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Highlights

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- Both stubborn cooperators and stubborn defectors inhibit the evolution of cooperation.
- Stubborn cooperators play a prior role in the inhibition of cooperation.
- The stubborn players prevent the expansion of cooperative clusters in different ways.
- A small noise can resist the detrimental effects induced by the stubborn players.

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Effects of stubborn players and noise on the evolution of cooperation in spatial prisoner's dilemma game

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ABSTRACT

The question of whether a minority of extremists can dominate the collective behavior in social dilemmas is crucial for understanding the evolution of cooperation in both human societies and animal worlds. We establish a spatial prisoner's dilemma game model consisting of both stubborn cooperators and stubborn defectors who never change their behavior. The results reveal that a minority of stubborn players can effectively inhibit the evolution of cooperation. By introducing noise faced by stubborn players, however, we find that the inhibition of cooperation by the stubborn players can be easily canceled by the noise, which suggests a reasonable method for undermining the detrimental effects induced by extremists.

1. Introduction

Why human cooperation can emerge and be maintained in social dilemmas is a challenging problem in current science [1–7]. Because cooperative behavior provides benefits to others but impose costs upon self, the cooperators may suffer fitness losses and thus be exploited by defectors. Without other mechanisms, natural selection always favors defection in the evolutionary process. As a standard paradigm to bridge the chasm between various research fields, the evolutionary Prisoner's dilemma game(PDG) has been proposed to solve the puzzle of large-scale cooperation in the human world. In a one-shot PDG, two players choose between cooperation and defection. Although mutual cooperation leads to a Pareto optimal outcome, defection is always a better choice for the self-interested players.

A great number of mechanisms have been proposed to investigate how cooperation can be favored in evolutionary games. These mechanisms can be categorized into five types: kin selection, direct reciprocity, indirect reciprocity, spatial(network) reciprocity, and multilevel selection [8]. The crucial role of these mechanisms is that they provide the opportunity for assortment, which allows the cooperators to interact with other cooperators more frequently than with the defectors. The role of assortment in promoting cooperation is still a fruitful area in the current research on evolutionary PDG [9,10].

Spatial structure often plays a significant role in providing the opportunity for assortment. For example, in the standard spatial prisoner's dilemma game(SPD) with square lattice, cooperators can form clusters such that they have greater payoffs than the surrounding defectors because of the so-called spatial reciprocity [3]. Spatial reciprocity is further investigated by introducing more spatial structures(graph topologies) other than square lattices, such as random regular graphs, random graphs, small-world networks, and scale-free networks [11–14]. The reason why a structured population often favors cooperation compared to a well-mixed population is comprehensively examined. Ref. [12] has found that a condition for cooperation in structured populations is that the average connectivity is sufficiently small, which partly explains the inability of well-mixed populations to support cooperation. Refs. [14,15] have extensively studied the impact of spatial structure with other related model features such as synchronicity and update rules and found the relationship between update rules and the robustness of the spatial effects. Refs. [11,13] have demonstrated that scale-free networks may provide the most effective structure for the domination of cooperation and the structure effectiveness is strongly dependent on the age correlation between individuals on the networks.

Furthermore, a growing body of recent research has established that some behavioral anomalies such as stubborn individuals, or "zealots", in the updating process may have consequences for the evolution of cooperation in social dilemmas [16,17]. The consequences may be diverse in different settings. It is demonstrated that the direction of the consequences highly relates to the instinct network reciprocity offered by the network topology *per se* [16]. The studies of "zealots" in social dilemmas provide additional evidence that a minority of "zealots" or "strongly opinionated" individuals is sufficient to dominate the collective behavior in both human society and the animal world [18–22].

In this paper, we further study the consequences of a minority of stubborn players in an SPD consisting of both stubborn cooperators and stubborn defectors. In our model, a small fraction of the players

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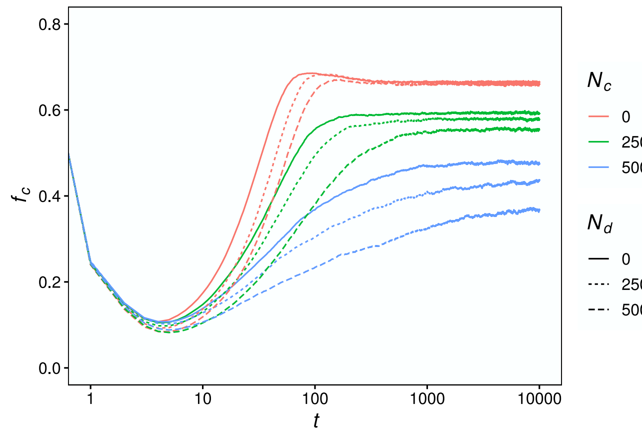
are stubborn and stick to their initial strategies (either cooperation or defection) through the entire evolutionary process. We can imagine that people's behavior in real society does not have the same level of flexibility. Although most individuals may respond to environmental changes quickly based on self-interest, others may have reasons (e.g., religious or ideological) to be stubborn and thus rarely change their behavior. For example, some individuals may see helping behavior as a moral imperative and therefore always cooperate in a social dilemma. On the other hand, some selfish individuals may always choose defection because it is the optimal solution for maximizing their utility. If some players always cooperate or always defect in the SPD, how will the evolution of cooperation be changed? We will find that the stubborn cooperators are even more detrimental to the evolution of cooperation compared to the stubborn defectors. In general, the existence of stubborn players inhibits the evolution of cooperation. We will investigate how the composition of two types of stubborn players affects the evolutionary process in a wide range of parameter settings.

2. Model

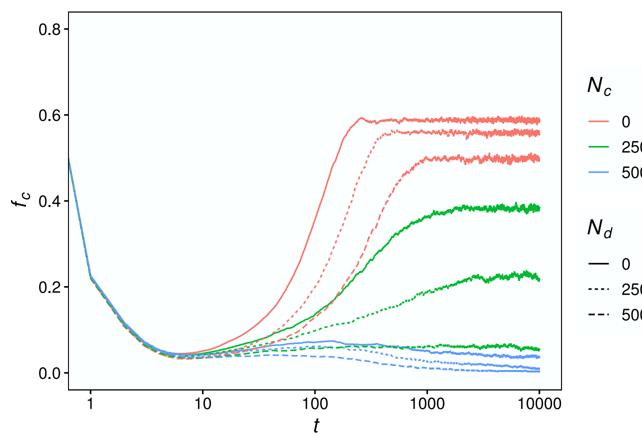
We consider an evolutionary PDG on an $L \times L = N$ square lattice (L is fixed at 100 in our simulations) with von Neumann neighborhood and periodic boundary conditions [3,23]. In each time step, the players may choose either cooperation or defection in a one-shot PDG where R represents the payoff for mutual cooperation, P represents the payoff for mutual defection, and T represents the payoff for unilateral defection, which leads to the payoff S for the cooperative player. For simplicity, we adopt the re-scaled payoff matrix: $T = b > 1$, $R = 1$, and $P = S = 0$ to allow us to characterize the game with the single "temptation" parameter b.

In our model, there are two different types of players. The active players are updated as in conventional SPDs. In contrast, the stubborn players, who may be either cooperators or defectors, are defined as the players who are never updated through the entire evolutionary process. All types of players are randomly distributed on a square lattice for each simulation. The active players are updated asynchronously in the following way: in each time step, each player could be chosen once on average as a focal player i interacting with his/her four direct neighbors to earn his/her cumulative payoff P_i and compare its payoff with that of its neighbors; if the richest neighbor's payoff is larger than that of the focal player i, the focal player will adopt the strategy of this neighbor with probability $1-\lambda$; the probability λ denotes environmental noise or trial-and-error behavior in our model which allows the active players to randomly reset their strategies and ensures that the evolutionary process can escape from frozen states.

In this paper, we will focus on the resulting cooperator frequency (f_C) in the active players. Thus, $f_C = \frac{N_{AC}}{N_A}$, where N_A is the number of active players and N_{AC} is the number of active cooperators. To investigate the effects of the stubborn players on the evolution of cooperation, we consider both the number of stubborn cooperators(N_c) and the number of stubborn defectors(N_d) as two important parameters for the studies. Note that if $N_d = 0$, the model here will partly degenerate to the zealots model discussed in Ref. [16]. Considering that even stubborn players may face noise in their behavior, we also provide a relaxation of the assumption that the stubborn players never change their strategies. We will introduce a small probability μ that a stubborn player may also update his/her strategy like the active players. If a stubborn player is chosen to be a focal player i to update, with probability $1-\lambda$, i adopts the strategy of the richest neighbor if i is poorer than the richest neighbor; with the probability λ, i randomly resets his/her strategy. If $\mu = 1$, the model degenerates into a standard SPD model, and we are interested in what parameter range of μ will the results of the modified model recover to a standard SPD.



(a) $b = 1.3$

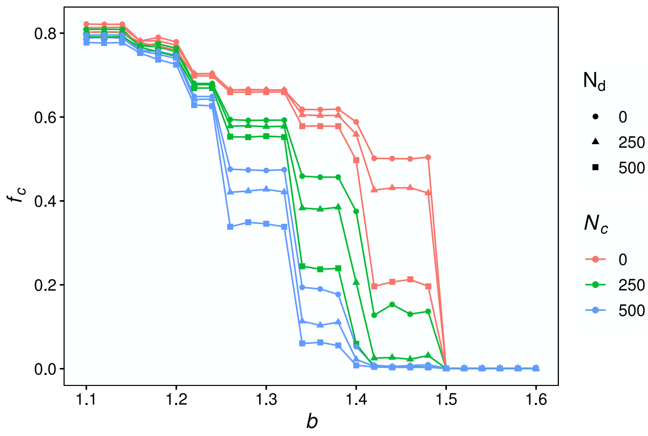


(b) $b = 1.4$

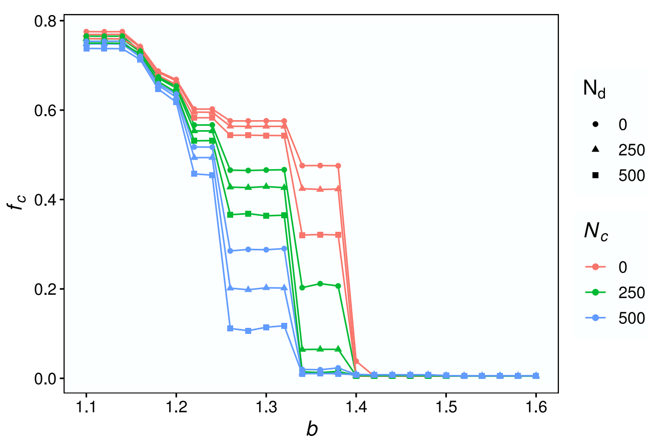
Fig. 1. The fraction of cooperators in active players as a function of time step t for different compositions of stubborn cooperators(N_c) and stubborn defectors(N_d) under different temptations b. Under both temptation levels, the structure of EXP periods is affected by the change of the numbers of stubborn players. Under low temptation $b = 1.3$, the existence of stubborn defectors does not affect the stationary cooperation level if there are no stubborn cooperators. When temptation is higher($b = 1.4$), both stubborn defectors and stubborn cooperators have more detrimental effects on the evolution of cooperation in active players. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results

First, we examine the evolutionary dynamics under some typical parameter settings and find out whether the stubborn players affect the outcome of SPD. Fig. 1 shows the fraction of cooperators in the active players as a function of time for different combinations of the numbers of stubborn players with temptation $b = 1.3$ and $b = 1.4$. In the $b = 1.3$ case, we see that there is always a demonstrable END period followed by an EXP period in the evolutionary process [9,24–27]. However, the quantitative outcomes of these periods are altered by the two types of stubborn players. When there are no stubborn defectors, N_c does not change the END period where the cooperators face a fast invasion of defectors, but the existence of stubborn cooperators significantly changes the evolutionary paths in the active players during the EXP period once the END period is over (see three solid lines with different colors). We also note that when there are no stubborn cooperators, the existence of stubborn defectors affects only the evolutionary path but not the stationary cooperation level. Moreover, it seems that the stubborn cooperators have more effects on the final cooperation level compared to the stubborn defectors. Controlling N_d (note the same type

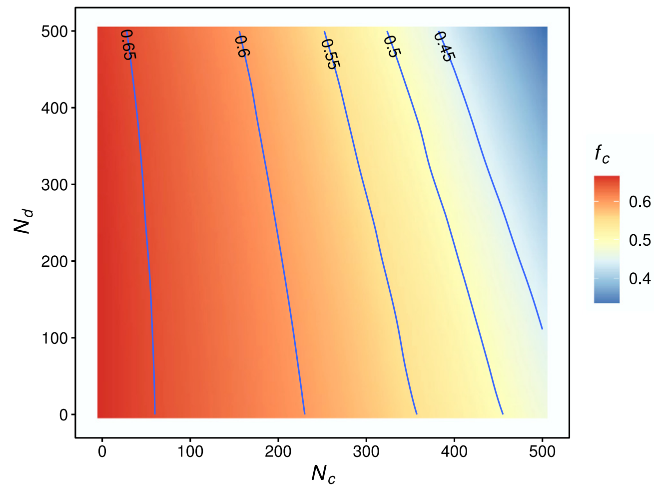


(a) $\lambda = 0.001$

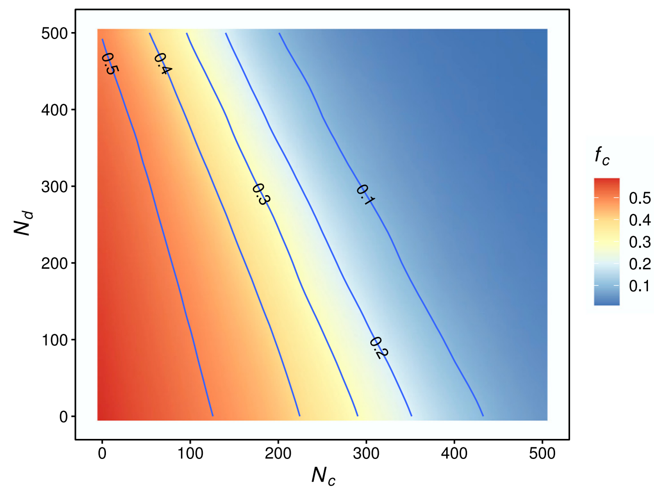


(b) $\lambda = 0.01$

Fig. 2. The fraction of cooperators in active players as a function of temptation b for different compositions of stubborn cooperators(N_c) and stubborn defectors(N_d) under different imitation noise λ. The cooperation level exhibits discontinuous transitions under both imitation noise. The critical points are almost the same if we only consider low temptation levels($b < 1.4$). When temptation is large, the high imitation noise may eliminate the condition for the survival of cooperators.



(a) $b = 1.3$



(b) $b = 1.4$

Fig. 3. The fraction of cooperators in the active players as a function of N_c and N_d under different temptation b. The stubborn cooperators always play a more significant role, but the detrimental effects of stubborn defectors can be enhanced if the evolution of cooperation is already inhibited by the other factors.

of lines), the increase of stubborn cooperators significantly reduces the final cooperation level. Overall, the mixture of the stubborn players not only alters the evolutionary path but also quantitatively changes the final cooperation level in the SPD.

In the $b = 1.4$ case, the stubborn players change not only the quantitative outcomes but also the qualitative features of the evolution. In this high temptation condition, the EXP periods may even disappear in some compositions of stubborn players. When there are no stubborn cooperators, the change of N_d changes both the evolutionary path and final cooperation level, which is different from the low temptation case. When N_c is moderate, the stubborn defectors have more significant detrimental effects on the cooperation level, indicating that the mixture of stubborn cooperators and defectors has some synergistic effects on the evolution. In the combination of $N_c = 250$ and $N_d = 500$, we see the first case where the EXP period disappears. Furthermore, a large N_c is sufficient to cause the disappearance of the EXP periods regardless of N_d, which again emphasizes the prior role of the stubborn cooperators.

The dependence of f_C on temptation b is shown in Fig. 2. Not surprisingly, we see that the cooperation level exhibits discontinuous transitions often found in other SPD models. The existence of stubborn players does not change the critical points of the transitions, but it will change the quantitative level of cooperation for most temptation levels.

In the case of low imitation noise($\lambda = 0.001$), when temptation is very low ($b < 1.25$), the cooperation levels are only reduced slightly by the stubborn players and are still at high levels, but the stubborn players may significantly reduce the cooperation level as the temptation is higher ($b \geq 1.3$). When $b = 1.3$, as seen in Fig. 1(a), stubborn defectors affect the cooperation level only if stubborn cooperator coexist. In this case, we note again the prior role of stubborn cooperators in the inhibition of cooperation. When $b = 1.36$, as another representative example, stubborn defectors may reduce the cooperation level whenever stubborn cooperators coexist, and when N_c is moderate or large, the reductions in cooperation level by stubborn defectors are more significant. When the temptation is at a high level ($b > 1.4$), Both the existence of stubborn cooperators and the existence of stubborn defectors have significant detrimental effects on the evolution of cooperation. This indicates that if the evolution of cooperation is already inhibited by the other factors, the stubborn players will further worsen the conditions for the emergence and maintenance of cooperation in evolution. In particular, a sufficient number of stubborn cooperators is enough to eliminate the existence of cooperators in the active players regardless of the number of stubborn defectors.

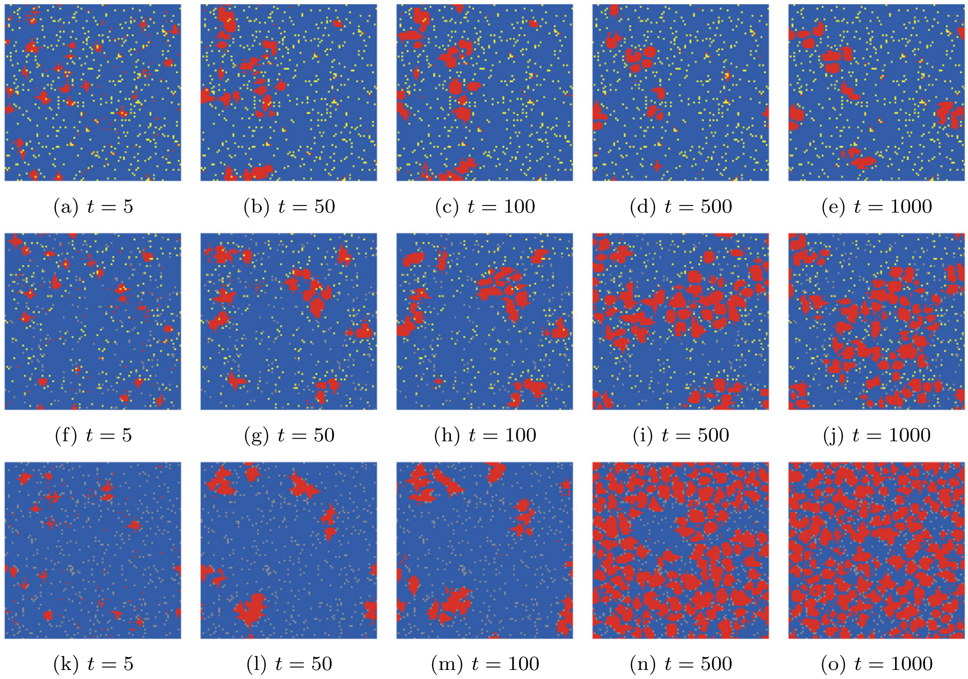


Fig. 4. Typical snapshots of distributions of active cooperators(red), active defectors(blue), stubborn cooperators(yellow), and stubborn defectors(gray) for different compositions of stubborn cooperators and defectors when the total number of stubborn players is fixed at 500. (a)-(e) Only stubborn cooperators exist without stubborn defectors($N_c = 500, N_d = 0$). (f)-(j) stubborn cooperators and defectors coexist($N_c = 250, N_d = 250$). (k)-(o) Only stubborn defectors exist without stubborn cooperators($N_c = 0, N_d = 500$). Note that the stubborn cooperators create parasitic defectors and hinder the expansion of cooperative clusters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

If the imitation noise is higher($\lambda = 0.01$), we see that although the high noise is a detrimental factor for cooperation, it does not change the critical points of the transitions when temptation is sufficiently low($b <$ 1.4). However, in addition to the quantitative decrease of cooperation levels, it will eliminate the range of temptation $b > 1.4$ for the survival of cooperators. Therefore, the critical point of the transitions in high temptation values may be changed by the high noise level.

Fig. 3 shows the stationary cooperation levels on a $N_c - N_d$ plane with different temptation levels. By comparing the two cases of $b = 1.3$ and $b = 1.4$, we see that although the stubborn cooperators always play a more significant role, the impact of stubborn defectors can be enhanced by enlarging temptation b or the number of stubborn cooperators N_c. If temptation is low, the stubborn defectors can hardly lower the cooperation level without the coexistence of stubborn cooperators. This means that the inhibition by the stubborn defectors only works under unfavorable conditions for the evolution of cooperation. A minority of defectors *per se* may not be sufficient to worsen the conditions for high cooperation level. The effects of stubborn cooperators are clear in both cases, but the effects are also dependent on the existence of stubborn defectors and temptation. When temptation is high enough, a minority of stubborn players consist of both cooperators and defectors in the population(less than 10%) suffice to eliminate the existence of active cooperators.

If a fraction of individuals always cooperate and play a role as exemplars to bootstrap a cooperative environment, can large-scale cooperation be boosted in a society? The above results show that so long as some individuals never alter their behavior (no matter what the initial strategies are chosen) to react to environmental changes, the whole society will be even more unfavorable compared to the situation where all individuals have adaptive reactions. We even found that stubborn cooperators are more detrimental to society compared to stubborn defectors. To understand this, let us now focus on the spatial patterns generated by our model shown in Fig. 4. In SPD, a crucial characteristic for the emergence of cooperation is that clusters of cooperators can be formed and avoid the invasion of defectors to further expand. Whether a high cooperation level can be attained depends on the scales of the clusters of cooperators that can be formed and enlarged. From the snapshots in Fig. 4, we can investigate the reason why two types of stubborn players inhibit the expansion of the cooperative clusters thus reducing the overall level of cooperation. We consider three cases where the total number of stubborn players is fixed at 500. When only stubborn cooperators exist, after the END period, some small cooperative clusters remain and try to further expand, but the expansion is heavily hindered by the surrounding stubborn cooperators. Only a small number of tiny clusters can be formed and remain. New clusters may emerge through mutation and selection, but the existing clusters may also disappear facing the invasion of defectors. Why do the stubborn cooperators hinder the expansion of cooperative clusters? The reason is clear from the snapshots. The stubborn cooperators are always surrounded by some active defectors who can constantly exploit the stubborn cooperators and play the role of a parasite. The coexistence of the stubborn and parasitic defectors, therefore, forms a consolidated wall to prevent the further expansion of the cooperative clusters. The clusters can never cross the walls to expand or connect to the other clusters to form larger and safer clusters to resist the invasion of defectors. When stubborn cooperators and defectors coexist, we also see that the expansion of cooperative clusters is heavily hindered by the surrounding stubborn players, but the number of clusters formed and maintained is larger than the $N_c = 500$ case. The stubborn defectors also become a wall to prevent the expansion of cooperative clusters, but they have no parasite to enhance the power of preventing expansion. Although the positions of stubborn defectors themself can resist the expansion to a specific direction, the cooperative clusters still have the chance to spill over to other directions without the appearance of stubborn players. We can have more knowledge of why the stubborn cooperators play a more significant role in preventing the expansion of cooperative clusters thus inhibiting the evolution of cooperation by comparing the effects of the two different types of stubborn players in the present case. Lastly, when only stubborn defectors exist, it is shown that although the emergence and expansion of cooperative

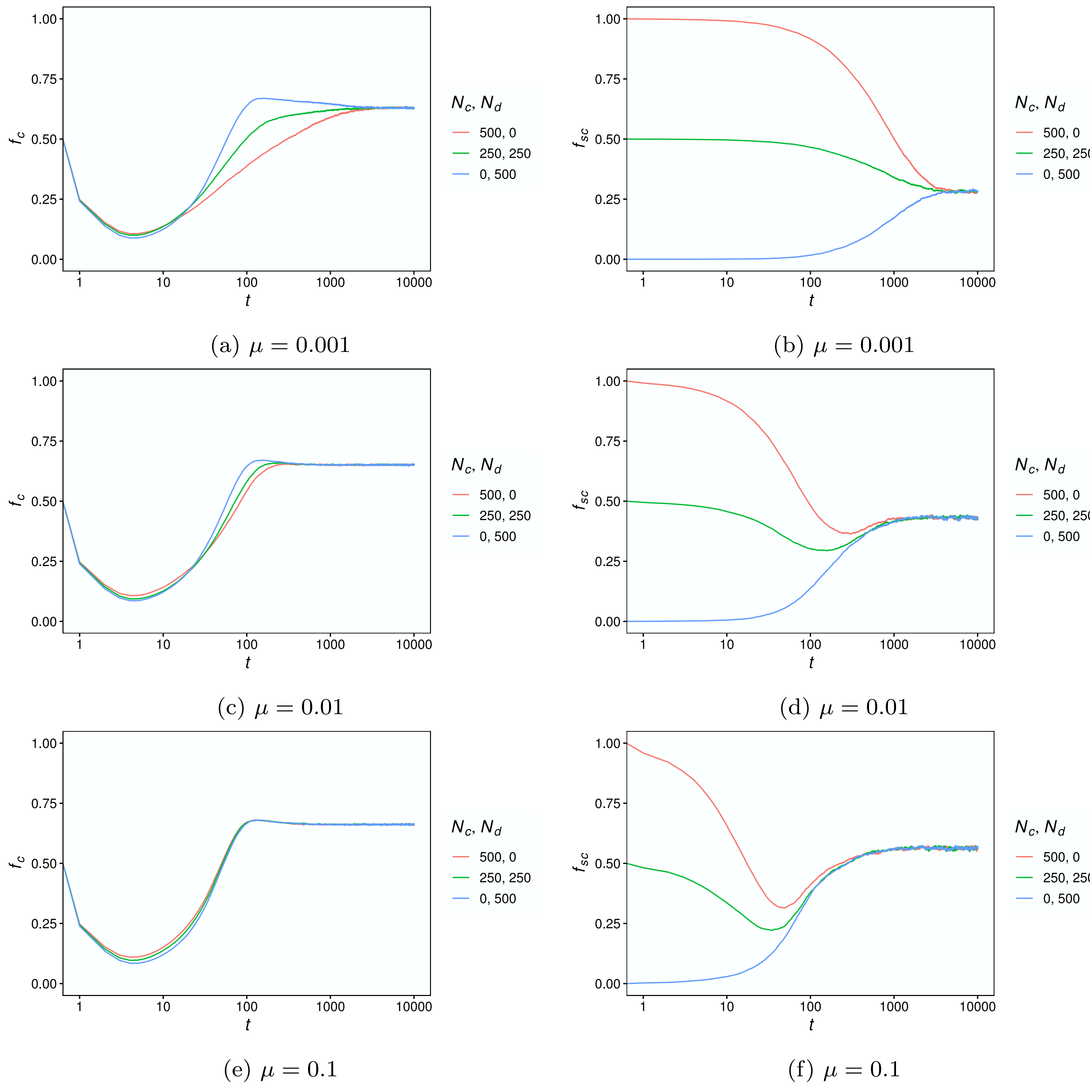
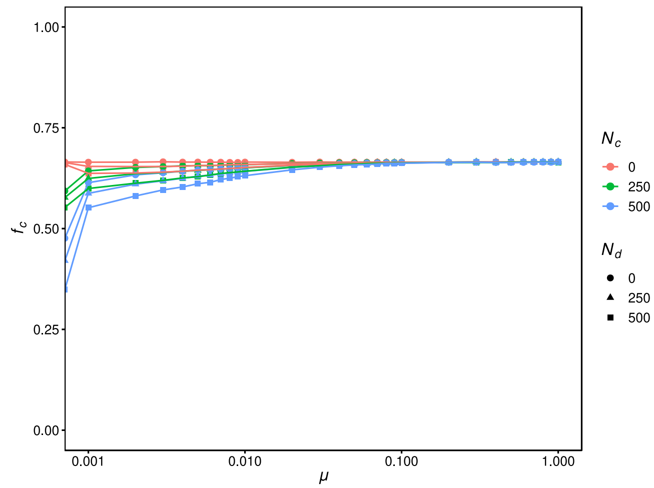


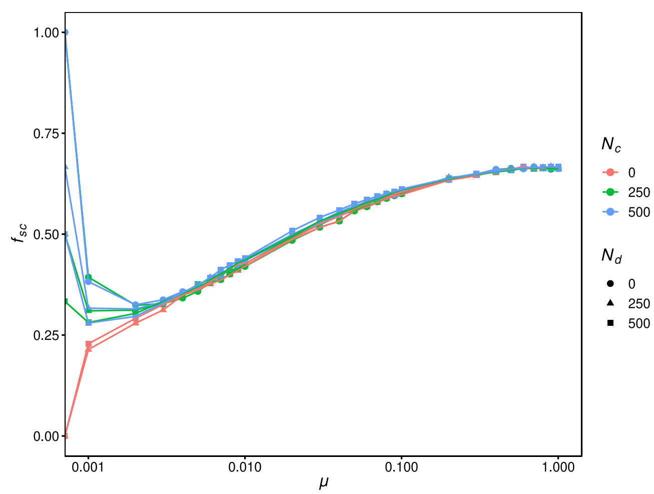
Fig. 5. The fraction of cooperators in the active players as a function of time step t for different compositions of stubborn cooperators(N_c) and stubborn defectors(N_d) under different μ. (a),(c,(e) The evolution of cooperation in active players under different μ. (b),(d),(f) The evolution of cooperation in stubborn players under different μ. If the stubborn players also update by chance, the results in the standard SPD can be approximated. The final stationary cooperation levels will converge for both active players and stubborn players if the total number of stubborn players is fixed.

clusters are slowed in the EXP period, the final cooperation level is only affected quantitatively. This is because stubborn defectors have no parasite and only the positions of defectors themself become very weak walls in preventing the expansion. The stubborn defectors can prevent only the connection and union between neighboring clusters, but not the emergence and maintenance of small cooperative clusters through mutation and selection in the long run.

From the above results, we have already known that when some players become static and never change their behavior, the evolution of cooperation in SPD will be inhibited because the effects of spatial reciprocity are weakened by the stubborn players surrounding the cooperative clusters. If this mechanism is in effect, it will become a real-world problem because stubborn individuals may exist in society. An individual who never defects will no longer be an exemplar of a good society, but become an enhancement factor for the proliferation of defectors. To assess the realistic effects of the stubborn players in our model for real society, we further explore our model by relaxing the key assumption that stubborn players never change their behavior throughout the evolution process. A small probability μ is introduced which allows a stubborn player may update he/her strategy (learn from others or mutate) when he/her is chosen as a focal player. Fig. 5 shows the evolution of cooperation in both active players and stubborn players under different update probability μ for stubborn players. Interestingly, a small probability μ is sufficient for our model to approximate, at least in the active players, the standard SPD. Firstly, if we fix the total number of stubborn players, the composition of stubborn cooperators and defectors does not affect the final stationary cooperation level. Of course, the composition still affects the evolutionary path quantitatively or qualitatively. The minimum cooperation level after the END period correlates to the initial composition: the higher the fraction of initial stubborn cooperators, the higher the minimum cooperation level in the active players after the END period. However, the existence of stubborn cooperators is not favorable for the expansion of active cooperators. We see the increase of active cooperators can be slowed by the higher fraction of stubborn cooperators especially when μ is small. In all cases, meanwhile, the composition of stubborn players also evolves to converge to the same stationary states regardless of the initial composition. In fact, the convergence in stubborn players is later than the convergence in the active players. This is because the effects of stubborn players diminish over time and the evolutionary process is eventually dominated by the active players. Another observation is that when μ is large, the stubborn players often face a slow END period after which their cooperation level recovers to a moderate level. The END period in stubborn players is beneficial to the evolution of



(a)



(b)

Fig. 6. The fraction of cooperators in the active players and stubborn players as a function of μ. (a) The fraction of cooperators in the active players when the stubborn players have chances to change their behavior. (b) The fraction of cooperators in stubborn players when they have chances to change their behavior. A small probability $\mu > 0.01$ is enough to ensure that the cooperation level in the active players approximates that in the standard SPD. The cooperation level in the stubborn players also converges to a high level if μ is sufficiently large.

cooperation in the active players because the defectors outside the cooperative clusters can hardly exploit the stubborn cooperators. If the reduction of stubborn cooperators is significant in this END period, the EXP period in the active players approximates that in standard SPD(see the $\mu_O = 0.1$ case). It is also noted that the stationary cooperation level in the stubborn players is lower than that in the active players in all cases. Therefore, we can expect that the stubborn players still have a quantitative impact on the stationary cooperation level.

We try to find the condition under which the model can approximate the standard SPD by investigating the effects of μ on the stationary cooperation levels in Fig. 6. In most cases, the higher the value of μ, the easier the cooperation level in the active players approximates that in the standard SPD. The only exception is that when only stubborn defectors exist initially, a small μ may slightly decrease the cooperation level compared to the $\mu = 0$ case. However, when μ becomes larger, the cooperation level will be recovered like in the other cases. The cooperation level in the stubborn players also will converge to some level regardless of the initial composition if μ is sufficiently large. Once the convergence can be reached, the higher the value of μ, the higher the cooperation level can be attained in the stubborn players. This is predictable because if μ approximates 1, the model will degenerate to the standard SPD. If the stubborn players update frequently like the active players when μ is sufficiently large, the cooperation level in the stubborn players must coincide with the cooperation level in the active players.

Finally, we also check the snapshots of the modified model in Fig. 7 to understand the evolutionary dynamics of both active players and stubborn players. In all three cases, the final results are similar regardless of the initial composition, but we also see that the initial stubborn cooperators can slow the expansion of cooperative clusters more significantly than the stubborn defectors. On the other hand, a stubborn cooperator outside of the cooperative clusters will change into a defector and thus no longer be a detrimental factor for the expansion of cooperative clusters. This long-run dynamic will lead the model to approximate the standard SPD. The snapshots also tell us why the stubborn players remain at a relatively low cooperation level. Most stubborn players will remain outside the cooperative clusters. A stubborn defector can never be inside a cooperative cluster because a defector inside a cooperative cluster will fully invade this cluster. A stubborn cooperator can be inside a cooperative cluster, but he/she may change into a defector by mutation in the long run and finally destroy the cluster. The players outside the cooperative clusters cannot maintain a high cooperation level therefore the overall cooperation level in stubborn players remain low. Fortunately, the relatively low level of cooperation in stubborn players is beneficial to the recovery of the high level of cooperation which approximates the level in standard SPD.

4. Conclusion

In this paper, we established an SPD model which consists of both stubborn cooperators and stubborn defectors to investigate how the anomaly in updating affects the evolution of cooperation. The simulation results show that both stubborn cooperators and stubborn defectors can inhibit the evolution of cooperation in the EXP period where spatial reciprocity plays a crucial role in the expansion of cooperative clusters. Furthermore, we have found that stubborn cooperators often play a dominant role in the inhibition of cooperation, which is consistent with the results in Ref. [16]. In the microscope analysis of the evolutionary dynamics and spatial patterns, we found the reason why stubborn cooperators are more detrimental to the evolution of cooperation compared to stubborn defectors. The stubborn defectors only resist the expansion of cooperative clusters to a narrow direction, and the cooperative clusters still have a chance to spill over and connect to other clusters. In contrast, the stubborn cooperators always have parasitic defectors surrounding them thus forming a solid wall to effectively prevent the expansion of cooperative clusters.

As stubborn individual behavior may be ubiquitous in human society, it is urgent to investigate how this stubbornness affects the social outcome in many areas such as infectious disease [17,28–30] and cooperative behavior [16]. Another perspective is that even stubborn individuals may face noise in their choice or perception, which is neglected in the previous studies. Like normal individuals, stubborn individuals may also be imperfect when perceiving the environment information or selecting their behavior. If such noise exists, will the results induced by stubborn players be changed? To answer this question, we have also provided a relaxation of the assumption that stubborn players never change. If the stubborn players face the noise which allows them to change behavior, the inhibitive effects on cooperation will be significantly weakened through the dynamics of the stubborn players themself. In particular, the stubborn cooperators outside the cooperative clusters will change into defectors in the long run and thus no longer prevent the expansion of cooperators along with the

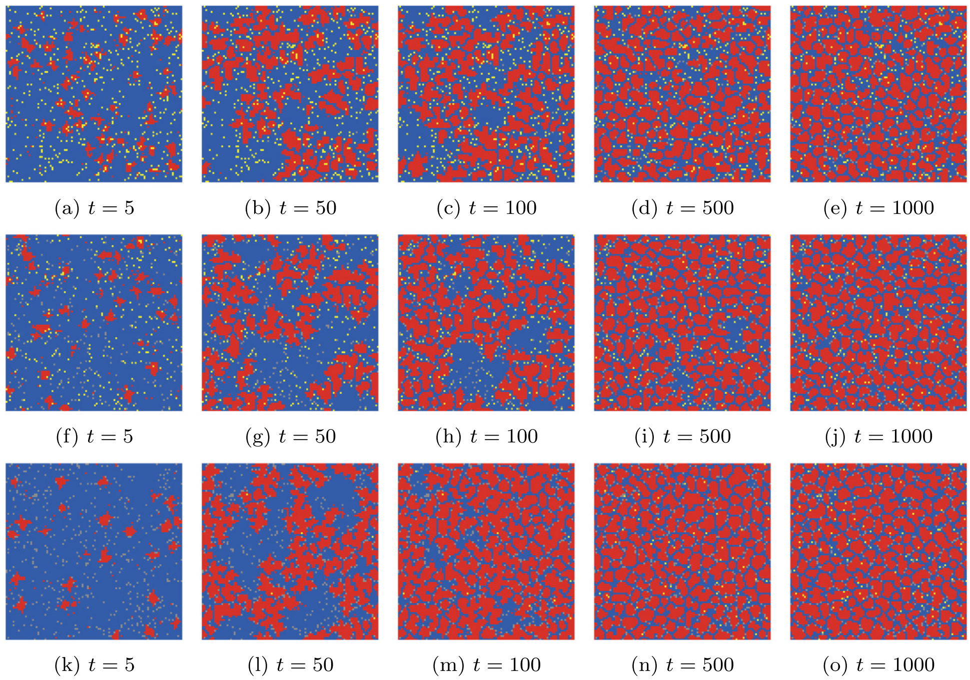


Fig. 7. Typical snapshots of distributions of active cooperators(red), active defectors(blue), stubborn cooperators(yellow), and stubborn defectors(gray) for different initial compositions of stubborn cooperators and defectors when the total number of stubborn players is fixed at 500, but the stubborn players have chances to abandon their current strategies and update just like active players. (a)-(e) Only stubborn cooperators exist without stubborn defectors($N_c = 500, N_d = 0$). (f)-(j) stubborn cooperators and defectors coexist($N_c = 250, N_d = 250$). (k)-(o) Only stubborn defectors exist without stubborn cooperators($N_c = 0, N_d = 500$). Other parameters: $b = 1.3$, $\lambda = 0.001$, $\mu = 0.01$. The stubborn cooperators may disappear outside of the cooperative clusters and can no longer create parasitic defectors to hinder the expansion of cooperative clusters. The initial composition of stubborn cooperators and stubborn defectors has little effect on the final cooperation level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

parasitic defectors. A small noise in stubborn players is sufficient to allow the evolutionary outcome to approximate the results in standard SPD. Considering that the existence of noise in stubborn individuals is a more realistic assumption(compared to the no-noise assumption), we can assess more precisely the effects of stubborn behavior on social life.

Another observation is that whether the noise in stubborn players exists or not, most of the stubborn players stay outside the cooperative clusters. This phenomenon indicates that stubborn individuals may be harder to integrate into a mainstream society where cooperation is established. Therefore, a real society may have sufficient adaptability to keep away from the detrimental effects of stubborn individuals. The phenomenon may also relate to social expulsion as an effective solution to promote cooperation in social dilemmas [31–36]. Although the underlying mechanisms are different, we can see similar patterns where the cooperators and defectors can be segregated to provide a sufficient assortment to bolster the proliferation of cooperation.

A limitation of the present work is that all the stubborn players are placed randomly in the lattice. In real society, however, stubborn individuals may have some preference in their choice of spatial location and therefore resulting in different social outcomes. As demonstrated in Ref. [37], strategic placement of cooperators may enhance the takeover of cooperation in SPD, which indicates that the design of initial states in networks is crucial for the evolutionary process. The method we used to place the initial stubborn players of both cooperators and defectors may also have an impact on the evolutionary process in SPD, especially for heterogeneous networks. Imagine if a hub node in heterogeneous networks is more likely to be a stubborn player, will the evolution of cooperation be damaged or further promoted compared to the conditions where all players are equally likely to be stubborn? Future work on this perspective can help us to further understand the effects of stubborn behavior in the real world.

CRediT authorship contribution statement

Hong Zhang: Conceptualization, Methodology, Software, Validation, Writing – original draft.

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.

Data availability

Data will be made available on request.

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