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Evolution of cooperation in the spatial prisoner's dilemma game with extortion strategy under win-stay-lose-move rule

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ABSTRACT

Extortion strategy and mobility have both been studied separately, and their roles for the evolution of cooperation are well known. In this paper, we combine these two mechanisms and explore the effects of one mechanism on another, especially for how spatial exclusion influences the dynamics. The model incorporates migration into the prisoner's dilemma game with extortion and allows agents to change their spatial position governed by win-stay-lose-move rule. By means of Monte Carlo simulations, we show that when the population density is intermediate (neither too high or too low), empty sites weaken the cooperation-extortion alliance and allow cooperators to form compact clusters through migration, which then enhance network reciprocity in the populations. In this way, cooperation can be maintained in the structured populations with mobility, we thus provide a deeper understanding for the evolution of cooperation.

1. Introduction

Cooperators, sacrifice their own interests for the collective, will be wiped out by defectors according to the theory of "survival of the fittest" [1,2]. However, this prediction is in sharp contrast with real life where cooperation is widespread in nature and human society [3–5]. Understanding the evolution of cooperation not only means understanding the evolutionary history of humans and all living things, but also helps to solve ecological, economic and social problems, which is of great significance [6].

In the study of the evolution of cooperation, evolutionary game theory plays a key role in providing an essential mathematical framework [2,7–9]. The prisoner's dilemma game (PDG) is one of the most classical game models [10–12], which describes the characteristics of social dilemma through two strategies: cooperation and defection. In the previous studies, cooperation can be facilitated by forming large and tight clusters in structured populations, which is known as network reciprocity [2,13]. Other mechanisms can also sustain cooperation [14,15]. Recently, Press and Dyson [16] proposed a novel class of strategies, called zero-determinant (ZD) strategies, which emphasize the linear relation between a player's own payoff and the opponent's payoff. It should be pointed out that the extortion strategies are a subset of ZD strategies, which are more favored than any other strategies since the payoff increment of an extortioner exceeds that of the co-player by a fixed percentage [17–19]. Although players prefer to adopt extortion under imitation rules, they can not always prevail in the population because extortioners receive nothing when they encounter non-cooperators, which implies that such extortion strategies are evolutionary unstable in well-mixed population [19]. Along this line, the stability of the extortion strategy has been widely studied and the results have been fruitful. Hilbe et al. [18] found that extortion strategies accelerated the evolution of cooperation among the sufficiently large well-mixed population. The results of Szolnoki et al. showed that extortion is evolutionary stable in structured populations if the myopic best response rule is used to update the strategies [20,21]. Hao et al. found that ZD strategies had stronger robustness in noisy games [22]. Further studies have shown that extortioners form the alliances with cooperators, and help the cooperators resist the invasion of the defector, cooperation thus can be facilitated even when the temptation to defect is considerable [23,24].

Mobility, one of the important characteristics of biological organisms, provides another perspective for the study of evolutionary games [25–28]. Some scholars have proposed different mobility models to study the effect of mobility in different games. Aktipis pointed out that cooperation can be maintained via win-stay-lose-move migration rule, which allows the cooperators to avoid the sustained invasion of defectors, thereby ensuring reciprocity [29].

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Vainstein et al. found that random migration changes the scope of interaction, and then helps the prevails of cooperation [30]. Sicardi et al. showed that random migration changes the spatial structure of the population and enhances cooperation in the prisoner's dilemma and the stag hunt games, but it works bad in the snowdrift game [31]. Helbing et al. proposed the "success-driven" migration rule, which brings powerful network reciprocity into the populations, and thus the beneficial temporal patterns create the conditions for cooperation to emerge and sustain [32,33]. Other researchers have explored the impacts of migration patterns and mobility velocity [34–42], all these efforts have enriched the study of this topic. Regarding the population density, it was argued that there is an optimal population density that amplifies the network reciprocity. However, if the population density is too low, vacant sites prohibit the formation of cooperative clusters. Too high population density, on the other hand, enables the effective invasion of defectors, which again undermines the network reciprocity [43–45].

We combine mobility and extortion strategies to investigate the evolutionary outcomes when both mechanisms work together. We study the evolution of cooperation in the PDG with extortion on the square lattice, the process of strategy updating is governed by the finite population analog of replicator-like dynamics [9,41,46], and the migration follows the win-stay-lose-move rule [29]. By means of Monte Carlo (MC) simulations, we find that cooperation is well established when the population density is intermediate (neither too high or too low) due to (i) empty sites weaken the cooperation-extortion alliance and (ii) cooperators can form more compact clusters through migration. The rest of this paper is organized as follows: we first describe our model and then present detailed results, finally we summarize the main results and discuss its potential implications.

2. Model

Strategies and payoffs We adopt the iterated PDG with extortion to study the evolution of cooperation. Each player holds one of the three strategies, namely, cooperation (C), defection (D), extortion (E_χ), to play pairwise games with the opponent. In a traditional PDG, a cooperative player can obtain a reward R (or sucker's payoff S) when his opponent is a cooperator (or defector), likewise, a defective player receives the temptation to defect T (or punishment P) under the same situations. Here, we assume $R = b - c$, $T = b$, $S = -c$ and $P = 0$, in which cooperator provides a benefits b by paying a cost c ($b > c > 0$), while defector contributes nothing. Under such assumptions, a classical version of PDG, known as donation game [2,19], is adopted in this model. With the introduction of extortion, the payoff matrix can be formulated as:

$$\begin{array}{c|ccc} & C & D & E_\chi \\ \hline C & b-c & -c & \frac{b^2-c^2}{b\chi+c} \\ D & b & 0 & 0 \\ E_\chi & \frac{(b^2-c^2)\chi}{b\chi+c} & 0 & 0 \end{array} \tag{1}$$

where χ ($\chi > 1$) is the extortion factor that determines the intensity of extortioners exploiting cooperators. For simplicity, we set $b - c = 1$, so that we just focus on two parameters, namely, the social dilemma strength factor b and the extortion factor χ [18].

*Imitation.*The evolutionary games perform in a $L \times L = N$ square lattice with periodic boundary conditions and 4-neighborhood (Von Neumman neighborhood), where each site of the lattice is either empty or occupied by a player. Then the population density can be defined as $\rho = n/N$, where n is the number of players. The iterated game is realized by MC asynchronous simulation. Players go through three stages, including interaction, imitation and migration, in a descending order at one time step. Initially, each player is designed to possess one of the three strategies randomly. In the interaction stage, each player has pairwise interaction with all of her/his direct neighbors and obtains total payoffs based on the above payoff matrix. Note that isolated players obtain nothing in this stage, they can skip the imitation stage and go straight to the migration stage. Besides the isolated players, each player selects one of her/his neighbors to learn strategy by comparing current total payoffs in the imitation stage. In detail, player x with strategy S_x decides whether to adopt the strategy of the randomly selected neighbor y (with strategy S_y) with probability

$$W_{(S_x \leftarrow S_y)} = \frac{P_y - P_x}{\max(k_x, k_y)H}, \tag{2}$$

where P_x (P_y) is the payoff of player x (y), and k_x (k_y) represents the degree of x (y), i.e. the number of players in direct connected sites. H is the maximal possible difference of payoffs between two players. Here, we set $H = b + c$ for $\chi > 1$ and $\frac{(b^2-c^2)\chi}{b\chi+c} < b$.

*Migration setting*Player can go through the migration stage only if there is at least one empty site in her/his neighborhood. Player who meets the criteria can decide whether or not to leave the current position via win-stay-lose-move rule, that is, player compares the expected payoff on the current site with that on a randomly selected empty site in the neighborhood. The lower payoff on the current site means that leaving the current position is more favorable. Finally, player who is willing to leave can move to the site that randomly selected from neighborhood only if it is empty.

In this work, we set $L = 200$ and the stable fraction of three strategies were obtained by averaging the last 3000 Monte Carlo time steps of the entire 1×10^5 steps. The final results were also obtained by averaging over 20 independent simulations.

3. Results

In order to investigate the impact of mobility on the evolution of cooperation in the PDG with extortion, we first study the fraction of cooperation (F_C), defection (F_D) and extortion ($F_{E\chi}$) in dependence on dilemma strength factor b and population density ρ by fixing extortion factor χ in Fig. 1. In principle, migration is impossible for $\rho = 1$. As population density decreases, a growing number of empty sites provide space for migration, which increases the mobility of agents. Note that mobility increases F_C compared with that of when $\rho = 1$. There are two reciprocity mechanisms in our model, one is the traditional network reciprocity, where cooperators can avoid the exploitation of defectors by forming compact clusters to support each other, the other one is the cooperation-extortion alliance, in which cooperators can survive that adhere to extortioners. If migration is possible, cooperators can thus escape from the exploitation of defectors and extortioners. According to the payoff matrix and the win-stay-lose-move rule, cooperators are more likely to gather together for the payoff of cooperation-cooperation pair is larger than the cooperation-defection pair and cooperation-extortion pair. In this way, the interaction among cooperators can be enhanced in spatial prisoner's dilemma game since migration provides another possible route for cooperation to escape the social dilemma. Especially, cooperation can be maintained and even dominant in the population, while extortioners and defectors can never survive when dilemma strength is weak ($b < 1.09$). For larger b, the distribution of strategies is different between $\chi = 1.5$ and $\chi = 5$. In fact, low value of χ implies that extortioners who earn slender payoffs from cooperators are unable to support cooperators to against defectors. Although cooperators can avoid being exploited by defectors through migration, cooperators still die out rapidly for strong dilemma strength ($b > 1.09$). When χ is large ($\chi = 5$), cooperation is maintained in the population even if the value of b is pretty high, as shown in Fig. 1(d). At this point, extortioners play a nontrivial role in the

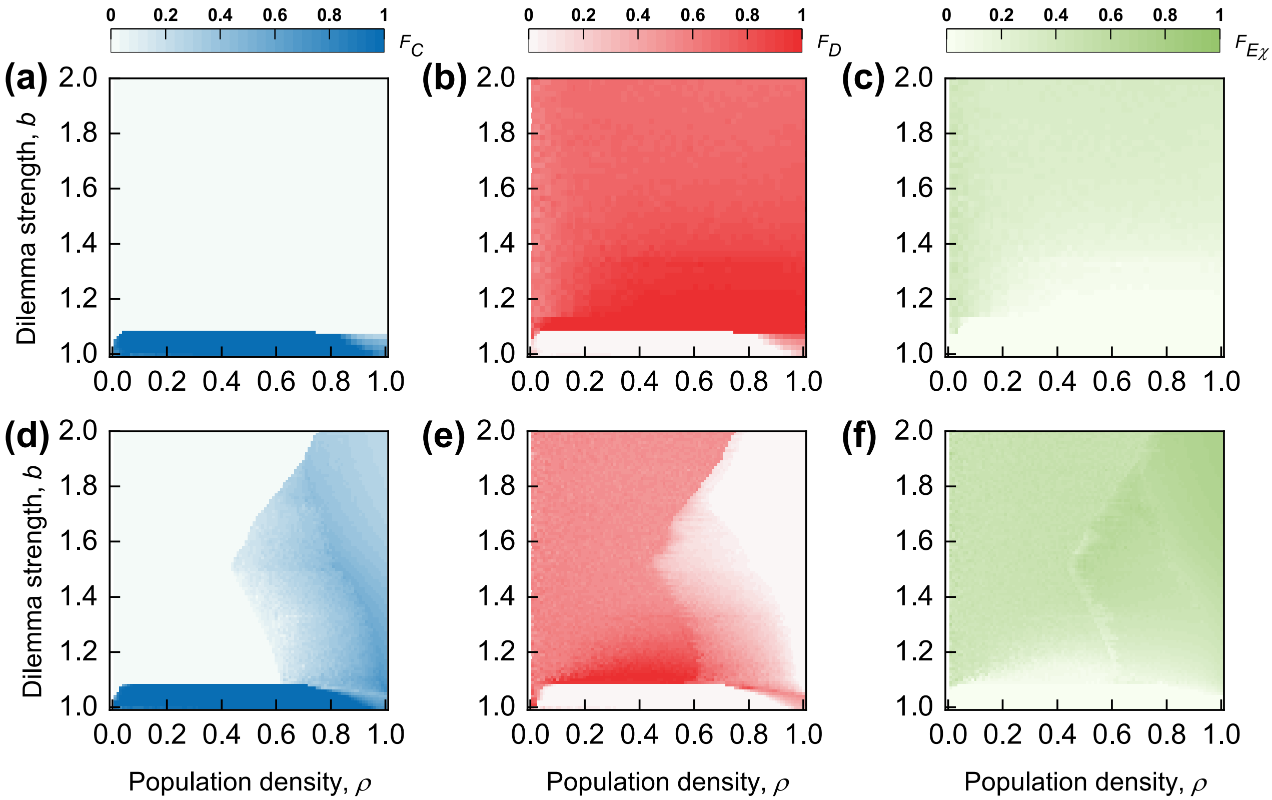

Fig. 1. The fractions of cooperation (F_C), defection (F_D), and extortion ($F_{E\chi}$) as functions of dilemma strength factor b and population density ρ for (a)–(c) $\chi = 1.5$ and (d)–(f) $\chi = 5$.

evolution of cooperation, where cooperators and extortioners establish an alliance to against defectors. Although mobility can be seen as a function that is conductive to cooperation, excessively high mobility separates cooperators from the protection of extortioners.

Then we mainly study the impact of extortion in Figs. 2 and 3. As shown in Fig. 2, extortion factor nearly has no effect on the evolution of cooperation, where F_C remains unchanged under the fixed dilemma strength in sparse population ($\rho = 0.3$). In detail, cooperators always dominate the system for small b, while die out when $b > 1.09$. In crowded population, the weak dilemma strength still favors cooperation whatever the value of extortion factor χ is, cooperators can also coexist with defectors and extortioners for high dilemma strength when χ is large enough ($\chi > 3.83$). When the population is mostly occupied by empty nodes, although high mobility allows cooperators to avoid the exploitation of defectors, it is difficult for cooperator to form clusters with other cooperators and extortioners, the isolated cooperators can not survive in population. However, when population density is high, the above mentioned clusters are more stable, so that cooperators have the opportunity to survive even if b is large. Moreover, it is difficult for extortioners to protect cooperators when χ is small, and extortioners tend to exploit cooperators when χ is large. Therefore, χ has an optimal value, where cooperators can survive under high dilemma strength and the threshold for b to support cooperation is decreasing correspondingly with increasing χ.

In Fig. 3, we depict the fractions of three strategies in dependence on population density and extortion factor for different dilemma strength. In accordance with the above phenomenon, cooperation mostly dominate the system whatever the value of χ is for weak dilemma strength ($b = 1.02$), except in the cases of crowded population. Migration in this case enhances network reciprocity among cooperators, which leads to the prevail of cooperators in the population without extortioners. In crowded population ($\rho > 0.89$). The lack of space limits the mobility of agents, and makes it difficult for cooperators to escape the exploitation of defectors [44]. When dilemma strength is strong ($b = 1.5$), only moderate extortion factor is conducive to cooperation in crowded population, and the optimal value of χ can be easily found. As mentioned before, mobility is advantageous for cooperators to form clusters regardless of extortion factor when dilemma strength is weak. However, when b is large, mobility is no longer the mechanism to benefit cooperators. In this case, cooperators survive through the alliance relationship with extortioners, where moderate χ makes this relationship possible.

In order to get more understanding for the above phenomenon, we present several cross-sections of phase diagrams (Figs. 1–3), as obtained for (a) $\rho = 0.55,\ \chi = 5$, (b) $b = 1.5,\ \rho == 0.7$, and (c) $b = 1.5$ and $\chi = 7$. respectively. In Fig. 4(a), when b is low (i.e. $b < 1.09$), cooperators dominant in the population since the network reciprocity is more effective than cooperation-alliance. With increasing b, cooperation first suddenly changes to defection and then with the formation of cooperation-extortion alliance, cooperation emerges in the system again through continuous phase transition (here, cooperation, defection, and extortion coexist in the system if b lies in the interval of (1.3, 1.71)). When b equals to 1.72, cooperation suddenly goes to extinction through discontinuous phase transition since too large values of b destroy the formation of alliance. Analogously, the effect of cooperation-extortion alliance only works when χ is moderate, too large or too small values of χ are not conductive to the formation of this alliance, as presented in Fig. 4(b). In Fig. 4(c), too many vacant sites not only weaken the network reciprocity, but also impede the formation of the cooperation-extortion alliance. Cooperation suddenly appears when $\rho = 0.527$ since the cooperation-extortion alliance is formed on this point. Although the alliance becomes stable as ρ increases,

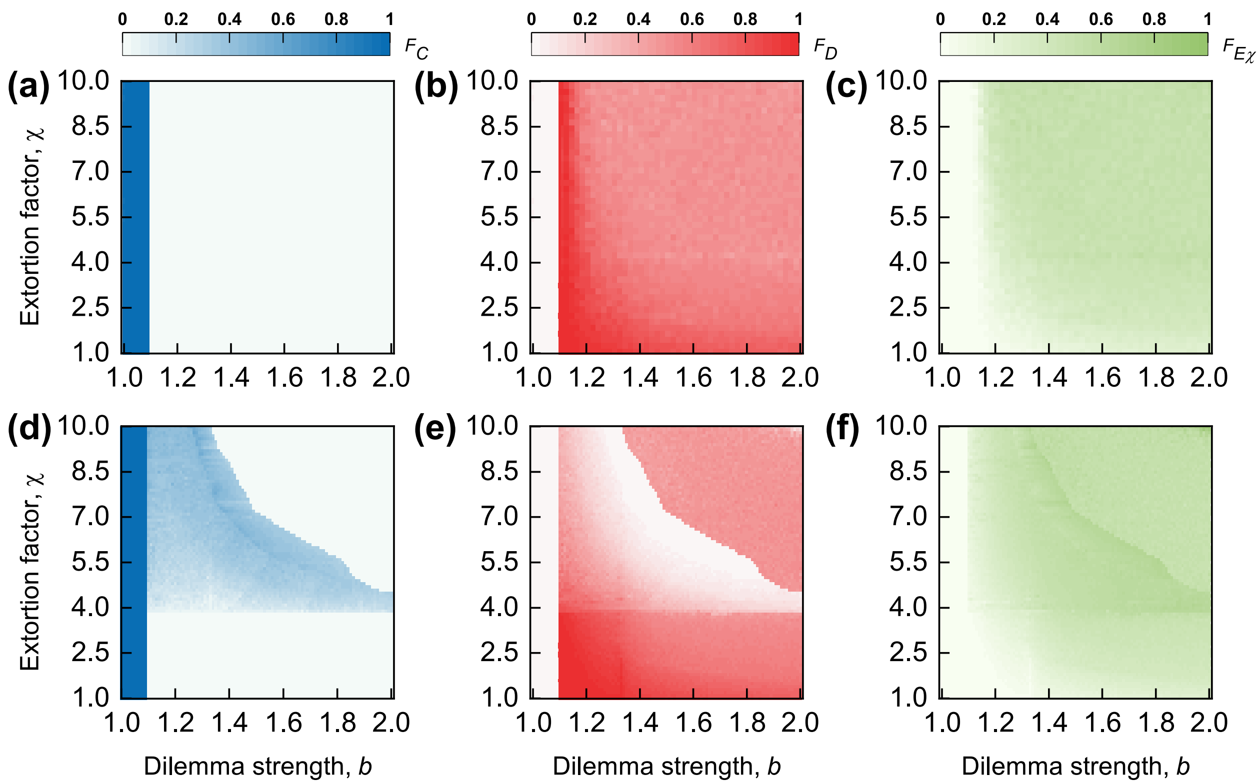

Fig. 2. The fractions of cooperation (F_C), defection (F_D), and extortion ($F_{E\chi}$) as functions of extortion factor χ and dilemma strength factor b for (a)–(c) $\rho = 0.3$ and (d)–(f) $\rho = 0.7$.

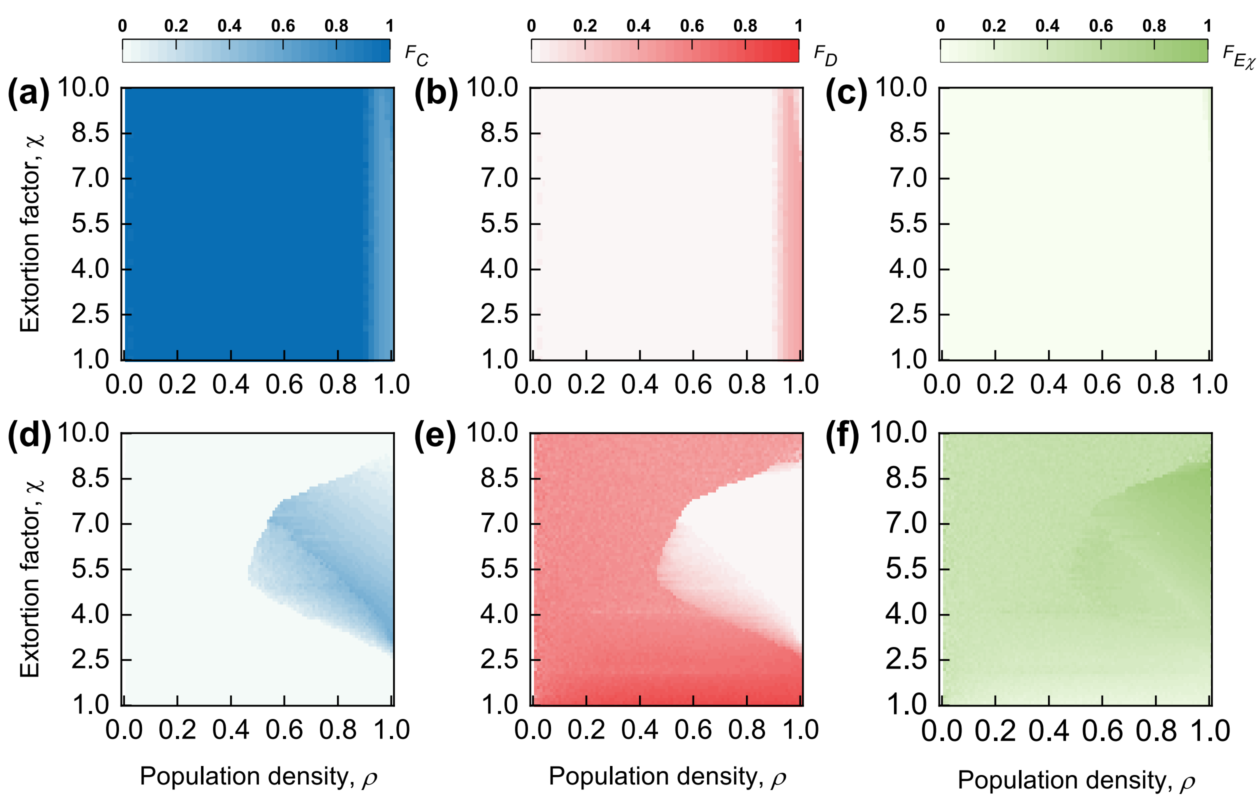

Fig. 3. The fractions of cooperation(F_C), defection(F_D), and extortion($F_{E\chi}$) as functions of extortion factor χ and population density ρ for (a)-(c) $b = 1.02$ and (d)-(f) $b = 1.5$.

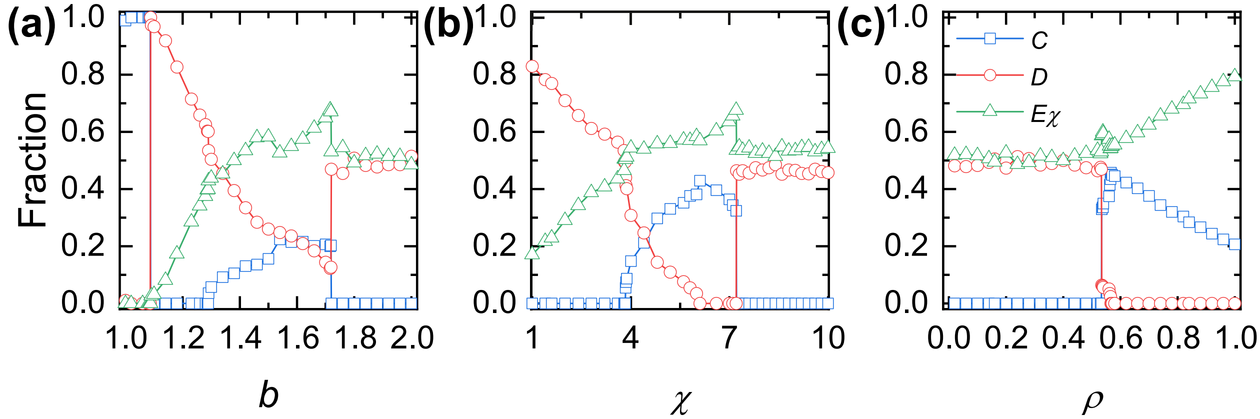

Fig. 4. Three representative cross-sections of phase diagram (Figs. 1–3), as obtained for (a) $\rho = 0.55$ and $\chi = 5$, (b) $b = 1.5$ and $\rho = 0.7$, and (c) $b = 1.5$ and $\chi = 7$.

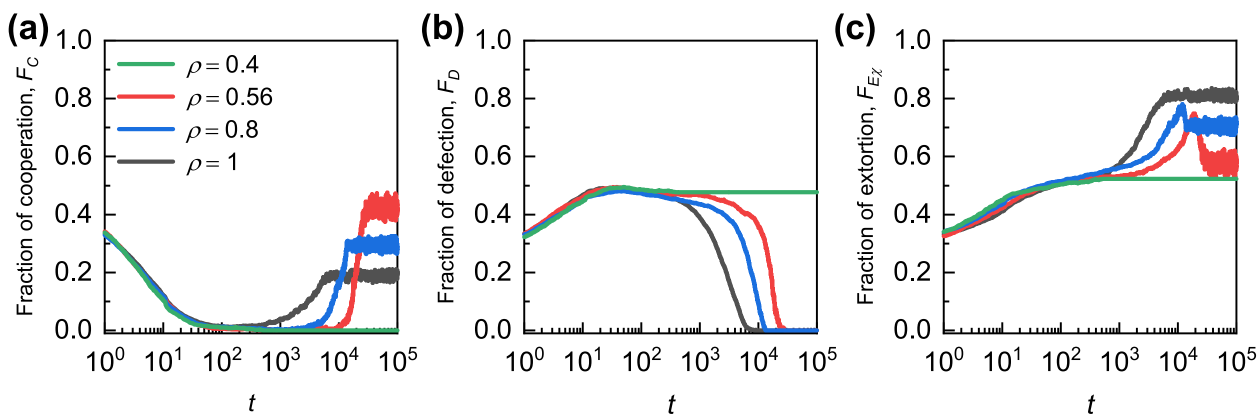

Fig. 5. The time evolution of (a) cooperation F_C, (b) defection F_D and (c) extortion $F_{E\chi}$ under different population densities $\rho = 0.4$ (green line), $\rho = 0.56$ (red line), $\rho = 0.8$ (blue line) and $\rho = 1$ (black line). The results are obtained for $L = 100$, $\chi = 7.2$ and $b = 1.5$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

it reduces the migration efficiency on cooperators, so that F_C decreases gradually after reaching the peak. The discontinuous phase transition is due to the competition of defectors and extortioners regarding to the aggression against cooperators. While the continuous phase transition is due to the increasing effectiveness of cooperation-extortion alliance that stems from the proper range of b or χ. In order to confirm the above results, the temporal evolution of three strategies in a log-log figure for several samples near the phase boundary are also presented in Fig. A.1.

Since mobility is significant in terms of the evolution of cooperation for strong dilemma strength, we explore the microscopic evolutionary processes under migration and present the time courses of the fractions of three strategies by fixing $b = 1.5$, $\chi = 7.2$ under $\rho = 0.4$, $\rho = 0.56$, $\rho = 0.8$ and $\rho = 1$ in Fig. 5, and the corresponding evolutionary snapshots of strategy links under $\rho = 0.56$ and $\rho = 1$ in Fig. 6 (In order to visualize the evolution process, we present videos in supplementary materials). For the situation without migration ($\rho = 1$), F_C decreases rapidly at the beginning since most cooperators are exploited by neighboring defectors and extortioners, only a few cooperators start to form clusters to protect themselves. Extortioners who are connected to cooperators can obtain the favorable payoffs, cutting off the connections between cooperators and defectors, thus defectors can be defeated. A few survived cooperators thus coexist with extortioners under cooperation-extortion alliance (see Fig. 6(a)). When nearly half of the nodes in the population are empty ($\rho = 0.56$), cooperators go through the negative feedback process and extortioners separate cooperators from defectors, like what happened in the case of $\rho = 1$. Then cooperation spreads in population with the help of the cooperation-extortion alliance. Cooperators tend to move to the more favourable location, that is, the site with more cooperative neighbors, so that mobility promotes the formation of tight and large cooperative clusters (see Fig. 6(b)). Besides, mobility inhibits the interaction between extortioners and cooperators, the cooperation-extortion alliance is weakened when cooperators evade extortioners, which leads to the perishment of some extortioners. In this way, mobility promotes the evolution of cooperation, the final F_C ($F_{E\chi}$) is higher (lower) than that of when $\rho = 1$. Obviously, the role of migration varies when population density is sparse or dense. For $\rho = 0.4$, cooperators cannot form stable clusters to against non-cooperators under high mobility, even when the cooperation-extortion alliance does not work, F_D and $F_{E\chi}$ remain stable after cooperation disappears. For $\rho = 0.8$, the lack of empty sites limits the ability of cooperators to evade extortioners. Note that $F_{E\chi}$ reaches to the peak first and then drops to the steady state after defectors disappear for the case with mobility, which means that the advantage of extortioners is diminished since the escape of cooperators.

Finally, to explain the above phenomenon, we focus on typical strategy links around cooperators, which are C-ϕ, C-C and C-$E\chi$ links. We show the probability density function (*PDF*) and cumulative distribution function (*CDF*) for the fraction of these strategy links during the evolution in Fig. 7. Here, *PDF* describes probability density of the fraction of strategy links that approaches a certain value within the given interval, while *CDF* describes the total probability of the fraction of strategy links accumulating from the minimum value of interval to a certain value. The value within the interval where *PDF* curve has highest probability density, the

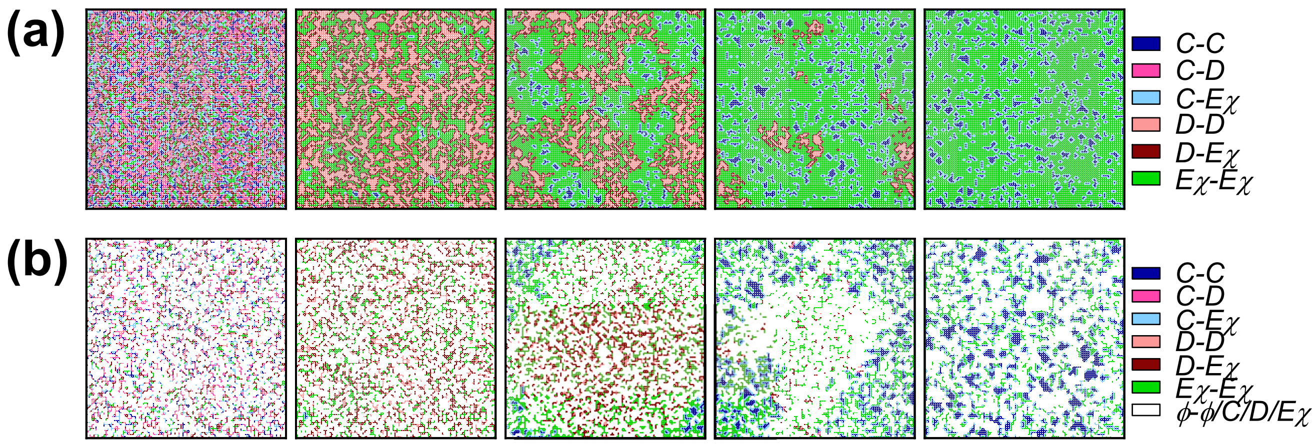

Fig. 6. Typical snapshots of distributions of the links between two strategies at different time step for (a) $\rho = 1$; $t = 1, 100, 2000, 5000, 40000$ and (b) $\rho = 0.56$; $t = 1, 1000, 15000, 22000, 40000$. The colors of lines represent respectively: dark blue, $C-C$ links (cooperation-cooperation); magenta, $C-D$ links (cooperation-defection); light blue, $C-E\chi$ links (cooperation-extortion); light red, $D-D$ links (defection-defection); brown, $D-E\chi$ links (defection-extortion); green, $E\chi-E\chi$ links (extortion-extortion) and white, the links are related to empty site ϕ. The parameters of each panel are fixed as $\chi = 7.2$ and $b = 1.5$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

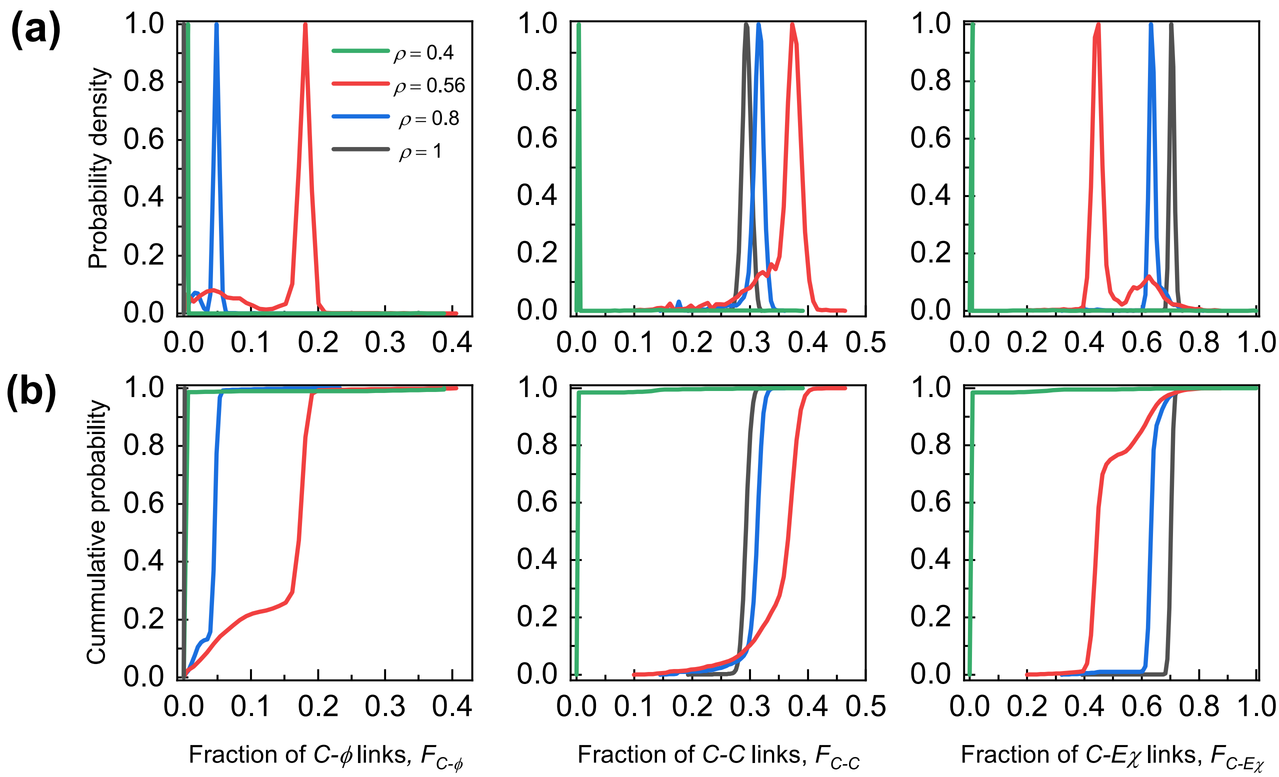

Fig. 7. (a) The normalization probability density distribution and (b) the cumulative probability distribution as functions of the fraction of $C-\phi$ links $F_{C\text{-}\phi}$, $C-C$ links $F_{C\text{-}C}$ and $C-E\chi$ links $F_{C\text{-}E\chi}$ under different population densities $\rho = 0.4$ (green), $\rho = 0.56$ (red), $\rho = 0.8$ (blue) and $\rho = 1$ (black). The parameters of each panel are fixed with that of in Fig. 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

corresponding *CDF* curve has maximum slope and thus the accumulative probability increases greatly, which indicates that the fraction of the strategy links equals to the value with the highest probability over the evolutionary process. When $\rho = 0.4$, too many empty sites impede the interaction among cooperators, and cooperators become vanish eventually, the corresponding three *PDF* curves thus reach the maximum density where the fraction of these links are equal to zero (see Fig. 7(a)), the corresponding *CDF* curve has the maximum slope and the accumulative probability increases greatly within this small range (see Fig. 7(b)), which implies that these strategy links do not exist in the population or its values are extremely low. The fraction of *C*-*C* (*C*-E_χ) links are higher than that of the case of without migration ($\rho = 1$), where the stable fraction of $F_{C\text{-}C}$ and $F_{C\text{-}E_\chi}$ are about 0.28 and 0.71, respectively. That's to say, extortioners can allow cooperation to survive that adhere to extortioners at the early stage, when defection goes to the extinction, cooperators have enough incentives to leave the extortion of E_χ players since the payoff of *C*-*C* links is greater than that of the *C*-E_χ links. The *C*-E_χ links are no longer stable, and it will change to either *C*-*C* links or *C*-ϕ links. In this way, cooperation-extortion alliance is weakened since the *C*-E_χ links are replaced by *C*-*C* and *C*-ϕ links, and the reciprocity among cooperators is enhanced by mobility since the payoff of *C*-*C* links is largest in the populations. As for why cooperation fares better if the intermediate population density is applied. It's clearly to get the evidence that intermediate population density (i.e. $\rho = 0.56$) provides more chances for cooperation to leave the exploitation of extortioners since the fraction of C-E_χ are lower compared with the case of $\rho = 0.8$.

4. Conclusions

To conclude, we have discussed how cooperation evolves in the spatial prisoner's dilemma game by combining two cooperation promotion mechanisms. The whole simulation process consists of three stages: each agent first plays with all its direct neighbors to collect its cumulative payoff, and then imitates the strategy of one random neighbor, finally migrates to an empty site through win-stay-lose-move rule. Through extensive numerical simulation, we show that cooperation flourishes for intermediate population density due to (i) empty sites weaken the cooperation-extortion alliance and (ii) migration helps the formation of compact cooperative clusters through self-organization.

Although the migration and extortion have both been studied separately and their effect for cooperation are also well investigated. In this paper, we wish to establish the understanding of what influences of one mechanism has on another, especially regarding how spatial exclusion can influence the evolutionary outcomes. It was verified that optimal population density enhances the network reciprocity, too low population prohibits the formation of cooperative clusters due to the existence of massive empty sites. While too high population enables the effective exploiting of defection [42–45]. Along with this line, the combination effect of mobility and population density was deemed as another effective path for cooperation to evolve since defectors not only can escape the retaliation from a former opponent but also lose its invading effectiveness to cooperative clusters under this situation. Besides, extortion is also reciprocity mechanism that supports the survival of cooperation by the formation of cooperation-extortion alliance, but this alliance is threatened by large value of extortion factor χ, cooperation can thus only emerge in a certain range of χ [23,24,47]. Here, the combined effect of both mechanisms for the evolution of cooperation weakens the cooperation-extortion alliance and strengthens network reciprocity when the population density ρ is intermediate. However, the cooperative clusters and cooperation-extortion alliance are destroyed for too low population density, cooperation thus vanishes without any reciprocity mechanisms. For too high population density, cooperation-extortion alliance is the exclusive factor that supports cooperation, but the cooperation level is lower than that of the situations of intermediate population density due to the low efficiency of migration. Besides, since empty sites prohibit the formation of cooperation-extortion alliance, with decreasing population density ρ, the survival range of cooperation regarding extortion factor χ is narrowed. We thus provide a deeper understanding regarding the joint effect of both migration and extortion.

Declaration of Competing Interest

The authors declare that they do not have any financial or non-financial conflict of interests.

CRediT authorship contribution statement

Zhixue He: Data curation, Visualization, Software. **Yini Geng:** Writing - original draft. **Chen Shen:** Methodology, Investigation. **Lei Shi:** Project administration.

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Appendix A

In Fig. A.1, we investigate the samples near phase transition boundary which are selected from Fig. 4. Results show that all of samples can reach the steady state eventually, and there are no

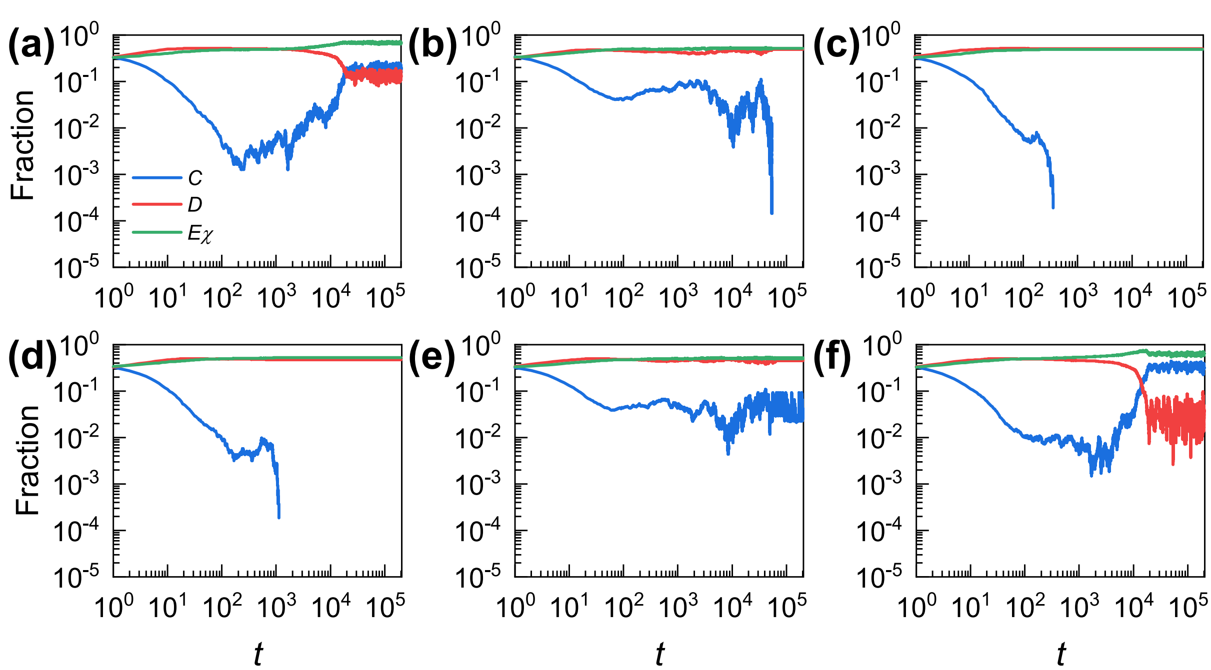

Fig. A1. The time evolution of cooperation (blue line), defection (red line) and extortion (green line) for (a)–(d) $\rho = 0.55$, $\chi = 5$, $b = 1.71$ and $b = 1.72$ respectively, (b)–(e) $b = 1.5$, $\rho = 0.7$, $\chi = 3.83$ and $\chi = 3.84$ respectively, (c)–(f) $b = 1.5$, $\chi = 5$, $\rho = 0.526$ and $\rho = 0.527$ respectively. The results are obtained for $L = 200$, entire 2×10^5 MC time steps. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

finite-size effects. In Fig. A.1(a)–(d), when b equals to 1.71, cooperation can endure the invasion of defection with the support of cooperation-extortion alliance at the early stage and finally coexist with defection and extortion in the populations. While a tiny increase of b (i.e. $b = 1.72$), cooperation is no longer endure the exploited of defection since this alliance is weakened at this point. The fluctuations are due to the fierce competition of the extortion and defection regarding the to the aggression against cooperation. This conclusion is also valid for the situations in Fig. A.1(b)–(e) and in Fig. A.1(c)–(f).

Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.chaos.2020.110421.

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