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Eliminating poverty through social mobility promotes cooperation in social dilemmas

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ABSTRACT

Numerous social problems can be directly related to poverty, and its elimination is thus often declared a grand challenge in modern human societies. Nevertheless, it is difficult to shake the belief that certain fractions of the population would like to see it maintained to ensure the availability of cheap workforce and its readiness to do the hardest jobs, as well as to keep the prices of natural resources in the afflicted countries as low as possible. Here we show, however, that by allowing low-income individuals to escape poverty, either by means of mobility to pursue potential opportunities in remote areas or by ending dilemmas through social learning in local areas, greatly increases cooperation and thus has the potential to raise the social capital. In particular, we find that mobility of low-income individuals can promote cooperation when the per capita mobility rate is as low as 10^{-3} in the order of magnitude as long as network reciprocity is still active. This synergy between network reciprocity and mobility is due to the emergence of large cooperative clusters that are in this size impossible without mobility. Moreover, we find that the mobility of defectors undermines cooperation, but only a few defectors actually move as they are typically well off when surrounded by cooperators. On the contrary, the higher the cooperation level, the greater the proportion of low-income cooperator that move. Our research thus shows that by providing ways out of poverty for individuals can raise whole societies out of economic gridlocks by elevating cooperation levels.

1. Introduction

Income inequality, or more specifically poverty, is one of the most immediate and serious challenges to individuals and the human society [1]. In traditional approaches, eliminating inequality mainly focuses on the efforts of better behaved individuals or the rich [2], e.g., placing heavy taxes on them or donations from them. Here we initialize the study from another perspective by enhancing cooperation among individuals. It is well known that deep and widespread cooperation contributes to progress of human society [3–5]. Additionally as the fundamental behavior of humans and certain animals in nature, social mobility plays a key role in the evolution of cooperation [6,7]. For example, one recent empirical study on the geography of social mobility in the US found that factors related to regional structures of interpersonal inequality and induced income inequality generate a persistent social mobility landscape [8]. In turn, here we propose that a well designed

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social mobility may provide a key to eliminate inequality and enhance cooperation in society. We argue that social mobility from low-income individuals based on social learning substantially helps to drive welfare benefits for the poor and decreases the level of inequality. Considering the following scenario: When a suitable level of social mobility is set, a part of low-income players are prone to migrate and seek fortunes and opportunities elsewhere due to the shortage of resources. Simultaneously inequality for local players declines due to such mobility. This mobility especially could happen for those players who earn the payoff below the average payoff in his/her community and would rather change actively than wait passively.

Previous studies presented two mechanisms of social mobility in response to inequality on incomes: partner choice by choosing similar interaction partners, or social learning to pursue better opportunities including payoff. The former induces cooperative individuals to leave a bad environment with defectors such that avoiding from exploitation by defectors [9], or to leave bad conditions of defectors [10]. Nevertheless, a recent human experiment research suggests that individuals do not choose friends based on cooperativeness when a reliable assessment of it is hardly achievable [11]. Under such situation, the partner choice only has a marginal contribution to the formation of cooperative clusters [11]. Instead, intrinsic social preferences which are not limited to local region, e.g., fairness and altruism, play a crucial role in forming cooperative clusters. Further, without a mechanism to form friendship networks, cooperation could still outbreak among success-driven players who migrate to another place to seeking higher payoff [12–15]. Such phenomenon is robust against noisy conditions dominated by selfishness and defection. As a result, overall cooperation is strengthened among the community. Based on these facts, we propose a model to extend the scope of social learning, where the players could migrate to other locations and learn the strategy of better behaved players there. Such a model combines characteristics of both traditional social learning and mobility.

Then the problem lies what is the better way of mobility to enhance cooperation. A recent study implied that a limited mobility away from defectors may be far more effective to cooperation, based on the result of simulations in a prisoner's dilemma game. It has been indicated that cooperators form compact cooperative clusters to defend against defectors. While low-income players prefer to migrate for better opportunities, defectors may prefer to stay at their original position, since the latter have advantages for a relative high-income in the local area. We note, and there may be many effective approaches in a prisoner's dilemma game for low-income players' migration to enhance cooperation and eliminate poverty. However in a real-world situation, detecting neighbors' strategies to discern defectors acquires an extra and often substantial amount of cost in the community. Thus an effective approach which works to eliminate poverty without the knowledge of defectors is practically and urgently necessary.

In this paper, we model how social mobility driven by low-income players affects the cooperation through a well designed prisoner's dilemma game. We find that a particularly limited social mobility of individuals with low-income promotes cooperation. The main reason is that the social mobility of cooperators with low-income is advantageous to cooperate where cooperators form sparse clusters. However, it is harmful for cooperation if defectors with low-income would also move. By carefully adjusting the mobility rate of low-income individuals, the contribution from cooperators could be dominant such that large cooperative clusters would emerge. The advantage of our approach is that it does not need to discern defectors throughout the game. Our results are helpful to set up an applicable pathway to relax growing inequality in a real world community.

2. Model

We adopted a regular periodic lattice here to characterize an interactive network, where sites are either empty or occupied by individuals randomly, and links between two sites represent their interacting relationship. Players could adopt cooperating (C) or defecting (D) strategy to gain payoff, which is calculated by prisoners' dilemma games (PDG). For the sake of simplicity as well as without losing universality, we set R=1, P=0, S=-0.1 as constants, and only by $T = b$ $(1 \leq b \leq 2)$ to characterize social dilemmas with different strength in this research.

Initially, the individuals are distributed on the lattice randomly with a ρ_e, which is designated as the density of empty sites, the population density is 1-ρ_e accordingly. Each individual chooses the strategy C or D randomly at first. The Monte Carlo method is adopted here to proceed the process of evolution. Theoretically, each individual could be chosen once in a time step, marked as t. In each time step, a focal i chosen randomly will interact with his/her direct neighbors one by one to earn his/her payoff P_i. If i has a lower payoff than the average payoff in his/her community (P_{AVG}), i is classified as a low-income one. As a low-income individual, he/she has two ways to improve his/her situation. One way is that he/she may either move into an empty site with probability p, provided at least one empty site available in direct neighborhood. In case of several ones, an empty site will be chosen randomly. If there is no empty site in the direct neighborhood, i will stay put. The other way is that he/she would rather throw himself/herself into social learning to improve his/her strategy with 1-p. However, if i is not a low-income individual, he/she prefers staying put to update his/her strategy. Considering the fact that people or animals are inclined to imitate successful one's behavior in their neighborhood, the best strategy updating rules thus will be employed in this model. To be more specific, one adopts the most rewarding strategy in his/her community.

In this research, we will focus on the parameter cooperation frequency (f_C), which represents the percentage of cooperators in whole population. Thus, $f_C = N_C/(N_t)$, where N_C and N_t) are number of cooperators and the total population. In order to figure quantitatively out impacts of mobility on network reciprocity, we define the parameter γ to represent the per capita mobility rate, which is calculated as

$$\gamma = N_m/(N_t), \tag{1}$$

where N_m is the number of the actual mobility behavior that low-income individuals have conducted. To characterize the compactness of cooperator clusters ρ_C, we define

$$\rho_C = N_C/(N_C + N_{CE}), \tag{2}$$

where N_{CE} is the number of empty sites in cooperator clusters. Furthermore, we averaged values of last 2000 time steps in 10,000 total time steps as one data point. Considering potential impacts of initial conditions, another 20 realizations are averaged as the final data.

3. Simulation results

Firstly, we represent the results of how f_C is changed with p for different b, as shown in Fig. 1 (A). In case of p=0.00, repeated interactions occur between two same PDG players. Due to direct reciprocity, cooperators could survive by helping each other to gain rewarding payoff. Particularly, since individuals are located on the lattice network, where he/he interacts with more than one partner with the same strategy. Therefore, the network reciprocity works actually. As p grows, the ratio of cooperators surges remarkably. However, f_C decreases sharply when p is bigger than a certain

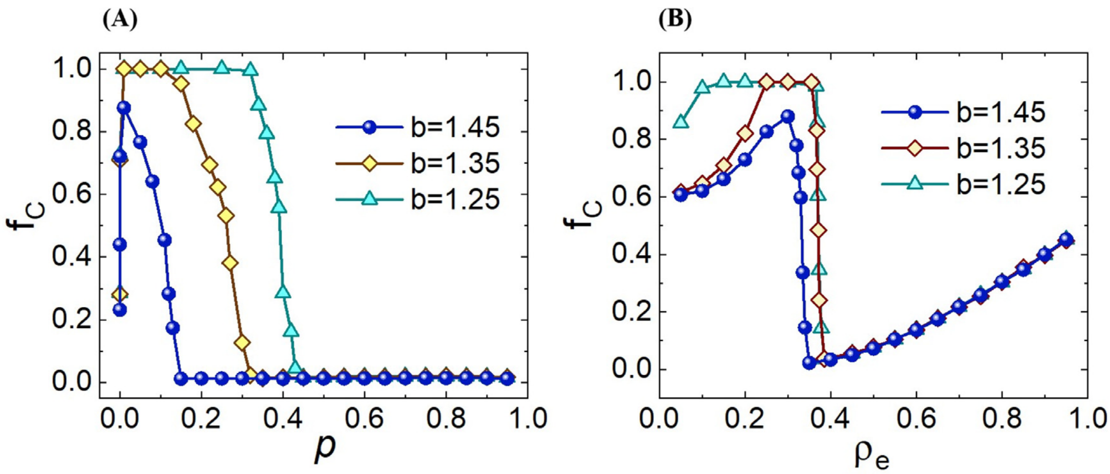

Fig. 1. The curve of cooperation frequency (f_c) with p and ρ_e. f_c curve with p for different b (A), and with ρ_e for different b (B). We set ρ_e=0.30 (A), and p=0.01 (B).

value which depends on b. Note that the scope of p promoting cooperation effectively narrows as b increases, and even converges to a peak when b=1.45. For the sake of mobility mechanism, it is essential to investigate how f_C is affected by the density of empty sites ρ_e. As shown in Fig. 1 (B), for small ρ_e, such as ρ_e=0.05, there are few empty sites available for low-income players to migrate into, which indicates that most of them stay put actually. It is similar with the case of p=0 that unmoveable cooperators survive through tacit acknowledgment, i.e. helping each other to gain rewarding payoff. However, it is yet significantly different that the values of f_C in case of p=0.01 for representative b ($f_C > 0.60$) are all higher than those of the case of p=0.00 for the same b ($f_C \approx 0.20$). Besides the slight difference of p, ρ_e is different too, ρ_e=0.30 and ρ_e=0.05 namely. Thus, it is reasonable to distinguish whether the remarkable difference of f_C is caused either by different p or ρ_e. In order to clarify this, we ran another simulation with the parameters $\rho_e = 0.05$ and p=0.00. Despite of the same $\rho_e = 0.05$, we get that $f_C \approx 0.32$ for p=0.0, which is far lower than $f_C \approx 0.60$ for p=0.01.

Comparing the above two cases, the probability of moving away for low-income individuals is slim actually due to only few empty sites available for small ρ_e=0.05. In spite of scarce empty sites, there are yet a few of low-income individuals who move away successfully for p=0.01. Obviously, the mobility will change the interacting neighbors, which will inevitably weaken network reciprocity. Despite of this, f_C is still much higher in case of p=0.01, which attributes to the mobility mechanism mainly. Apparently, the opportunities of moving away to improve their own payoff for those low-income ones may strengthen the confidence of cooperators. Particularly, with the growth of ρ_e in Fig. 1 (B), low-income individuals have more empty sites to migrate into to improve their payoff. Thus, f_C increases sharply. However, it is observed that f_C decreases when ρ_e is bigger than a certain value. Particularly for the social dilemmas with high temptation b, the effective scope of ρ_e on enhancing cooperation narrows down. As ρ_e increases, the population density declines. Under this situation, the probability of social learning is also slim because the neighbor sites are basically empty. Theoretically, f_C will converge to 0.50 or so for high ρ_e.

We now investigate spatial patterns of three representative p, as shown in Fig. 2. For the sake of comparison, the initial states are all the same in panel (A), (E) and (I), where either cooperators or defectors are evenly and randomly distributed throughout the lattice with ρ_e=0.30. In case of p=0.00, it is shown that cooperators are organized in bunches due to network reciprocity (B). As time goes by, the system ends up with an evolutionary stable state, where the patterns seem frozen (C) and (D), f_C is about 0.23 eventually. When low-income individuals are allowed to move away with a small probability, like p=0.01, it is found that some large cooperative clusters emerge (F), and further evolve and becoming larger (G) and (H), $f_C \approx 0.88$ eventually. As p grows, such as p=0.10, it is observed that cooperator clusters are larger than the case of p=0.01 when t=1000(J), whereas the number of large cooperator clusters have stagnated without further expansion, which is far less than that in case of p=0.01 (K)-(L), and $f_C \approx 0.56$ eventually.

Obviously, the evolution of cooperation is the outcome of comprehensive effects of both network reciprocity and mobility mechanism mainly. The value of p could characterize the situation where one of both takes the main effect in promoting cooperation. Theoretically, for $p \to 0.00$, network reciprocity works mainly. Extremely, only network reciprocity is active in case of p=0.00. As $p \to 1.00$, high-mobility causes population approximating to be well-mixed, which certainly weakens the impact of the network structure, whereas the effect of the mobility mechanism is gaining momentum. Under this condition, mobility itself may affect the evolution of cooperation alone. As to the low-income mobility mechanism itself, the cooperation level could not be improved or even worse by mobility alone without network reciprocity. Further, it could contribute a lot to further understanding the synergy of both mechanisms if we could reveal quantitatively the thresholds for each mechanism to work, as well as roles of mobile individuals playing in the evolution of cooperation.

When it comes to the mobility behavior who conducts, there are only two possibilities, cooperators and defectors namely. Therefore, we further explore how f_c evolves in the two conditions where either only low-income cooperators or only low-income defectors move (marked as the L-Cs-move and the L-Ds-move mechanism respectively). The results of f_c curves versus p for both mechanisms, as well as the current mechanism are shown in Fig. 3 (A). It is interesting to observe that f_C of the L-Ds-move mechanism changing over p is close to a constant, which is the value of f_C for p=0.00, whereas the other two curves of f_C are rather different from this. In case of p=0.0, all low-income individuals stay put. Cooperators survive ($f_C \approx$0.22) owing to network reciprocity. For limited p, such as p=0.01, it is shown that both f_C curves of L-Cs-move mechanism and the current mechanism peak. As p rises, both f_C decrease. However, the both curves have totally different shapes when p continues to increase. Remarkably, f_C of the L-Cs-move mechanism is about 1.00 when $p > .50$.

It seems too rash to draw a conclusion that the mobility of low-income cooperators play the key role in promoting coopera-

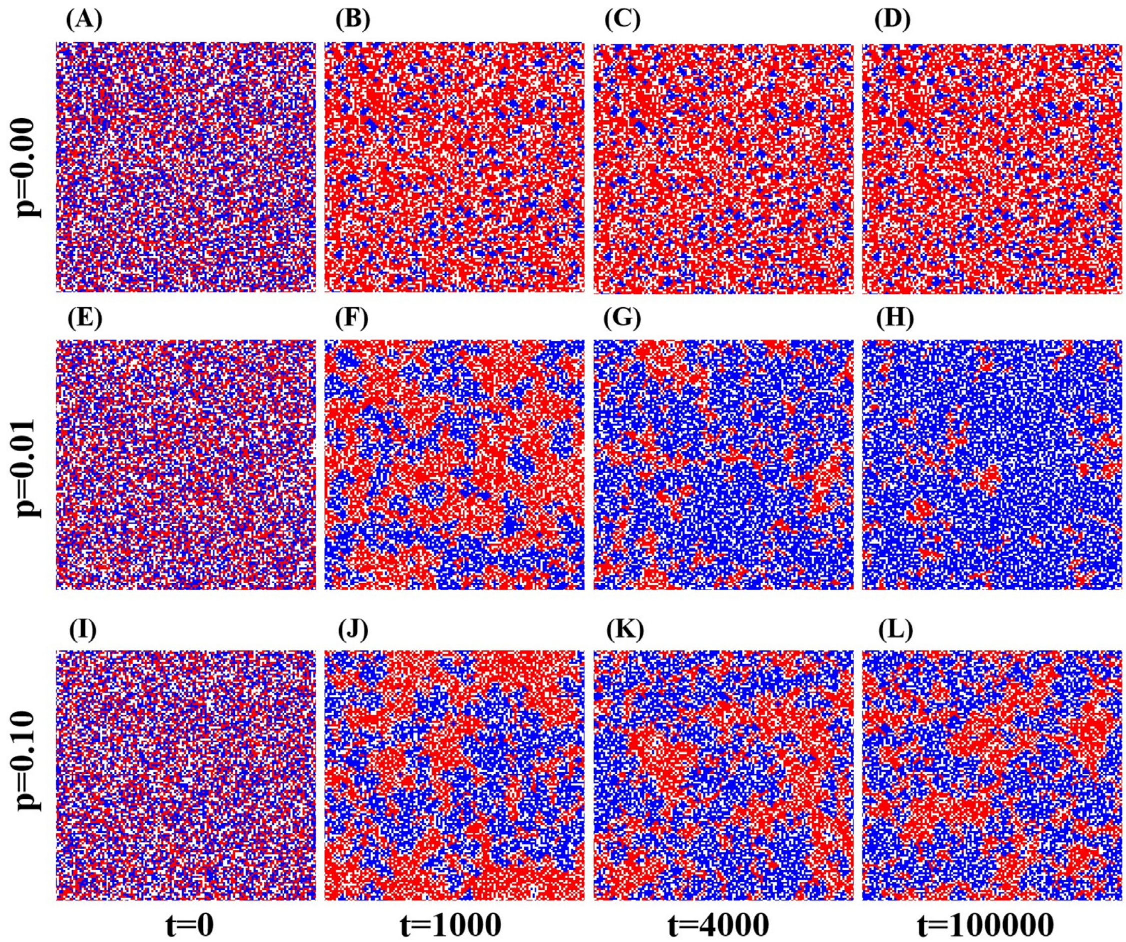

Fig. 2. The snapshots of spatial pattern for representative p. Panels (A)–(D) are for p=0.00, and panels (E)–(H) are for p=0.01, and panels (I)–(L) are for p=0.10. Initially, cooperator (marked as blue) and defectors (marked as red) are equally and randomly scattered around the whole lattice with a certain empty site rate (Panel (A), (E) and (I)). Here, empty site is white. We set b=1.45, ρ_e=0.30. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

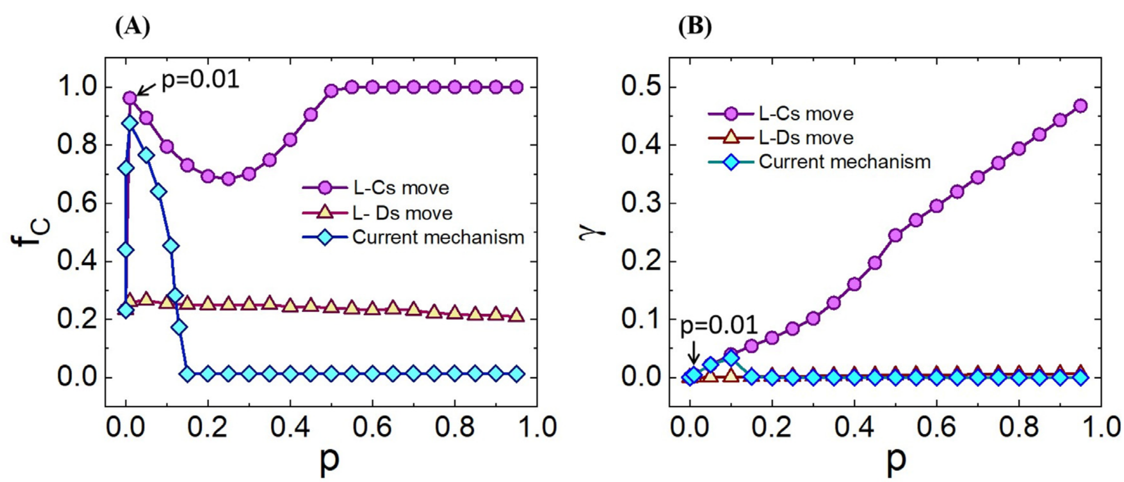

Fig. 3. The curve of f_c with p (A), and the curve of per capita mobility rate γ with p (B) for different mechanisms. The mechanisms are illustrated as follows, L-Cs-move: only low-income cooperators move, L-Ds-move: only low-income defectors move, and current mechanism, low-income individuals move actually. We set b=1.45 and ρ_e=0.30.

tion. More investigations are required to support this insight. Next, we calculated the per capita mobility rate γ as a function of p for the above 3 mechanisms, as shown in panel (B) of Fig. 3. In case of p=0.00, each player is occupied with social learning without mobility. Here, γ=0.00 definitely. For p=0.01, it is calculated that γ for both the L-Cs-move and the current mechanism is about 0.005, the order of magnitude of which is 10^{-3}. For the sake of peak value of cooperation frequency, we believe that the impact of limited mobility on the network structure is so negligible that the preserved network reciprocity is still active in the evolution of cooperation. Having in the remarkable enhancement of the mobility mechanism itself on cooperation addition, the synergy of both mechanisms is impressive. As p further rises, γ continues to mount, about 0.033; when p=0.10, the order of magnitude of which turns out to be 10^{-2}. As γ increases, the network structure has been further weakened. Hence as one falls, another rises. The mobility mechanism itself plays an increasingly role as γ mounts. However, the according f_C for both mechanisms decrease in panel (A) of Fig. 3. Under this condition, the network reciprocity has been damaged by "high" mobility. Yet, γ is too low to reflect the potential of the mobility mechanism. Whether the situation can be retrieved out of dilemmas or not by mobility depends on the mobility mechanism itself.

However, the situation for cooperators in the L-Cs-move mechanism is more optimistic than the current mechanism, f_C is still as high as up to 0.80 in case of p=0.10. The only difference between both mechanisms is that defectors are allowed to move in the current mechanism, which indicates mobile defectors undermine cooperation. Confronting invasions from defectors, it is more interesting to figure out how mobile cooperators defend against them. As shown in Fig. 3 (B), we find that γ increases in proportion to p for the L-Cs-move mechanism. For large p, such as p=0.9, $\gamma \approx$0.44, which is far bigger than the threshold for network reciprocity to work. Although in the absence of network reciprocity, f_C still reaches the maximum 1.00, which attributes to the positive feedback of mobility of low-income cooperators. For the current mechanism, we calculated that more than 80.00% of all mobility is carried out by low-income cooperators. The higher f_C is, the higher the proportion of low-income cooperators accounts for. Particularly, the proportion of low-income cooperators accounts for 97.00% among all mobility in case of p=0.01, where f_C peaks. So far, we draw the conclusion that the mobility of low-income cooperators is conducive to promoting cooperation.

As shown in Fig. 3 (A), it is found that f_C of the L-Ds-move mechanism changing with p is close to a constant, which is the value of f_C in the traditional model with the fixed lattice. It seems that network reciprocity works well instead of being affected by mobility. In order to verify this, we zoom in the curve of γ over t for different p for the L-Ds-move mechanism, as shown in Fig. 4 (A). One observes that γ increases slightly as p increases. Nevertheless, the values of γ are all in the order of magnitude of 10^{-3}, within the threshold that network reciprocity works. Some local cooperators could thus survive.

Concerning the question why less low-income defectors move, we try to lay out an analysis by employing a unit community, where 5 sites are available. Although the actual situation is far more complicated than that characterized by the unit community, it makes sense to employ it to analyze the local situation for the sake of the fact that the complex system is composed of a large number of unit communities due to interacting Von Neumann neighbors adopted. As shown in Fig. 4 (B), i locates at the center with four direct neighbor sites. For simplicity, the $\rho_e \approx$0.20, which indicates that one site is empty in this unit community in probability. There are four situations, where we calculated i's payoff as well as the average payoff P_{AVG} respectively. It is found that there is barely no chance to observe that i moves away, for i's payoff is not lower than P_{AVG}. Actually, most defectors are not likely to be the low-income unless in some cases, such as the defectors who are surrounded by other defectors, one of whom may earn higher payoff by exploiting their cooperative partners.

Even though only a few low-income defectors may move away, the negative impact on cooperation is impressive. In case of p=0.01, f_C of the current mechanism is far lower than that of the L-Cs-move mechanism just due to the fact that only 3.00% of all mobility behavior is conducted by defectors. Confronting invasion from defectors, some vulnerable cooperative clusters may disappear. To verify this further, we investigated the spatial pattern of different mechanisms for p=0.01, as well as the compactness of

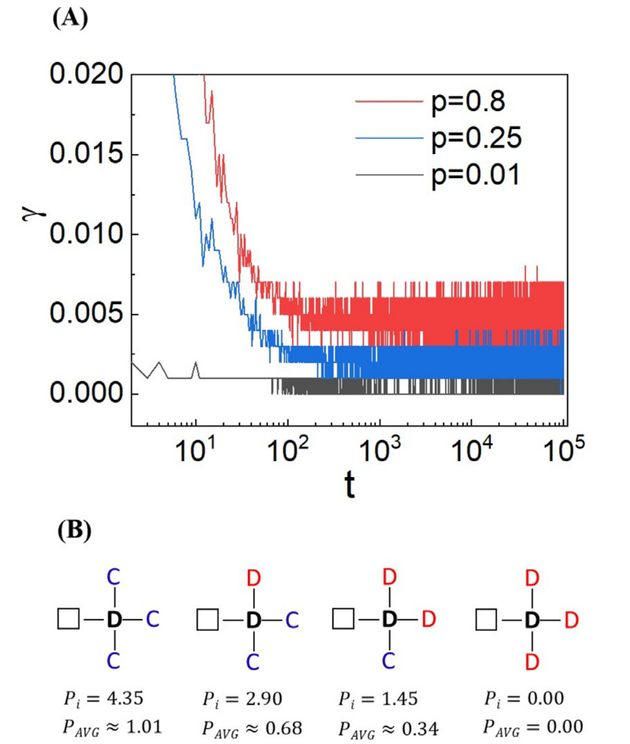

Fig. 4. The diagram of low-mobility for low-income defectors. The per capita mobility rate γ as a function of p for low-income defectors (A), as well as the illustration of the situations where a defector may locate in a unit community, and the according payoff (B). We set b=1.45, R=1.0, S=-0.1, P=0 and ρ_e=0.20.

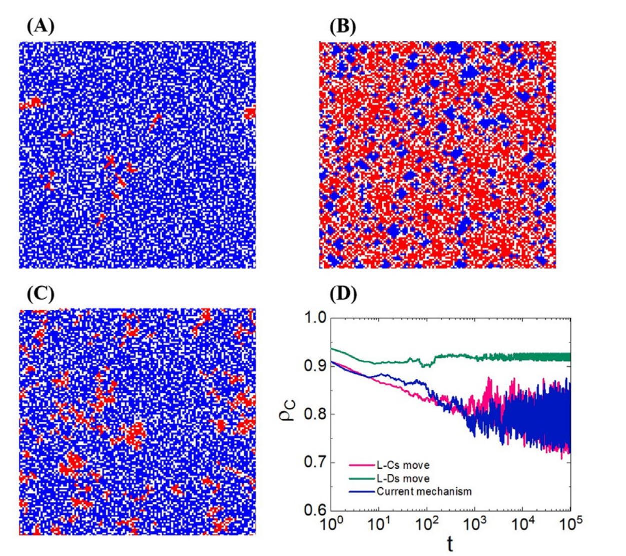

Fig. 5. The spatial patterns of cooperative clusters with limited mobility for L-Cs-move (A), L-Ds-move (B), and current mechanism (C). The compactness of cooperative clusters ρ_C versus time for different mechanisms are calculated in panel (D). The mechanisms are illustrated as follows: L-Cs-move: only low-income cooperators move, L-Ds-move: only low-income defectors move, and current mechanism, low-income individuals move actually. We set p=0.01, b=1.45 and ρ_e=0.30.

cooperative clusters ρ_C, as shown in Fig. 5. The cooperative clusters in both the L-Cs-move (A) and the current mechanism (C) are similar. To be more specific, the cooperative clusters are loose, regardless of different f_C. The corresponding ρ_C for both cases is about 0.80, as shown in panel (D). Whereas the cooperative clusters are compact ones in the L-Ds-move mechanism apparently (B). The corresponding ρ_C is about 0.92, which is far higher than the other two cases. Generally, the cooperators only in compact clusters could fight against continuous invasion from defectors, and survive eventually. The mechanism that defectors move may offer a way for defectors to invade and destroy cooperative clusters.

4. Discussion

Generally, the higher the level of cooperation is, the more prosperous the society will be. Facing high temptation, individuals may defect to exploit others to be rich, whereas suckers' profit will be really decreased. Worse yet, the strategy of defecting would be spread among individuals because of social learning. Therefore, scientists have been carrying out extensive and considerable studies to find approaches which promote the cooperation level among individuals, such as network reciprocity [16,17], punishment [18,19], conformity [20] and reputation [21–23].

As one of the key factors affecting cooperation, how to eliminate poverty without an extra investment has attracted attentions [24,25]. Noticing that mobility is a fundamental behavior for individuals in nature and society, we deliberated whether the dilemma caused by poverty could be retrieved by a self-organized mobility [26–32]. To this end, we constructed a model where low-income individuals either move away or stay put to compete for limited local resources. Our results show clearly that mobility of low-income ones could promote cooperation when the per capita mobility rate is about the order of magnitude 10^{-3}, where both the network reciprocity and mobility mechanism are active. As the per capita mobility rate rises to the order of magnitude 10^{-2}, the remaining network reciprocity has been greatly weakened. Without network reciprocity, the mobility mechanism alone determines the evolution of cooperation. Under this condition, it is essential to analyze the mobility mechanism itself.

Since both cooperators and defectors may move in current model, we extended our study by exploring how the mobility related to each of them contributes respectively to promoting the cooperation level. Specifically, we found that the mobile low-income cooperators play a key role in enhancing cooperation, whereas the mobile defectors undermine cooperation. Therefore, cooperation could be enhanced greatly if only low-income cooperators move. Comparing the cooperation frequency f_c curve of the L-Cs-move mechanism, where only low-income cooperators move with the current mechanism for the moving probability p=0.01, f_c for the latter has a big decrease due to defectors' far fewer mobility which accounts for only 3.00% of total mobility ratio. Without a negative effect of defectors' mobility, f_c could even rise up to 1.00 in the L-Cs-move mechanism when $p>0.50$. We note, however, that with the presence of mobile defectors some cooperators could still survive owing to the existence of network reciprocity. Especially, the cooperators in compact clusters could fight against mobile defectors by helping each other even without mobile advantage. Luckily, it seems that there is no upper limit on the per capita mobility rate in the L-Cs-move mechanism, and that low-income defectors usually keep a very low mobility rate of the order 10^{-3} or less in the long run for different values of the moving probability p.

To conclude, in this paper we proposed and verified that poverty could be eliminated by mobility, particularly cooperators' mobility. Such mobility would promote cooperation level among individuals. And in the situation where the cooperators are not accessible to distinguish, the per capita mobility rate should be controlled in the order of magnitude 10^{-3}. Nevertheless, all the data and results presented in this paper are acquired on a regular lattice. Whether the same phenomenon still appears in real social networks, or whether actual data support this insight, is still an open problem. We look forward to new further investigations in this matter. By now, our results have shed light on the common issue how to eliminate poverty without extra investment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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