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Coevolution of cooperation and network structure in social dilemmas in evolutionary dynamic complex network

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ABSTRACT

Emergence of cooperation in social dilemmas is an essential phenomena for the functioning of numerous multilevel and complex systems. The evidence of cooperation ranges from the elementary biological organisms to the most sophisticated human societies. Although emergence of cooperation is widely experienced, but its evolution is not well explained, since natural selection typically promotes selfish behaviours which are often not socially optimal. In this paper the coevolution of network structure and emergence of cooperation is studied in four classes of social dilemmas, representing the prisoner's dilemma, Hawk–Dove, snowdrift and coordination classes of games, in structured populations defined by weighted complex networks. The strength of interaction between two individuals is represented by network (edge) weight, which changes according to individuals' preference through the evolutionary network dynamics. Using evolutionary dynamic network based simulations of the games model on randomly weighted complete networks, we present a detailed study of the evolution of dynamic complex network through the evolution of the structural properties of a network, such as clustering coefficient, assortativity coefficient, entropy of degree distribution, average strength of interaction and the promotion of cooperative behaviour in all four classes of games. The effect of changing the cost-to-benefit ratio on these network properties and evolution of cooperation is also reported.

1. Introduction

The evolution and maintenance of cooperation in social dilemmas is an essential aspect for the functioning and sustainability of many complex systems, ranging from elementary replicating molecules to multi-cellular organisms and up to human societies [35,36,58]. A few examples of cooperative behaviour in social dilemmas are noted in following cases: assembly of the earliest replicating molecules to form larger replicating entities capable of encoding more information [6,18], vampire bats donating blood meals to roost mates [60], allogrooming in social animals [21], Co-operation in human society [5,36], differential production of intracellular products needed for replication in an RNA phage [53], contribution to providing public goods such as social security programs [7] and many more. In spite of being widely experienced, the origin and stability of cooperation in social dilemmas could not attain satisfactory explanations [18,24,30]. The paradox resides itself in the nature of a social dilemma, as it is classically defined as a game which possesses at least one socially inefficient Nash equilibrium [13]. Though by the definition of Nash equilibrium there is no incentive for any individual to change their behaviour, yet there are numerous examples where a system could attain more favourable outcomes for most of the individ-

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uals through evolution and by maintaining cooperative behaviour. In these social dilemmas, adopting the socially inefficient strategy is considered to be defection, while adopting the socially efficient strategy is said to be cooperation.

In the study of cooperation in social dilemma four fundamental class of symmetric, two-player, two-strategy (i.e., symmetric 2×2) games became popular. These games namely – the prisoner's dilemma, hawk-dove, snowdrift and coordination classes; represent different social dilemmas and model conflict and competition. The donation game is the fundamental exemplar in the prisoner's dilemma class of games, and have been extensively studied as the basic game theoretic model for altruism. The hawk-dove class of games provide models for conflicts and competition [19,20,24,40]. The snowdrift class of games could model certain types of cooperative behaviour that differ from pure altruism [24]. The rowing game or sculling game, is an exemplar of a social dilemma in the coordination class of games which have been widely used as models for conventions [61,62], but yet less studied as models of cooperation [38,41]. A lot of extensive literatures in the context of the evolution of cooperation in structured populations in different type of evolutionary game network were published in past years. Many studies have focused on the evolution of cooperation in regular lattices structured spatial populations in different evolutionary games like prisoner's dilemma game or variants of it [12,23,29,39], Hawk–Dove game or the snowdrift game [9]. In recent years, the attention has been shifted towards studying the evolution of cooperation in structured populations, modelled by complex networks [1,2,59]. The number of studies are focused on the behaviour of various versions of the prisoner's dilemma game [12,39,50,58] in different type of complex network, yet some studies also have analysed other games such as the snowdrift game [39,54] or staghunt game [39].

The traditional evolutionary game theory has provided fundamental framework that enable to study the evolution of cooperation; yet due to the complexity of such systems methods of non-equilibrium statistical physics also requires to be used for better understanding cooperation in social dilemmas. The application of methods of statistical physics on collective behaviour of complex system is relatively recent development in this aspect [5,35,36,57,58]. Many recent researches are focused on the mechanisms which could promote cooperation and its temporal evolution [32,44,46,47]. A number of different mechanism to explain the evolution of cooperation in social dilemmas have been studied which include: kin selection [8], direct reciprocity [25,26], indirect reciprocity [27,28], evolution in structured-network populations [29,9,12,39], and evolution in group structured populations [16,52]. Also voluntary participation [10,42], social diversity [33], heterogeneous teaching activity [45], and the impact of long-term learning [56] have been provided interesting possibilities that may emerge in real-life systems. Some of the recent work has also analysed the effect of network perturbation and parameter variation on the evolution of cooperation in structured populations [13,14,31,43]. Recently some researchers has focused on the coevolution of some other properties like aspiration [4] and coevolution in different circumstances under multigame [49] or coevolutionary rules [48] along with cooperation. Also a few extensive reviews works are available in this concern [32,34,36,57].

The main conclusion that emerges from previous studies is that different variants of the prisoner's dilemma in structured populations exhibit cooperation under suitable circumstances, which is not likely for well mixed population [29,12,23,39,50]. For other games it is not so obvious; in Hawk–Dove game on lattice structured populations increase in levels of cooperation was observed [17]. Whereas, for the snowdrift game, cooperation may be inhibited [9] or promoted [39] by different population structures and in stag hunt game structured populations can also promote the cooperation [39]. Despite the large number of studies on the evolution of cooperation in structured populations, a little is known about how the fundamental properties of a network structure such as link density, heterogeneity in degree distribution, clustering, assortativity etc. and its effects on the evolution of cooperation. However the effect of average network degree on the evolution of cooperation in the prisoner's dilemma game is studied in recent past [50]. But yet almost nothing being known about the effect of other structural properties of networks on the evolution of cooperation in different classes of social dilemma. Moreover the limitation of previous studies of cooperation in networked populations is that there is no methodology to compare the levels of cooperation that arise in games representing different classes of social dilemmas. Also the evolution of cooperation in different structured networks eventually depends upon the network parameter as well as the nature of the social dilemma. However in recent time a study is published focusing the comparison of level of cooperation in different social dilemma in similar structured network [15]. As a result of this previous work on the evolution of cooperation in structured populations has led to many isolated results, but not yet attained general understanding of comparison of level of cooperation and its applications across a wide range of social dilemmas.

In this paper we study the evolutionary dynamics of the donation, Hawk–Dove, snowdrift, and sculling games in structured populations on a weighted complex network which coevolves with the evolutionary games through evolutionary network dynamics, where vertices represent individuals in the population and weight of edges between vertices indicates the strength of interaction between corresponding individuals. Interestingly in different evolutionary games representing social dilemmas, the weight of interaction between two individuals depends upon the motivation of each individual, which could be considered as state variables similar with the probability of strategies chosen by each agent. We argue that in an evolutionary time frame the network structure of evolutionary game shouldn't be invariant, that is to understand the emergence of cooperation one should study the social dilemmas in dynamic networks. In this paper we consider the network weight of the population evolves through the evolutionary dynamics for network weight which governs by the assumption that if an agent receives better payoff than the average for a particular interaction he will increase its strength otherwise the strength of interaction will decrease. We use evolutionary dynamic network-based simulations to investigate the evolutionary dynamics of those games and present a study on the evolution of network properties, such as clustering coefficient, assortativity coefficient, average link density, entropy of degree distribution and the promotion of cooperative behaviour in