Journal of Theoretical Biology 349 (2014) 50–56

Contents lists available at ScienceDirect

Journal of Theoretical Biology

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

Rewarding evolutionary fitness with links between populations promotes cooperation

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HIGHLIGHTS

- Rewarding successful players across interdependent populations promotes cooperation.
- Rewarded players enhance network reciprocity.
- Percolation of rewarded players is crucial for the rewarding to take effect.
- Formation of links outside the immediate community is an effective way to reward.

ARTICLE INFO

Article history:
Received 16 December 2013
Received in revised form
25 January 2014
Accepted 28 January 2014
Available online 5 February 2014

Keywords:
Evolutionary games
Interdependent networks
Reward
Coevolution
Self-organization

ABSTRACT

Evolution of cooperation in the prisoner's dilemma and the public goods game is studied, where initially players belong to two independent structured populations. Simultaneously with the strategy evolution, players whose current utility exceeds a threshold are rewarded by an external link to a player belonging to the other population. Yet as soon as the utility drops below the threshold, the external link is terminated. The rewarding of current evolutionary fitness thus introduces a time-varying interdependence between the two populations. We show that, regardless of the details of the evolutionary game and the interaction structure, the self-organization of fitness and reward gives rise to distinguished players that act as strong catalysts of cooperative behavior. However, there also exist critical utility thresholds beyond which distinguished players are no longer able to percolate. The interdependence between the two populations then vanishes, and cooperators are forced to rely on traditional network reciprocity alone. We thus demonstrate that a simple strategy-independent form of rewarding may significantly expand the scope of cooperation on structured populations. The formation of links outside the immediate community seems particularly applicable in human societies, where an individual is typically member in many different social networks.

1. Introduction

Recent research has highlighted rewarding as an effective means to promote public cooperation (Rand et al., 2009; Szolnoki and Perc, 2010; Hauert, 2010; Mesterton-Gibbons et al., 2011). In comparison to peer (Fehr and Gächter, 2002; Semmann et al., 2003; de Quervain et al., 2004; Fowler, 2005; Hauert et al., 2007; Gächter et al., 2008; Ohtsuki et al., 2009; Rockenbach and Milinski, 2009; Deng et al., 2012; Vukov et al., 2013) and pool punishment (Sigmund et al., 2010; Szolnoki et al., 2011; Perc, 2012; Traulsen et al., 2012), rewarding may lead to higher total earnings without potential damage to reputation (Milinski et al., 2002) or fear of retaliation (Dreber et al., 2008). The application of rewarding also avoids the problem of antisocial punishment (Herrmann et al., 2008), which has been shown to significantly challenge the effectiveness of sanctioning (Rand et al., 2010; Rand and Nowak, 2011). Although the majority of previous studies addressing the "stick versus carrot" dilemma (Sigmund et al., 2001; Hilbe and Sigmund, 2010) concluded that punishment is more effective than rewarding in sustaining public cooperation (Sigmund, 2007), evidence suggesting that rewards may be as

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http://dx.doi.org/10.1016/j.jtbi.2014.01.037
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effective as sanctions is mounting. Recent human experiments (Yamagishi et al., 2012; Egloff et al., 2013) also challenge the strong reciprocity model (Fehr et al., 2002), and related theoretical explorations (Szolnoki and Perc, 2013a) indicate that the application of either reward or punishment, but not both, is evolutionary most advantageous.

Another relatively recent development is the study of evolutionary games on interdependent networks (Wang et al., 2012b; Gómez-Gardeñes et al., 2012a, 2012b; Wang et al., 2012a, 2013b; Jiang and Perc, 2013; Szolnoki and Perc, 2013b). The subject has gained on prominence after the discovery that even seemingly irrelevant changes in one network can have catastrophic and very much unexpected consequences in another network (Buldyrev et al., 2010). Since the evolution of cooperation, especially in human societies (Apicella et al., 2012; Rand and Nowak, 2013; Helbing, 2013), also proceeds on such interdependent networks, it is therefore of interest to determine to what extent this interdependence influences the outcome of evolutionary games. It has been shown, for example, that biased utility functions suppress the feedback of individual success and lead to a spontaneous separation of time scales on interdependent networks (Wang et al., 2012b). If utilities are symmetric, cooperation is promoted by means of interdependent network reciprocity that relies on the simultaneous formation of correlated cooperative clusters on both networks (Wang et al., 2013a). In addition to these examples, non-trivial organization of cooperators across the interdependent layers (Gómez-Gardeñes et al., 2012b), strategy-independent information sharing (Szolnoki and Perc, 2013b), probabilistic interconnectedness (Wang et al., 2012a), as well as optimal interdependence (Wang et al., 2013b), have all been shown to extend the boundaries of traditional network reciprocity (Nowak and May, 1992) past its limits on isolated networks (Santos et al., 2006; Ohtsuki et al., 2006; Szabó and Fáth, 2007; Perc and Gómez-Gardeñes, 2013).

Here we wish to extend the scope of evolutionary games on interdependent networks by introducing rewards for high-enough evolutionary fitness of individual players in the form of additional links that bridge the gap between two initially disconnected populations. We introduce a utility threshold E that, if met or exceeded, allows the pertinent player to connect with the corresponding player in the other network. These rewards effectively introduce interdependence between the two populations, and they allow the rewarded players to increase their utility with a fraction of the utility of the player in the other population. However, as soon as the fitness of a player no longer reaches the threshold, its external link is terminated, although it may eventually be re-awarded if and when the utility of the player again becomes sufficiently large. Importantly, the on–off nature of the interdependence between the corresponding players in the two populations draws exclusively on the current level of fitness, without regard of previous evolutionary success or strategy. We consider the weak prisoner's dilemma game as representative for social dilemmas that are governed by pairwise interactions, and the public goods game which is representative for social dilemmas that are governed by group interactions. We also consider different types of networks to describe the interactions among players in each of the two structured populations. As we will show, regardless of these details, the self-organization of fitness and reward promotes the evolution of cooperation well past the boundaries imposed by traditional network reciprocity (Nowak and May, 1992), as well as past the boundaries imposed by interdependent network reciprocity (Wang et al., 2013a), if only the utility threshold is sufficiently large. On the other hand, the threshold must not exceed a critical value, which could be well below the maximal possible utility a cooperator is able to reach if it would be fully surrounded by other cooperators. We will extend and explain these results in detail in Section 3, while in the subsequent section we proceed with the description of the studied evolutionary games.

2. Evolutionary games

The evolutionary games are staged on two disjoint square lattices or random regular graphs with periodic boundary conditions, each of size N, where initially each player x is designated either as a cooperator ($s_x = C$) or defector ($s_x = D$) with equal probability. The weak prisoner's dilemma game is characterized by the temptation to defect $T=b$, reward for mutual cooperation $R=1$, and both the punishment for mutual defection P as well as the suckers payoff S equaling 0, where $1 < b \leq 2$ (Nowak and May, 1992). In this case a player receives its payoff by playing the game with all its neighbors. For the public goods game, players are arranged into overlapping groups of size G, where every player is thus surrounded by its $k=G-1$ neighbors and is a member in $g=G$ different groups (Santos et al., 2008; Perc and Gómez-Gardeñes, 2013). In each group, cooperators contribute 1 to the public good, while defectors contribute nothing. The sum of contributions is subsequently multiplied by the factor $r>1$, reflecting the synergetic effects of cooperation, and the resulting amount is equally shared amongst the G group members. Here the total payoff of a player is the sum of payoffs from all the g groups where she is a member.

We simulate the evolutionary process on both networks in accordance with the standard Monte Carlo simulation procedure comprising the following elementary steps. First, a player x is selected randomly and its payoff Π_x is determined based on the governing evolutionary game (either the weak prisoner's dilemma game or the public goods game). Next, a neighbor y from the same network is chosen randomly and acquires its payoff Π_y in the same way. Lastly, player y adopts the strategy of player x with the probability

$$W(s_x \to s_y) = \frac{1}{1+\exp[(U_y - U_x)/K]}, \tag{1}$$

where $K=0.1$ quantifies the uncertainty related to the strategy adoption process (Szabó and Fáth, 2007), while U_x and U_y are the utilities of players x and y, respectively. All those players that have an external link to the corresponding player x' in the other network have the utility

$$U_x = \Pi_x + \alpha \Pi_{x'}, \tag{2}$$

while those that do not have an external link retain $U_x = \Pi_x$. We emphasize at this point that the external links are directed. Hence, only player x benefits from the additional link, but not player x'. We also do not allow a direct interaction between the two mentioned players. Based on our preceding work (Wang et al., 2013b), where we have studied the general impact of the value of α and the related optimal interdependence between two networks, we here use a fixed value of $\alpha = 0.5$ without loosing generality. Monte Carlo simulations are performed on sufficiently large networks ranging in size from $N = 4 \times 10^4$ to 2.5×10^5 near transition points to avoid accidental extinction of the two competing strategies. The stationary fraction of cooperators ρ_C is recorded after the system reaches dynamical equilibrium, i.e., when the average cooperation level becomes time independent. More specifically, we perform 10^4 Monte Carlo steps (MCS) to reach the stationary state, and subsequently 10^6 more steps to record ρ_C. Moreover, we average the final outcome over up to 100 independent initial conditions to further improve accuracy.