



## Interim Report

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### Does migration cost influence cooperation among success-driven individuals?

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## Abstract

Migration as an important social factor has been recently considered in evolutionary games on graphs. However, the migration-related cost is largely ignored in previous works, which may indeed influence individual migration decision in human society. Here we propose a model of the success-driven migration with migration costs where individuals decide whether to migrate or not according to the migration cost and expected payoff. We consider two different calculation schemes for the migration cost, i.e., distance-dependent and distance-independent costs, and study their effects on the evolution of cooperation in the spatial prisoner's dilemma, respectively. It is found that although the migration cost inhibits the migration of individuals, it does not necessarily lead to the suppression of cooperation. We explain the phenomenon by investigating the spatial patterns of cooperators and defectors. Interestingly, the curves of cooperation exhibit step structures and the corresponding heuristic analysis is provided. Our work complements previous studies and deepens the understanding regarding the success-driven migration on the evolution of cooperation.

*Key words:* prisoner's dilemma, cooperation, migration cost

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## 1 Introduction

Cooperation is fundamental to social and biological systems. Cooperators incur costs to benefit others while defectors reap the benefits but dodge the costs. Thus, natural selection favors defectors over cooperators, although group of cooperators perform better than groups of defectors. Yet cooperation is ubiquitous in social and biological systems, and hence understanding the evolution of cooperation becomes a challenging issue [1,2]. To explain and understand the widely observed cooperative phenomena, evolutionary games, which provide a suitable theoretical framework, have been studied extensively by many researches from various disciplines over the past decades [3–5]. The evolutionary prisoner’s dilemma game (PDG) in particular, which describes the conflict between cooperative and selfish behaviors, has attracted considerable attention in theoretical as well as experimental studies [1]. In a typical prisoner’s dilemma [5], two individuals simultaneously decide whether to cooperate or defect. They will receive the reward  $R$  for mutual cooperation, and the punishment  $P$  for mutual defection. For a pair of individuals adopting different strategies, the defector gets the temptation  $T$  while the cooperator gets the sucker’s payoff  $S$ . The ranking of the four payoffs is  $T > R > P > S$ . It is clear that defection is always the better strategy maximizing one’s payoff, irrespective of the opponents decision. To explain the observed widespread cooperation, several mechanisms supporting the evolution of cooperation have been identified (see [6] for a review).

Since the pioneering work of Nowak and May [7], spatial games have received ample attention, and especially, evolutionary games on complex networks have been extensively studied [8–11]. In the context of spatial games, network topology and hierarchies have been identified as a crucial determinant for the success of cooperative behavior [12–18], where in particular the scale-free topology has proven very beneficial for the evolution of cooperation. The participation cost or generally the links-related cost can, however, dismiss the advantage of heterogeneous networks in the evolution of cooperation [19–21]. Other approaches facilitating the evolution of cooperation include the introduction of noises to payoffs and updating rules [22–27], asymmetry between interaction and replacement graphs [28,29], diversity [30–34], differences between time scales of game dynamics [33,35–37], interaction stochasticity [38], as well as the adoption of simultaneous different strategies against different opponents [39]. Somewhat more personally-inspired features supporting the evolution of cooperation involve memory effects [40], heterogeneous teaching activity [41–43], preferential learning [44,45], aspiration [46–48], age [49], rationality [50], myopically selective interactions [51,52], local contribution [53], and coevolutionary partner choice [54–57], to name but a few examples studied in recent

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years.

Recently, many efforts have been directed towards the role of migration in the emergence of cooperation, see refs. [58–69]. In particular, Helbing *et al.* recently proposed a mechanism of so-called success-driven migration and demonstrated that the mechanism can trigger the sudden outbreak of predominant cooperation in the evolutionary prisoner’s dilemma game on a spatial lattice [60]. Afterwards, Yu further studied the effect of migration on cooperation by extending the interaction structure from spatial lattices to complex networks [61]. However, the success-driven migration relies on quite extensive information, obtaining which may require individuals to pay some costs, as pointed out in the refs. [60,61]. For example, individuals may need to overcome some hindrances to leave a place. Obtaining information for neighborhood testings that cannot be obtained directly through game interactions may require individuals to pay some efforts. Moving from the original sites to the new locations may also demand some fees. Besides, individuals may need to pay some prices to adapt gradually to the environments in the new neighborhoods, etc. However, all the costs mentioned above are largely neglected in refs. [60,61]. How the migration cost affects the evolution of cooperation is still unknown to us. Investigating its effect on cooperation complements the previous studies, as well as enables us to understand the success-driven mechanism more completely, and thus it is worth studying. Note that other types of costs, e.g., the links-related cost or the so-called participation cost were considered before in previous works [19–21].

In this paper, we consider the migration cost and explore its role in the success-driven migration. Since the migration cost involves several ingredients, and some of them are associated with the migration distance (e.g., moving to a farther site needs individuals to pay more fees), while some of them are not (e.g., the cost for obtaining information about the neighborhood of the new site is independent of the distance to a large extent), there exist difficulties in determining exactly the relationship between the migration cost and the migration distance. For the sake of completeness of this research along this line, we consider both the distance-dependent cost (DDC) and distance-independent cost (DIC) for migration. For the former, the cost increases linearly with the migration distance while in the latter case, the cost for once migration is fixed, irrespective of the migration distance. As we will show, although the cooperation levels for DDC and DIC are not identical, the overall changing tendencies of the curves of cooperation as a function of the migration cost for the two computational schemes are qualitatively similar.

## 2 Model

For reasons of comparison, our study is also carried out for the PDG, as in Ref. [60]. Following common practice [7,22], we adopt the rescaled payoff matrix of the PDG depending on one single parameter  $b$ :  $T = b > 1$ ,  $R = 1$ , and  $P = S = 0$ .

We assume  $N$  individuals locate on a square lattice with periodic boundary conditions and of  $L \times L$  sites, which are either empty or occupied by one individual. We denote by  $d_0$  the density of population on the square lattice. Individuals perform migration and strategy update asynchronously, in a random sequential order. The randomly selected individual explores the expected payoffs for the empty sites within a migration distance  $d$ , which is measured by the number of links along the shortest path between the focal individual and the target site. Both the distance-dependent cost (DDC) and distance-independent cost (DIC) for migration are considered. By DDC, we mean that the overall cost of once migration is proportional to the distance, i.e., the cost of moving to a site with distance  $d$  is  $dc$ ,  $c$  being the migration cost of unit distance. For DIC, it is assumed that the cost for once migration is  $c$ , irrespective of the migration distance.

Before an individual migrates, it explores the expected payoffs for the empty sites within the migration distance  $d$ . If the migration is profitable, that is, the expected payoff minus the migration cost is higher than that in the current location, it moves to the site with the highest net profit and, in the case of several sites with the same net profit, to the closest one, otherwise it stays put. After migration, the individual interacts simultaneously with all direct neighbors in the von Neumann neighborhood. The overall payoff is accumulated over all interactions with neighbors. Then, it compares the overall payoff with that of each neighbor and copies the strategy of the best performing neighbor with certainty, if its own payoff is lower.

Simulations of this PDG model are performed by means of an asynchronous updating rule, using  $L = 50$  system size. Initially, an equal percentage of cooperators and defectors are homogeneously distributed over the whole square lattice. The key quantity for characterizing the cooperative behavior of the system is the density of cooperators, which is defined as the fraction of cooperators in the whole population. In all the simulations, the maximum migration distance is  $d = 5$ .

### 3 Results

Let us first investigate how the migration cost affects individual migration behavior. The results are shown in Fig. 1. One can find that the rates of migration decrease as  $t$  increases, irrespective of the value of  $c$ , indicating that as the system evolves, less and less individuals engage in migration. For  $c = 0$ , the percentage of the migrant individuals here is about 0.3%, while for  $c > 0$ , it is zero, that is, the final state for  $c > 0$  is frozen. By comparing the results for different values of  $c$ , one can find that the migration is indeed inhibited by the migration cost, since the decline of the curves for larger value of  $c$  is even faster. Moreover, the inhibitive effect is stronger for DDC than DIC, as indicated by the results for  $c = 1.0$ .

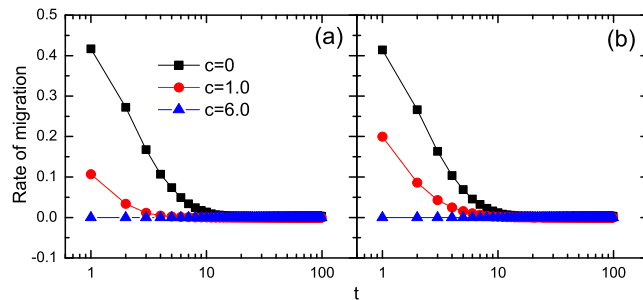


Fig. 1. Time courses depicting the rate of migration of individuals for (a) DDC and (b) DIC. The population density is  $d_0 = 0.4$ . The rate of migration is obtained by calculating the fraction of migrant individuals in the entire population. The results are obtained by averaging over 100 realizations.

We next investigate how the migration cost affects the evolution of cooperation. Figure 2 illustrates the density of cooperators  $\rho_c$  as a function of the migration cost  $c$ . One can find that DDC and DIC lead to different cooperation levels, except when the migration cost  $c$  is sufficiently large. The difference of the resulting cooperation levels tends to decrease as  $d_0$  increases. Despite the difference, there exist similarities between the results for DDC and DIC. First, the overall changing tendencies of the cooperation level with increasing  $c$  are similar, which reveals that there is actually no essential difference in the effects of DDC and DIC on cooperation. Second, both of the cooperation levels display step structures when  $c$  is an integer, and the step structures become more regular for large values of  $d_0$  (the reason will be given below). Third, for both DDC and DIC, the minimum cooperation level occurs at intermediate values of  $c$ , although for large values of  $d_0$ , this becomes less pronounced. Moreover, for small values of  $b$ , the sufficiently large value of  $c$  proves to be favorable to cooperation as compared with  $c = 0$  when  $d_0$  is small. As  $d_0$  increases,  $\rho_C$  tends to descend monotonously with  $c$ , indicating that the larger the values of the migration cost, the more unfavorable cooperation becomes. While for large values of  $b$ , sufficiently large  $c$  can almost always facilitate the emergence of cooperation as compared to  $c = 0$ . The promotive effect on

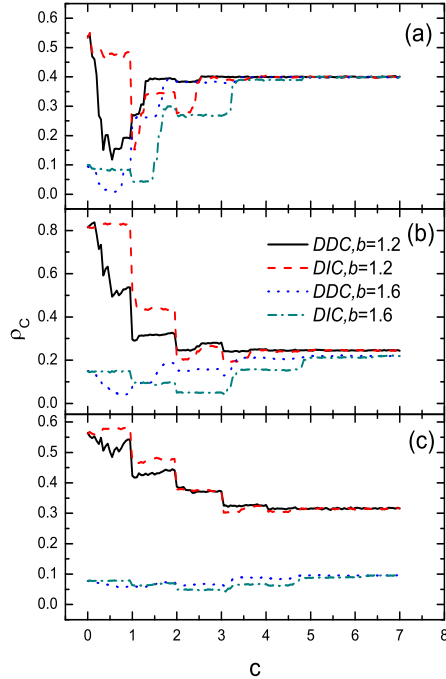


Fig. 2. Cooperator density  $\rho_C$  in dependence on the migration cost  $c$  for different values of the population density  $d_0$ : (a)  $d_0 = 0.1$ , (b)  $d_0 = 0.4$ , (c)  $d_0 = 0.8$ . The quantity  $\rho_C$  is obtained by averaging over 200 different realizations, and for each realization, we average over 200 time steps after 1000 time steps.

cooperation becomes, however, less pronounced for higher densities of population. In addition, for each value of  $d_0$ , there exists a critical value of  $c_{crit}$  (e.g.,  $c_{crit} = 1.0$  for  $d_0 = 0.1$  and  $b = 1.2$ ), and when  $c < c_{crit}$ , DIC leads to a higher density of cooperation than DDC while when  $c > c_{crit}$ , the opposite result occurs. Note also that  $\rho_c$  corresponding to  $c = 0.0$  for  $d_0 = 0.4$  is higher than those for  $d_0 = 0.1$ , which is consistent with the results shown in Fig. 2 of Ref. [65], where one can find that  $\rho_c$  is maximized for moderate values of  $d_0$ .

Figure 3 shows  $\rho_c$  as a function of  $b$ . Since for  $c = 0$  and  $c \rightarrow \infty$ , the calculation scheme of the migration cost becomes irrelevant, we, therefore, do not distinguish DDC from DIC. On the other hand, since cooperation is almost a monotonically decreasing function of  $c$  for  $d_0 = 0.8$ , we show only the results corresponding to  $c = 0$  and  $c \rightarrow \infty$ . One can observe that the levels of cooperation decrease monotonically with increasing  $b$ , irrespective of the values of  $d_0$  and  $c$ . This is because increasing  $b$  makes defection more tempted. Let us now look at the results for  $c = 0$  and  $c \rightarrow \infty$ . It can be observed that a crossover occurs between them (when  $d_0$  is large, e.g.  $d_0 = 0.8$ , the crossover becomes ambiguous), and before the crossover,  $c = 0$  leads to a higher cooperation level than  $c \rightarrow \infty$ , while after the crossover, the opposite results occur. This suggests that when the temptation to defect is small, migration without any cost is favorable to cooperation, whereas when the temptation to defect is large, constraining individuals to the original locations is favorable to cooperation

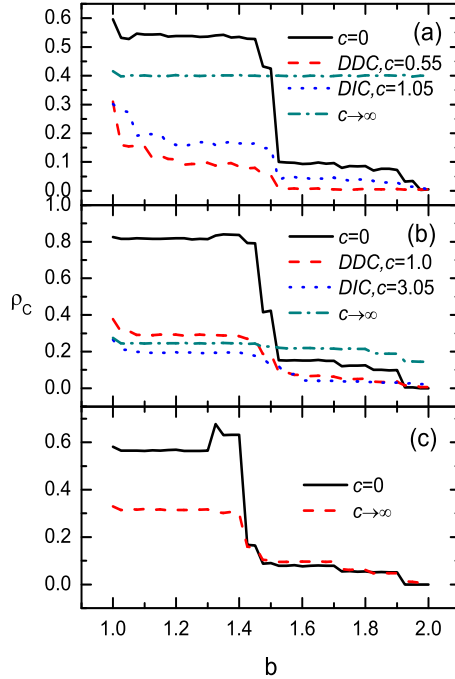


Fig. 3. Cooperator density  $\rho_C$  in dependence on the temptation to defect  $b$  for different values of the migration cost  $c$  under different population densities  $d_0$ : (a)  $d_0 = 0.1$ , (b)  $d_0 = 0.4$ , (c)  $d_0 = 0.8$ . The quantity  $\rho_C$  is obtained in the same way as in Fig. 2.

instead. This reveals that the success-driven migration does not always favor cooperation, and no migration may be helpful to cooperation (especially for large values of  $b$ ), which is interesting and nonintuitive. Apart from this, we also show the results for  $c$  at which the lowest cooperation levels occur, which are consistent with those reported in Fig. 2.

To explain the obtained results, we investigate the spatial patterns of cooperators and defectors in the stationary state, as shown in Fig. 4. One can find that for  $c = 0$ , cooperators cluster together and defectors primarily locate at the boundaries. Whereas for  $c \rightarrow \infty$ , since the movement of individuals is completely suppressed, cooperators and defectors can only distribute isotropically when the population density is very low, and even if for higher densities of population, only small clusters can be formed. For intermediate values of  $c$ , the cooperator clusters are smaller than those for  $c = 0$  but larger than those for  $c \rightarrow \infty$ , and there exist a large number of defectors scattering randomly over the square lattices and being separated from cooperative clusters. Noteworthy, the patterns in panels (e) and (h) are similar to those shown in panels (c) and (a) of Ref. [60], respectively.

We next discuss the formation mechanisms of the patterns shown in Fig. 4. When  $c = 0$ , individuals can migrate freely without any cost. At this moment, due to the mechanism of the success-driven migration, defectors are attracted



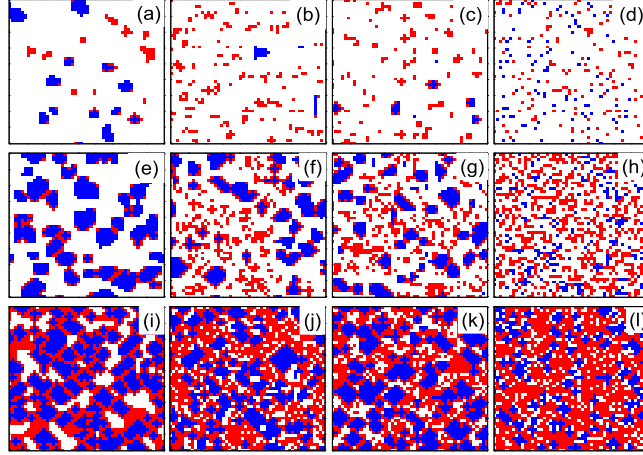


Fig. 4. Snapshots of representative stationary distributions of cooperators and defectors: (a)  $d_0 = 0.1$ ,  $c = 0$ , (b) DDC,  $d_0 = 0.1$ ,  $c = 0.55$ , (c) DIC,  $d_0 = 0.1$ ,  $c = 1.05$ , (d)  $d_0 = 0.1$ ,  $c \rightarrow \infty$ , (e)  $d_0 = 0.4$ ,  $c = 0$ , (f) DDC,  $d_0 = 0.4$ ,  $c = 0.5$ , (g) DIC,  $d_0 = 0.4$ ,  $c = 1.5$ , (h)  $d_0 = 0.4$ ,  $c \rightarrow \infty$ , (i)  $d_0 = 0.8$ ,  $c = 0$ , (j) DDC,  $d_0 = 0.8$ ,  $c = 1.5$ , (k) DIC,  $d_0 = 0.8$ ,  $c = 1.5$ , and (l)  $d_0 = 0.8$ ,  $c \rightarrow \infty$ . Cooperators are depicted in blue and defectors in red and the results are obtained for  $b = 1.2$ .

to cooperator clusters and then being turned into cooperators. Thus the clusters expand in size gradually. Because defectors inside cooperator clusters can trigger the splitting of cooperative clusters, defectors in the stationary state can only locate at the boundary. In contrast, when  $c \rightarrow \infty$ , individuals' movement is completely inhibited and no individuals engage in migration. Hence the initial random distribution is maintained and the result of the imitation-only case with no noise is reproduced (see Fig. 1(a) of Ref. [60]).

In Fig. 2, the lowest cooperation level occurs at intermediate values of  $c$  (especially when the population density is low), which can be explained by inspecting the patterns shown in Fig. 4. When there is no migration cost, cooperators can assist each other by forming cooperator clusters by which cooperators can be favored. When  $c \rightarrow \infty$ , the strong inhibition to the movement of defectors makes defectors have no chance to invade cooperators such that cooperators can have the chance to survive. The lower the population density, the more apparent the above effect becomes. When  $d_0$  is small, since the vast majority of individuals are isolated such that defectors have no chance to contact cooperators. Therefore, cooperators can evade defectors (see Fig. 4(d)). However, as  $d_0$  increases, individuals increasingly connect with each other, and hence, even if the movement is inhibited, defectors can also exploit their cooperative neighbors and then invade them. By this means, defectors can expand their territory and eventually dominate the population, as shown in Figs. 4(h) and (l). This is why with increasing  $d_0$ , the effect of  $c$  on cooperation turns from promotive to inhibitive. For small intermediate values of  $c$ , all individuals can still move to a certain extent. The movement, however, is not sufficiently free such that cooperators can form compact clusters, as in pattern Fig. 4(a), but

it is also sufficient for defectors to invade cooperators in their neighborhoods. Consequently, one can find that only fortunate cooperators can survive.

We now analyze the difference between DDC and DIC as well as the results obtained with them, as shown in Fig. 2. One can find that for both  $b = 1.2$  and  $b = 1.6$ , DDC results in a lower cooperation level than DIC at small values of  $c$ , which can be explained as follows. For small  $c$ , cooperation can generally be inhibited. For the same value of  $c$ , DDC leads to large migration cost since migrating to farther sites need individuals to pay more price. Accordingly, DDC can be more detrimental to cooperation than DIC. While as  $c$  increases, large migration cost is helpful to cooperation such that DDC instead leads to a higher cooperation level, as shown in Fig. 2(a).

One can observe the occurrence of step structures of the curves at  $c = 1.0, 2.0, 3.0$ , as illustrated in Fig. 2. Here, we give a simple heuristic analysis for the point at which the cooperation level increases or decreases sharply. Note that individuals engaging in migration are nothing more than cooperators and defectors. For cooperators, all the possible payoffs are 0, 1.0, 2.0, 3.0 and 4.0. For cooperators to migrate, the payoff difference between those for the targeted location and the current site needs to be larger than a certain value. Therefore, the quantity mattered currently is the payoff difference. Because of the discreteness of individuals' payoffs on a square lattice, the possible payoff differences are 1.0, 2.0, 3.0 and 4.0. When  $c$  is larger than a critical point, the migration of cooperators with the payoff difference equal to  $c$  is hampered such that sudden change of  $\rho_C$  can occur. These critical points may include 1.0, 2.0, 3.0 and 4.0. Note that, the payoff difference 4.0 means an isolated cooperator migrates to an empty site surrounded by four cooperators, which is actually a rare case. Hence, the abrupt change of  $\rho_C$  at  $c = 4$  can only be vaguely observed for high densities of population, e.g.,  $d_0 = 0.8$ . Similarly, for defectors, all the possible payoffs are 0.4,  $0.3 + b$ ,  $0.2 + 2b$ ,  $0.1 + 3b$  and  $4b$ . All the possible payoff differences are  $b - 0.1$ ,  $2(b - 0.1)$ ,  $3(b - 0.1)$  and  $4(b - 0.1)$ . In consequence, the only point where the sudden change can occur is  $b - 0.1$ . For  $b = 1.2$  and  $b = 1.6$  they are  $c = 1.1$  and  $c = 1.5$ , respectively. Sudden changes at  $c = 1.1$  and  $c = 1.5$ , however, are not observed, indicating that the migration of defectors has little effect on the evolution of cooperation. On the other hand, although the overall trend is that sudden changes occur at the predicted points, the changes are not identically apparent which is due to the different densities of population.

To further probe the effect of the migration cost on the evolution of cooperation, we investigate the time evolution of the spatial patterns, as shown in Fig. 5. One can find that overall, cooperator clusters in the absence of the migration cost [see the blue and green areas in panels (a), (b) and (c)] are larger than those in the presence of it [panels (d), (e) and (f)]. By comparing results illustrated in panels (a) and (d), where the strategy changes of individuals

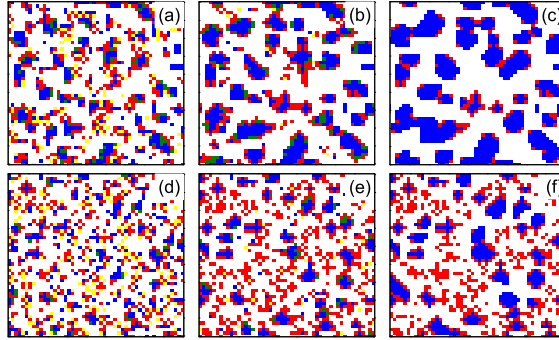


Fig. 5. Time evolution of the snapshots of representative distributions of cooperators and defectors obtained with DDC (red, defector; blue, cooperator; white, empty site; green, defector who became a cooperator in the last iteration; yellow, cooperator who turned into a defector). (a)  $c = 0$ ,  $t = 1$ ,  $\rho_c = 0.448$ , (b)  $c = 0$ ,  $t = 3$ ,  $\rho_c = 0.647$ , (c)  $c = 0$ ,  $t = 100$ ,  $\rho_c = 0.836$ , (d)  $c = 0.5$ ,  $t = 1$ ,  $\rho_c = 0.357$ , (e)  $c = 0.5$ ,  $t = 3$ ,  $\rho_c = 0.33$ , (f)  $c = 0.5$ ,  $t = 100$ ,  $\rho_c = 0.416$ . We have checked that at  $t = 13$ , for both  $c = 0$  and  $c = 0.5$ , the system has reached the equilibrium. The results are obtained for  $d_0 = 0.4$  and  $b = 1.2$ .

from  $t = 0$  to  $t = 1$  are shown for  $c = 0$  and  $c = 0.5$ , respectively, one can find that when the migration cost arises, cooperators have a lower opportunity to come together, as indicated by the fact that the cooperator clusters in panel (a) are larger than those in panel (d). This is apparently caused by the migration cost, that is, due to the inhibition to migration by the cost, cooperators' movement is suppressed to a certain extent such that the chance for them to form clusters decreases. Actually, the initially established cooperator clusters are crucial since initially many individuals change their strategy frequently [see the green and yellow areas in panels (b) and (e)] and they can attract defectors and then turn them into cooperators [see the green areas in panels (b) and (e) indicating that boundary defectors can be frequently turned into cooperators]. It can also be observed by comparing panels (b), (c) and (e), (f), respectively, that because of the migration cost to individuals' movement, a large number of isolatedly distributed defectors have no chance to join in the groups of cooperators and thus have no chance to become cooperators. Note also that no strategy changes of individuals in the stationary state occur since here we incorporate no noises into our model (for the definition of the noises, see Ref.[60]).

Note that we can also explain the results reported above from the perspective of strategy communication among individuals, as in Ref. [65]. When  $c = 0$ , individuals can move within a wider range such that individuals can contact more individuals. That is, individuals can perform strategy communication within a wider range, and the communication successfully leads to the change of defectors into cooperators, and hence the promotion of cooperation. When the migration cost is considered, such strategy communication is, however, inhibited, which leads to the separation of cooperators from defectors and

eventually the inhibition to cooperation.

#### 4 Discussion and conclusion

In summary, we have systemically investigated the effect of the migration cost on the evolution of cooperation in the prisoner's dilemma game under different population densities. We have considered both the distance-dependent and distance-independent costs and shown that the influences of the two calculation schemes of the migration cost on cooperation are qualitatively similar, although there exist differences in the resulting cooperation levels for small values of the migration cost. It is found that although the migration cost inhibits the migration of individuals, it does not always lead to the suppression to cooperation (especially when the migration is large enough). Actually, the lowest cooperation levels occur at intermediate values of the migration cost, and large values of the migration cost can facilitate the evolution of cooperation, although this effect becomes weaker as the density of population increases. Interestingly, the curves of cooperation as a function of the migration cost display step structures, which has been explained by the configurational analysis. We have also investigated spatial patterns for typical parameters for intuitively understanding the obtained results.

Note that since our primary aim is to uncover the effect of the migration cost on the outbreak of cooperation rather than the effect of noises in the evolutionary process, we concentrate on the noiseless case (see Ref.[60] for the definition of the noises). Despite this, we have also checked that when noises are involved, the results are qualitatively the same. Note also that here the maximum migration distance is set to  $d = 5$ . We have checked that increasing or shortening the maximum migration distance in an appropriate range does not qualitatively alter the results. In addition, currently the game is occurring on the square lattice with von Neuman neighborhood, We have also investigated the game on a square lattice with Moore neighborhood and found that the results are qualitatively unchanged.

The result that the success-driven migration leads to the outbreak of cooperation in the prisoner's dilemma game in Ref.[60] is no doubt quite significant, considering that migration is a key feature in real ecosystems and human societies. However, it may require individuals to pay some cost to implement the success-driven migration. Ignoring such cost may lead to deficiencies in the obtained results. Here we investigate how the migration cost affects the outbreak of cooperation, which complements the original study. Our model may be more realistic and the obtained results may be more significative in understanding the role of success-driven migration in the outbreak of cooperation in the prisoner's dilemma game. Our results may have potential implications

in the design of coordination and cooperation mechanism in the multi-agent systems.

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