Physica A 392 (2013) 4956–4965

Contents lists available at ScienceDirect

Physica A

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

The coevolution of partner switching and strategy updating in non-excludable public goods game

Yixiao Li [a], Bin Shen [b,*]

[a] School of Information, Zhejiang University of Finance and Economics, Hangzhou 310018, PR China
[b] Ningbo Institute of Technology, Zhejiang University, Ningbo 315100, PR China

HIGHLIGHTS

- We incorporate the non-excludable property of public goods into the spatial public goods game.
- We study the influence of non-excludable partner switching over the evolution of cooperation.
- A negative effect of partner switching upon cooperation is reported.
- The incorporation of costly punishment helps resolving the problem of cooperation prohibition in non-excludable public goods game.

ARTICLE INFO

Article history:
Received 5 March 2013
Received in revised form 5 May 2013
Available online 10 June 2013

Keywords:
Directed network
Cooperation
Costly punishment

ABSTRACT

Spatial public goods game is a popular metaphor to model the dilemma of collective cooperation on graphs, yet the non-excludable property of public goods has seldom been considered in previous models. Based upon a coevolutionary model where agents play public goods games and adjust their partnerships, the present model incorporates the non-excludable property of public goods: agents are able to adjust their participation in the games hosted by others, whereas they cannot exclude others from their own games. In the coevolution, a directed and dynamical network which represents partnerships among autonomous agents is evolved. We find that non-excludable property counteracts the positive effect of partner switching, i.e., the equilibrium level of cooperation is lower than that in the situation of excludable public goods game. Therefore, we study the effect of individual punishment that cooperative agents pay a personal cost to decrease benefits of those defective neighbors who participate in their hosted games. It is found that the cooperation level in the whole population is heightened in the presence of such a costly behavior.

1. Introduction

Cooperation is pervasive in the universe. It paves the way for integration of various systems at different levels, ranging from unicellular organisms to the global earth village. The ubiquitous existence of cooperation leads to a remarkable complexity of biological, human and man-made systems [1–5]. From an individual perspective, cooperation simply means helping another at a cost to itself. If natural selection among individuals favors the survival of the fittest or humans face ruthless competition, how cooperation sustains or evolves? Since Darwin's time, this conundrum has daunted generations

* Corresponding author. Tel.: +86 13685714607.
E-mail addresses: tsingbin@zju.edu.cn, tsingbin@nit.net.cn (B. Shen).

0378-4371/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physa.2013.05.054

of scientists. Strategic games are often employed as a metaphor to model the interplays between individuals. Two simple strategies have been abstracted as cooperation (C) and defection (D). In the famous prisoner's dilemma game (PDG) [6], the Nash equilibrium is that both two players defect. In the context of evolution, cooperation is an evolutionarily disadvantaged strategy [7]. For the maintenance or evolution of cooperation, additional rules or mechanisms are required, such as kin selection, group selection, network reciprocity, direct reciprocity and indirect reciprocity [4,8].

It is quite usual that a number of independent individuals have some goals or benefits in common, often referred to as public goods. For example, bacteria produce costly exoproducts which benefit all cells in the local environment [9,10]. As for humans, public goods are essential elements for every society, e.g., a tribe of savages hunt together for animals, all nations unit to combat the problem of global warming [11]. Public goods game (PGG) is thus developed to mimic the interplays among members in a group [12–16]. In a typical PGG, group members can make a choice on whether or not to contribute to a common pool. Their contributions are amplified through their collective effort. However, the final goods are shared equally among all group members, irrespective of their initial contributions. Since this reason, there is no need to contribute to the public goods for selfish individuals. Therefore, the free-rider problem arises in PGGs, which is also widely known as *tragedy of the commons* [12]. Theoretical models predict that defectors will dominate if the amplification factor of the PGG is lower than the size of the PGG group. However, such asocial behaviors are frequently at odds with empirical findings. Therefore, great efforts have been paid to explain the discrepancy between theoretical and empirical results.

Szabó and Hauert introduced a spatial public goods game where spatial structures define the patterns of PGG interactions [16]. On a square lattice where agents interact only with their nearest neighbors, the equilibrium frequency of cooperation exhibits a phase transition as the amplification factor of PGG increases. Cooperators survive in local scope in the presence of a non-trivial structure of PGG participation [17]. When some other behaviors are incorporated into the spatial public goods game [18–20], cooperation can be promoted. Santos et al. found that the structural properties of scale-free networks or double-star structure have a strong effect in prohibiting the spreading of defection, thus boosting cooperation [21]. Scale-free networks are characterized by high heterogeneity in connectivity and studies have shown that increasing this heterogeneity promotes cooperation [22,23]. Connectivity heterogeneity is only one polygon of the polyhedron of social diversity. Moreover, researchers have found that a number of mechanisms reflecting the nature of social diversity favor the evolution of cooperation in the framework of evolutionary PGG, such as inhomogeneous teaching [24,25], heterogeneous allocation [26,27] and heterogeneous investment [28].

A fixed-network population leads to the outbreak of cooperation and some structural patterns enhance cooperation substantially. In conditions where agents are capable to adjust their partnerships, the reciprocity of dynamical adjustment brings about high-level cooperation [29–40]. The driving force behind such mechanisms is that cooperators can lessen exploitation of defectors by severing ties to the latter. Via switching from the lowest reputation neighbor to the highest reputation one of his next nearest neighbors, a myopic agent is involved in the process of partner switching [41,42]. When all agents are able to perform such a myopic way of partnership adjustment, the whole population evolves high-level cooperation. Van Segbroeck et al. found that the discrimination in treating adverse interactions promotes cooperation in the coevolution [37,39]. Spiekermann studied public goods games on dynamic networks [36]. In computer simulations, cooperative agents manage to cluster with cooperators and avoid defectors, thereby promoting cooperation in dilemma situations. Zhang et al. introduced an aspiration-induced reconnection mechanism into the spatial public goods game [43]. They found that an intermediate aspiration level can promote cooperation best. Similarly, an intermediate value of the critical mass results in the highest level of cooperation under the assumption that the collective benefits of public goods can only be harvested if the critical mass (the fraction of cooperators within the group) exceeds a threshold value [44].

In most previous models of evolutionary PGG assuming either fixed interactions or dynamical interactions, mutual relationship between two individuals is symmetric; namely, if an agent hosts a game in which another one participates, he definitely participates in the game hosted by the latter. In the partnership network, edges connecting two interacting individuals are undirected. However, symmetric participation might not always happen. Pure public goods, a vital ingredient in humans, are characterized by two properties: (1) non-excludability and (2) non-rivalry [45,46]. Non-excludability implies that no agent can be excluded from consuming the public goods. Since Samuelson's inaugural paper [45], research on public goods has been one of the most important economic problems.

Inspired by previous works on the non-excludability of public goods, this paper is devoted to studying the coevolutionary dynamics of cooperation and non-excludable partnership in evolutionary PGG. In the present model, agents are able to adjust their participation in the games hosted by others, whereas they cannot exclude others from their own games. As evolutionary time goes by, a directed and dynamical network which represents asymmetric partnerships among autonomous agents is evolved. The coevolutionary dynamics is investigated by means of numerical simulations. It is found that the equilibrium level of cooperation is lower than that in the situation of undirected networks, due to the non-excludable feature. Though agents cannot get rid of defectors' exploitation, they are able to pay a personal cost to decrease benefits of their defective partners. When this factor is incorporated, the whole population arrives at a regime of high-level cooperation.

The remainder of this paper is structured as follows. Section 2 describes a coevolutionary model which incorporates non-excludable property into public goods game. In Section 3, the coevolutionary dynamics is investigated based upon numerical simulations. The negative effect of non-excludability on cooperation is presented, and the feasibility of individual punishment is further incorporated into the model. In the last section, we will summarize the findings and make a discussion.