Lastly, we discuss the implication of our results for the modelling of the evolutionary process of human cooperation.